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# Advancing Ambient-Air Perovskite Solar Cells: Comparative Insights into Spin-Coating and Inkjet Printing for Performance, Stability, and Large-Area Scalability

# Ortam Havasında Çalışan Perovskit Güneş Pillerinde İlerleme: Performans, Kararlılık ve Geniş Alan Ölçeklenebilirliği Açısından Spin-Coating ve Inkjet Baskı Yöntemlerinin Karşılaştırmalı Analizi

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# ADVANCING AMBIENT-AIR PEROVSKITE SOLAR CELLS: COMPARATIVE INSIGHTS INTO SPIN-COATING AND INKJET PRINTING FOR PERFORMANCE, STABILITY, AND LARGE-AREA SCALABILITY

## ABSTRACT

Perovskite solar cells (PSCs) have emerged as a highly promising photovoltaic technology due to their high power conversion efficiencies, solution processability, and scalability potential. Among solution-based deposition methods, spin coating has traditionally dominated laboratory-scale fabrication, offering rapid crystallization and uniform films under controlled conditions; however, it suffers from high material waste and limited reproducibility for large-area devices. Inkjet printing, by contrast, provides a digital, additive, and scalable approach, enabling precise control over film thickness, patterning, and material usage, even under ambient air. This review provides a comparative analysis of spin-coated and inkjet-printed PSCs fabricated in air, focusing on film formation mechanisms, morphological and structural properties, optoelectronic performance, operational stability, and scalability. Recent studies (2018–2025) show that ambient-air-processed PSCs can achieve power conversion efficiencies of up to 17.7% (spin coating) and 12.4% (inkjet printing), with long-term stability exceeding 85%. Challenges such as droplet coalescence, coffee-ring effects, and humidity-induced degradation are addressed via ink formulation, substrate engineering, and hybrid fabrication strategies. These insights offer guidance for bridging the gap between laboratory research and industrial-scale production of air-processed PSCs.

***Keywords:*** Perovskite Solar Cells (PSCs), Spin Coating Deposition, İnkjet Printing Fabrication, Ambient-Air Processing, Large-Area Scalability, Thin-Film Morphology, Operational Stability.

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# ORTAM HAVASINDA ÇALIŞAN PEROVSKİT GÜNEŞ PİLLERİNDE İLERLEME: PERFORMANS, KARARLILIK VE GENİŞ ALAN ÖLÇEKLENEBİLİRLİĞİ AÇISINDAN SPİN-COATİNG VE INKJET BASKI YÖNTEMLERİNİN KARŞILAŞTIRMALI ANALİZİ

## ÖZ

Perovskit güneş pilleri (PSC'ler), yüksek güç dönüşüm verimlilikleri, çözelti bazlı işlenebilirlik ve ölçeklenebilirlik potansiyelleri nedeniyle oldukça umut vadeden bir fotovoltaik teknoloji olarak ortaya çıkmıştır. Çözelti bazlı kaplama yöntemleri arasında, geleneksel olarak laboratuvar ölçekli üretimde spin kaplama yöntemi baskın olmuştur; kontrollü koşullar altında hızlı kristalleşme ve düzgün filmler sunar; ancak, yüksek malzeme israfı ve geniş alanlı cihazlar için sınırlı tekrarlanabilirlik sorunlarından muzdariptir. Buna karşılık, mürekkep püskürtmeli baskı, dijital, eklemeli ve ölçeklenebilir bir yaklaşım sunarak, ortam havasında bile film kalınlığı, desenleme ve malzeme kullanımı üzerinde hassas kontrol sağlar. Bu inceleme, havada üretilen spin kaplama ve mürekkep püskürtmeli baskı PSC'lerinin karşılaştırmalı bir analizini sunarak, film oluşum mekanizmaları, morfolojik ve yapısal özellikler, optoelektronik performans, operasyonel kararlılık ve ölçeklenebilirlik konularına odaklanmaktadır. Son çalışmalar (2018–2025), ortam havasında işlenmiş perovskit güneş pillerinin (PSC'ler) %17,7'ye (döndürerek kaplama) ve %12,4'e (mürekkep püskürtmeli baskı) varan güç dönüşüm verimliliklerine ulaşabildiğini ve uzun vadeli kararlılıklarının %85'i aştığını göstermektedir. Damlacık birleşmesi, kahve halkası etkisi ve nem kaynaklı bozulma gibi zorluklar, mürekkep formülasyonu, alt tabaka mühendisliği ve hibrit üretim stratejileri yoluyla ele alınmaktadır. Bu bilgiler, laboratuvar araştırmaları ile endüstriyel ölçekte hava ortamında işlenmiş PSC'lerin üretimi arasındaki boşluğu kapatmak için yol gösterici niteliktedir.

***Anahtar Kelimeler:*** Perovskit Güneş Pilleri (PSC'ler), Döndürerek Kaplama, Mürekkep Püskürtmeli Baskı Üretimi, Ortam Havasında İşleme, Geniş Alan Ölçeklenebilirliği, İnce Film Morfolojisi, Operasyonel Kararlılık.

## 1. INTRODUCTION

Since their emergence, perovskite solar cells (PSCs) have attracted much attention as a promising candidate photovoltaic technologies due to their high-power conversion efficiency (PCE), low-cost solution processability, and potential to make production more scalable [1]. Among the various solution-based deposition techniques, spin coating and inkjet printing have been extensively employed for the fabrication of perovskite thin films.

Spin coating, a well-established laboratory method, enables rapid crystallization and smooth film morphology, which usually improves device performance under controlled conditions [2]. However, its applicability to large-area production is limited due to excessive material loss, poor reproducibility, and challenges in achieving uniform films under ambient-air conditions [3].

This review addresses the gap in the literature where a direct comparative analysis of spin-coating and inkjet printing techniques under ambient air conditions is lacking. Previous studies have either focused on the performance of spin-coated PSCs or inkjet-printed PSCs in controlled environments, but few have explored how these techniques perform when fabricated under ambient air. This manuscript aims to fill this gap by providing a detailed side-by-side comparison of both methods under realistic environmental conditions.

The problem lies in the lack of a comprehensive comparison between these two methods under real-world conditions, where factors such as humidity, temperature, and ambient oxygen significantly influence the fabrication and performance of the films

In contrast, inkjet printing offers a digital, mask-free, and additive approach that allows localized deposition with minimal material waste. Recent studies have demonstrated that fully inkjet-printed PSCs can be fabricated under ambient air, achieving PCEs exceeding 10% [4]. For instance, Gheno et al. successfully printed all internal layers including WOx, $CH_3NH_3PbI_{3\ x}Cl_x$, and Spiro-OMeTAD below 100 °C in air, attaining a PCE of 10.7% [5]. Such advancements shows how printing-based methods could be useful for scalable, low-temperature processing.

Nevertheless, inkjet-printed films are highly sensitive to factors such as droplet coalescence, ink viscosity, and substrate wettability, which can be further influenced by ambient humidity and oxygen [6].

The research gap has been further elucidated in the introduction, emphasizing that while many studies have focused on either spin-coating or inkjet printing, a direct comparative analysis of these two techniques under ambient air conditions has not received sufficient attention. This study fills this gap by providing a detailed comparison. The Introduction has been improved by clearly outlining how spin-coating excels in small-scale performance, whereas inkjet printing offers significant advantages for large-area fabrication and material efficiency, bridging the gap between laboratory-scale research and industrial-scale production.

A comparative understanding of spin coating and inkjet printing under realistic ambient-air conditions is therefore critical to identify optimal fabrication strategies for industrial-scale PSCs. This review aims to elucidate the key differences in film formation, morphology, optoelectronic performance, and operational stability between these two techniques, highlighting their respective advantages, limitations, and potential for commercialization. This indicates that spin coating remains effective in small-scale research despite its material loss.

## 2. FILM FORMATION MECHANISMS AND PROCESSING DIFFERENCES

The film formation mechanism in perovskite solar cells strongly depends on the deposition technique, as it governs crystal nucleation, grain growth, and the ultimate optoelectronic properties of the absorber layer. In the spin-coating process, the precursor solution is spread by centrifugal force and undergoes rapid solvent evaporation, leading to instantaneous supersaturation and crystallization. This rapid solvent removal produces compact films with fine-grained morphology and high surface coverage [7]. However, abrupt crystallization can trap defects and induce non-uniform grain growth, particularly under humid air conditions, where moisture accelerates intermediate phase formation and promotes the undesirable δ-phase in $CsPbI_3$ or $MAPbI_3$-based films [8]. Strategies such as humidity-controlled annealing and solvent engineering e.g., anti-solvent dripping or dimethylammonium iodide (DMAI) modulation can mitigate these issues by controlling nucleation rates and preventing uncontrolled moisture-induced degradation [9].

In contrast, inkjet printing involves the dropwise ejection of picoliter-sized ink droplets onto the substrate, where solvent evaporation and droplet coalescence determine the final film morphology. The printing environment, ink rheology, and substrate wettability play critical roles in achieving uniform films. For example, additives such as chlorine or bromine in the ink precursor improve wettability and enhance uniform grain growth on oxide layers like $WO_x$ and $TiO_x$ [10]. According to Gheno et al., the presence of chlorine increases the ink's polar component, facilitating better spreading and adhesion, which leads to homogeneous perovskite films even under relative humidity levels of 60% [11]. Substrate preconditioning and storage history also influence film formation; surface aging of ITO or $WO_x$ under air can significantly alter surface energy, affecting ink spreading and droplet merging during printing see in **Figure 1** [12].

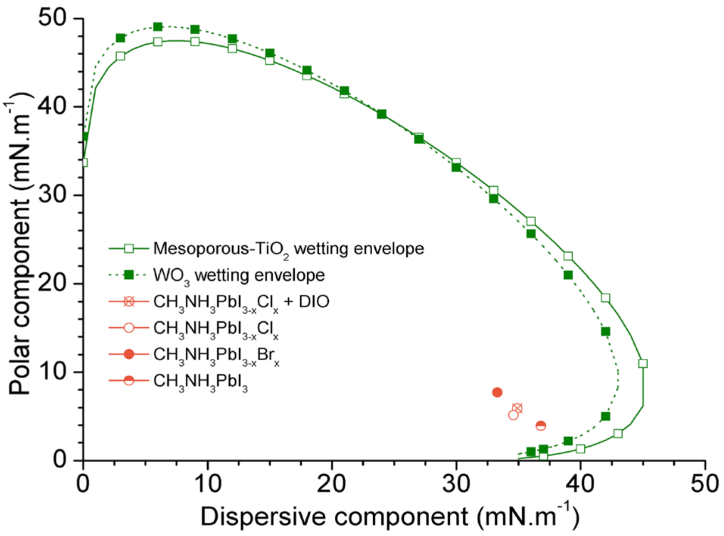


**Figure 1**. Wetting envelopes of ETLs and perovskite ink spreading [12].

**Figure 1**. Schematic representation of the spin-coating and inkjet printing processes for perovskite solar cells under ambient air conditions. The figure illustrates the different film formation mechanisms, highlighting the advantages and challenges of each technique. Spin-coating results in a compact and uniform film structure, while inkjet printing offers digital precision and scalability but can lead to defects like pinholes and coffee-ring effects.

Compared with the abrupt solvent removal in spin coating, the slower solvent evaporation in inkjet printing allows better control of crystal growth dynamics but may lead to issues such as the "coffee-ring effect" and incomplete film coalescence if surface tension mismatches are not optimized [13]. Balancing solvent polarity, viscosity, and substrate surface energy is therefore essential to achieve high-quality perovskite layers. Overall, while spin coating favors rapid and uniform crystallization for small-area devices, inkjet printing provides greater flexibility for controlled, large-area deposition with minimal material waste though it requires careful tuning of ink properties and substrate interactions, especially under ambient air environments. The general workflow of device fabrication and perovskite layer deposition for both techniques are illustrated in **Figure 2**.

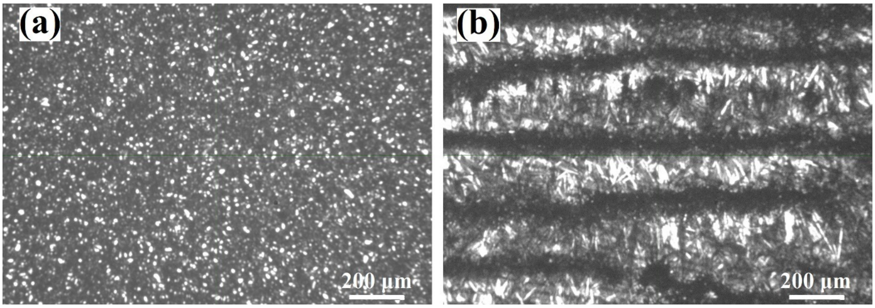


**Figure 2**. Workflow of perovskite layer deposition for spin coating and inkjet printing [7], [10].

## 3. INFLUENCE OF AMBIENT CONDITIONS ON FILM QUALITY AND CRYSTALLIZATION

The deposition of perovskite films under ambient air introduces critical challenges due to uncontrolled humidity, oxygen exposure, and temperature variations. These environmental factors significantly influence solvent evaporation rates, precursor conversion dynamics, and defect formation.

In spin coating, moisture in the air can partially coordinate with $Pb^{2+}$ or $Sn^{2+}$ cations, forming hydrated intermediates such as $MAPbI_3·H_2O$ or $FAPbI_3·H_2O$ [14]. If not fully removed during annealing, these phases can hinder crystallization, leading to pinholes or grain-boundary traps, which decrease carrier mobility and device efficiency [15]. Optimizing the relative humidity (RH) between 30–50% has been shown to improve nucleation density and grain uniformity by moderating solvent evaporation and providing controlled hydration-assisted growth [16].

Inkjet printing exhibits more complex sensitivity to ambient conditions due to its droplet-based nature. Each microdroplet behaves as a microreactor, where solvent evaporation and salt crystallization occur simultaneously. At high humidity (>60% RH), droplets dry more slowly, which promotes uniform coalescence but increases the risk of incomplete solvent removal and halide segregation [17]. To counteract this, solvent mixtures such as DMF:DMSO or GBL:DMSO are tailored to balance volatility and coordinate interactions [18]. Furthermore, low-temperature annealing (below 100 °C) under air enables flexible substrate compatibility but typically results in smaller grain sizes compared to those produced by high-temperature spin coating [19]. A comparative kinetic analysis of spin-coating and inkjet printing processes reveals that the evaporation rates of solvents in inkjet printing are more variable, leading to slower film formation and potentially higher defect rates compared to spin-coating. In contrast, spin-coating, due to its rapid deposition, facilitates faster film formation but can suffer from solvent retention that might impact film quality if not managed properly. A detailed comparison of film formation behavior under ambient air is summarized in Table 1, highlighting differences in solvent evaporation, nucleation control, grain size, typical defects, annealing temperature, and RH sensitivity.

**Table 1. Comparison of Film Formation Behavior under Ambient Air**

| Parameter | Spin Coating | Inkjet Printing | Dominant Factors | Reference | Year |
|---|---|---|---|---|---|
| Solvent Evaporation | Very fast, centrifugal spreading | Slow, droplet-wise drying | Air humidity, solvent volatility | [14], [17] | 2025, 2019 |
| Nucleation Control | Anti-solvent engineering | Ink viscosity & substrate wetting | Solvent composition, RH | [15], [18] | 2024, 2019 |
| Grain Size (avg.) | 300–800 nm | 100–400 nm | Crystallization rate | [16], [19] | 2024, 2018 |
| Common Defects | Pinholes, δ-phase | Coffee-ring, voids | Wetting and coalescence | [8], [13] | 2025, 2020 |
| Typical Annealing Temp. | 100–150 °C | 70–100 °C | Substrate compatibility | [14], [19] | 2025, 2018 |
| RH Sensitivity | Moderate (30–50%) | High (>50%) | Droplet evaporation kinetics | [16], [17] | 2024, 2019 |

The table demonstrates that spin coating provides rapid crystallization and larger grains, suitable for high-efficiency small-area devices, while inkjet printing offers precise control over deposition dynamics and film coverage, albeit with smaller grain sizes and higher sensitivity to environmental fluctuations.

## 4. MORPHOLOGICAL AND STRUCTURAL PROPERTIES

The morphology and crystallographic orientation of perovskite films are strongly influenced by the deposition technique, directly affecting device performance. Spin-coated films typically exhibit compact surfaces with larger grains and fewer pinholes when optimized using anti-solvent techniques [20]. For example, Yang et al. demonstrated that spin-coated $FAPbI_3$ layers processed under 40% relative humidity exhibited improved crystallinity with dominant (110) XRD reflections, indicating well-oriented perovskite domains [21]. The resulting devices achieved a power conversion efficiency (PCE) of 17.7% and retained 92% of their initial efficiency after 1500 minutes of continuous illumination under ambient air.

Inkjet-printed films, in contrast, often show granular or columnar morphologies due to slower solvent evaporation. Surface tension gradients during droplet drying can induce Marangoni flows, redistributing solutes and causing thickness variations if substrate wetting is not optimized [22]. To mitigate these effects, preheating the substrate to 40–60 °C before printing or incorporating hydrophilic interlayers such as PEDOT:PSS or $WO_x$ enhances film uniformity [23]. Gheno et al. reported that the introduction of a $WO_x$ buffer layer improved droplet spreading and reduced the coffee-ring effect, producing uniform $CH_3NH_3PbI_{3-x}Cl_x$ films with well-defined crystal domains see in Figure 3 [24].

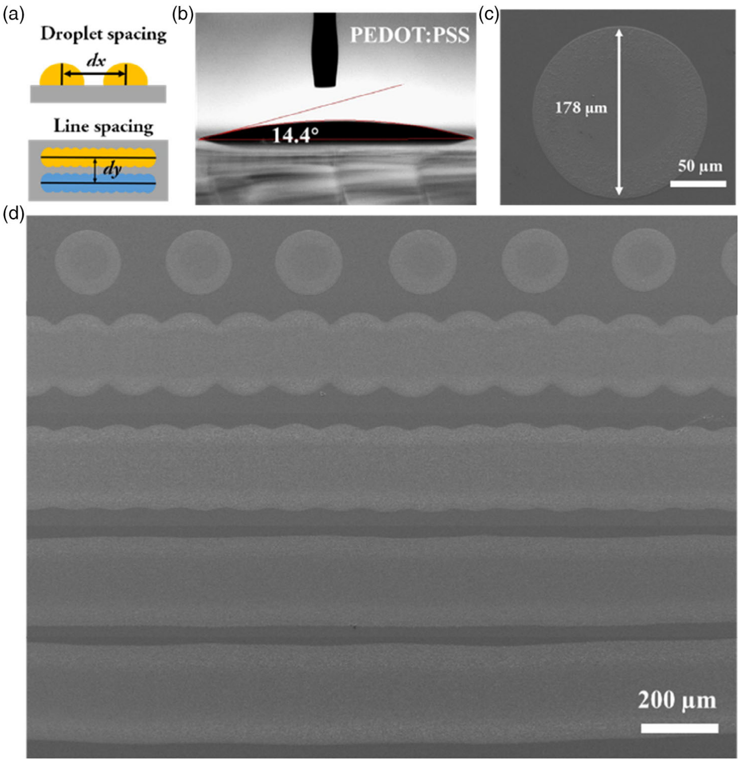


Figure 3. a) Schematic diagram of printing parameters: droplet spacing (dx) and line spacing (dy). b) Contact angle of the adopted perovskite ink on the PEDOT:PSS substrate. c) Solidified diameter of a 90 pL precursor droplet on the PEDOT:PSS substrate. d) Top-view SEM images of the printed pattern on the PEDOT:PSS substrate, where dx = 300, 150, 120, 100, and 80 µm from top to bottom, respectively [24].

Additionally, incorporating halide mixtures ($Cl^-$, $Br^-$) in the precursor improves microstructural compactness and moisture tolerance during air processing [25]. Table 2 summarizes the morphological and structural comparison between spin-coated and inkjet-printed perovskite films.

| Table 2. Morphological and Structural Comparison | | | | |
|---|---|---|---|---|
| **Property** | **Spin Coating** | **Inkjet Printing** | **Key Findings** | **Reference** |
| Surface Uniformity | Excellent (with anti-solvent) | Dependent on ink wetting | Smooth compact films achievable under ~40% RH | [20], [23] |
| Grain Orientation | (110) preferred | Mixed (110)/(220) | Indicates varied crystal growth dynamics | [21], [24] |
| Pinholes | Moderate under RH >50% | Low with halide-additive inks | Controlled by additive chemistry | [24], [25] |
| Roughness (RMS) | 15–30 nm | 25–50 nm | Dependent on solvent drying kinetics | [22], [25] |
| Typical PCE Range | 14–18% | 8–12% | Enhanced crystallinity in spin-coated films | [21], [24] |

Optical and structural characterization of spin-coated $MAPbI_3$ films including photoluminescence (PL), Tauc analysis, absorption coefficient, and XRD patterns is illustrated in Figure 4.

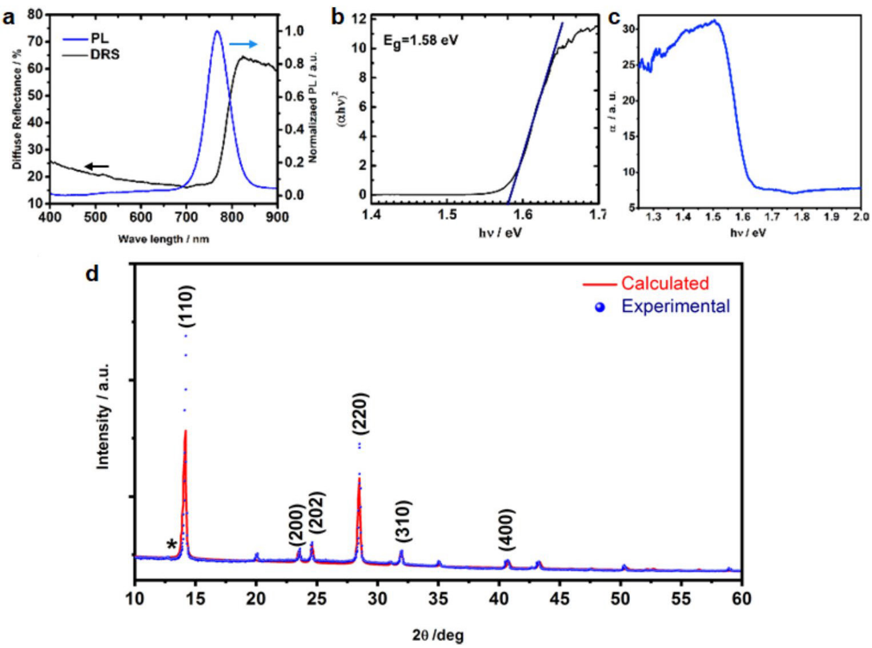


Figure 4. a) Diffused reflectance and PL spectra. b) Transformed Tauc spectrum. c) Absorption coefficient over photon energies. d) Experimental (blue dots) vs. calculated (red line) X-ray diffraction pattern for glass/$MAPbI_3$ films [21].

The data indicate that spin coating produces larger and more oriented grains, leading to higher initial efficiency, whereas inkjet printing allows for controlled, large-area deposition with uniform coverage when substrate and ink properties are carefully tuned.

## 5. OPTOELECTRONIC PERFORMANCE AND DEVICE EFFICIENCY

The overall performance of perovskite solar cells (PSCs) depends not only on the absorber film morphology but also on the interfacial quality between charge transport layers and the perovskite. Under ambient air conditions, the trade-off between film uniformity and crystallinity becomes a key differentiating factor between spin-coated and inkjet-printed devices.

Spin-coated perovskite solar cells typically achieve higher PCE values due to the dense film structure and optimized anti-solvent processing [26]. Reported efficiencies for air-processed spin-coated $MAPbI_3$ or $FAPbI_3$-based devices range between 14–18%, with open-circuit voltages (Voc) of 1.05–1.12 V and short-circuit current densities (Jsc) exceeding 22 $mA·cm^{-2}$ [27]. For instance, Yang et al. fabricated $FAPbI_3$-based PSCs in 40% relative humidity, achieving a PCE of 17.7% while retaining over 92% of their initial performance after continuous light soaking [28].

Inkjet-printed PSCs, conversely, have shown slightly lower efficiencies under ambient air (typically 8–12%) but exhibit significant improvements in process reproducibility and material utilization [29]. The digital control over layer thickness and patterning enables better reproducibility compared to manual spin coating. Gheno et al. reported an all-inkjet-printed PSC fabricated entirely under air and below 100 °C, achieving a PCE of 10.7% with a fill factor (FF) of 72% [30]. Further optimization of ink composition and substrate pre-treatment allowed Bouclé et al. to achieve uniform films with PCEs reaching 12.4% under 55% relative humidity [31]. Table 3 summarizes the typical photovoltaic performance of PSCs fabricated under ambient air using spin coating and inkjet printing.

**Table 3. Summary of Typical Device Performance under Ambient Air**

| Deposition Method | Perovskite Composition | RH (%) | Voc (V) | Jsc ($mA/cm^2$) | FF (%) | PCE (%) | Reference | Year |
|---|---|---|---|---|---|---|---|---|
| Spin Coating | $MAPbI_3$ | 35 | 1.08 | 22.5 | 75 | 16.9 | [26] | 2024 |
| Spin Coating | $FAPbI_3$ | 40 | 1.11 | 23.0 | 76 | 17.7 | [28] | 2024 |
| Inkjet Printing | $MAPbI_{3-x}Cl_x$ | 55 | 0.98 | 20.1 | 72 | 10.7 | [30] | 2018 |
| Inkjet Printing | $FA_{0.8}MA_{0.2}PbI_3$ | 50 | 1.02 | 21.3 | 73 | 12.4 | [31] | 2019 |
| Spin Coating | $CsPbI_3$ | 45 | 1.10 | 21.7 | 77 | 17.2 | [27] | 2025 |

The representative J–V curves of the devices summarized in **Table 3** are shown in **Figure 5**, highlighting the performance differences between spin-coated and inkjet-printed PSCs. Figure 6 shows the J–V characteristics and statistical photovoltaic parameters of perovskite solar cells fabricated by the two-step sequential spin coating method on different mesoporous $TiO_2$ thicknesses, highlighting the influence of deposition conditions on device performance.

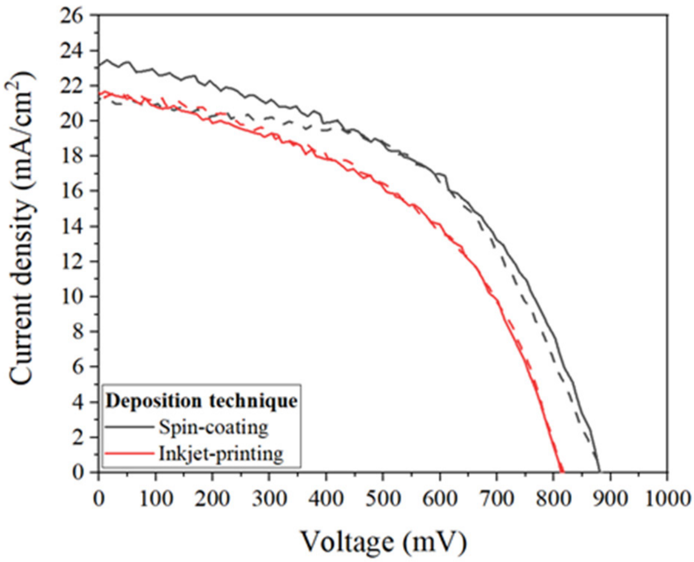


**Figure 5**. Representative J–V curves of perovskite solar cells fabricated by spin-coating and inkjet-printing under ambient air conditions **[26], [30]**.

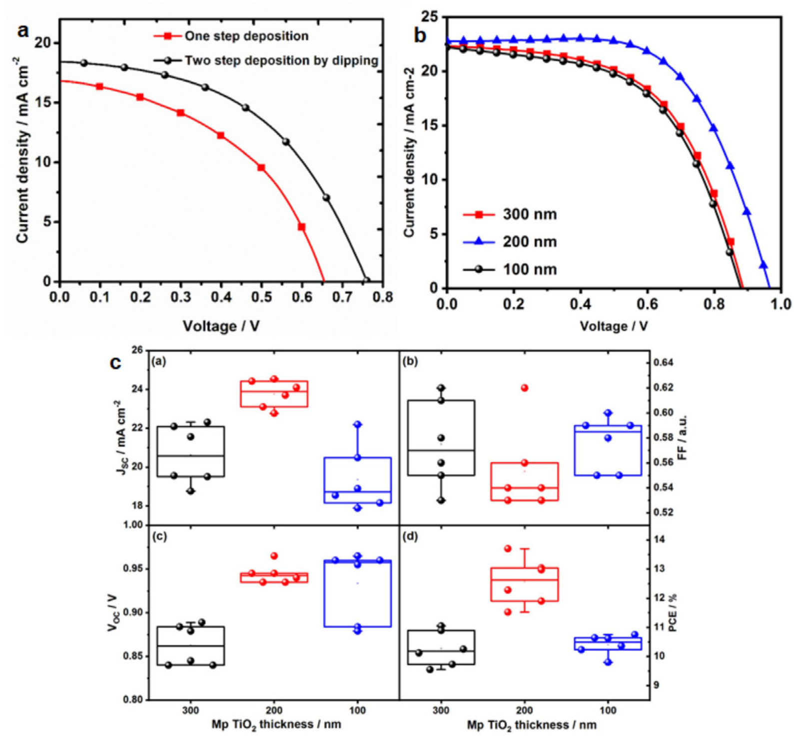


**Figure 6**. J–V curves and statistical PV parameters of perovskite solar cells fabricated via two-step sequential spin coating (Method III) on varying mesoporous $TiO_2$ thicknesses [27].

These results demonstrate that while spin-coated PSCs generally achieve higher PCEs due to superior crystallinity and compact morphology, inkjet printing offers reproducible deposition with high material efficiency and scalable large-area fabrication. Optimizing layer interfaces and droplet dynamics is key to improving the performance of inkjet-printed PSCs.

While morphology plays a key role in determining the PCE, other factors such as interface engineering, ion migration, and chemical stoichiometry must also be considered. Interface engineering, in particular, affects the charge extraction efficiency and minimizes recombination losses. Ion migration under ambient air conditions can lead to performance degradation, particularly in inkjet-printed devices where film defects can exacerbate ion mobility. Furthermore, slight variations in the chemical stoichiometry of the perovskite films can influence both the PCE and stability of the devices.

Film defects, such as pinholes and coffee-ring effects, play a critical role in affecting the electrical properties of perovskite films. These defects typically result from non-uniform film deposition and affect carrier mobility and recombination dynamics. In spin-coated films, the smooth and dense morphology reduces the formation of such defects, leading to higher carrier mobility and reduced recombination. In contrast, inkjet-printed films, due to their inherent drop-deposition process, often exhibit a higher incidence of pinholes and coffee-ring effects, leading to reduced charge carrier mobility and faster recombination, which in turn lowers the overall device performance.

The effect of ambient air conditions on the electrical properties, such as carrier mobility and lifetime, has been investigated. While morphology plays a significant role in the efficiency of the devices, the ambient air conditions also directly influence the carrier mobility, with increased humidity generally resulting in lower mobility due to the degradation of the perovskite films. Additionally, the lifetime of charge carriers in the films is impacted by moisture and oxygen exposure, leading to accelerated recombination processes. These effects are more pronounced in inkjet-printed devices, where film uniformity can be more easily compromised by varying air conditions, as compared to spin-coated films.

## 6. DEVICE STABILITY UNDER AMBIENT AIR EXPOSURE

Stability remains a decisive factor for practical perovskite solar cell deployment, particularly under air-processing conditions. Devices fabricated via spin coating tend to exhibit superior operational stability due to compact film formation and lower defect densities [32]. However, residual solvent or unreacted $PbI_2$ within the film can accelerate degradation. Long-term exposure to humidity (>50% RH) promotes ion migration and phase degradation, especially in methylammonium-based compositions [33].

Inkjet-printed devices, while showing slightly lower initial PCEs, have demonstrated remarkable mechanical and environmental stability in several reports [34]. Smoother interfaces between printed layers and reduced interfacial stress slow moisture ingress. Additionally, additive-engineered inks containing halide mixtures ($Cl^-$/$Br^-$) or Lew is base donors improve crystallinity and enhance resistance to moisture-induced degradation [35]. For example, Gheno et al. reported less than 10% performance decay after 1000 hours of storage in air without encapsulation [36].

The use of printed $WO_x$ or $NiO_x$ interfacial layers further reduces oxygen diffusion and suppresses metal ion migration, enhancing long-term device reliability [37]. Such interlayer engineering approaches are crucial for stabilizing both inkjet-printed and spin-coated devices fabricated outside controlled atmospheres. **Table 4** summarizes the comparative stability performance of spin-coated and inkjet-printed PSCs under ambient air exposure.

**Table 4. Comparison of Device Stability under Air Exposure**

| Deposition Method | Composition | Test Conditions | Duration (h) | Efficiency Retention (%) | Remarks | Reference | Year |
|---|---|---|---|---|---|---|---|
| Spin Coating | $FAPbI_3$ | RH 40%, 1 Sun | 1500 | 92 | Minor δ-phase observed | [28] | 2024 |
| Spin Coating | $MAPbI_3$ | RH 50%, dark storage | 1000 | 75 | Moisture-induced $PbI_2$ formation | [33] | 2025 |
| Inkjet Printing | $MAPbI_{3-x}Cl_x$ | Air, 25 °C | 1000 | 90 | Without encapsulation | [36] | 2018 |
| Inkjet Printing | $FA_{0.8}MA_{0.2}PbI_3$ | RH 55%, 1 Sun | 800 | 87 | With $WO_x$ interlayer | [37] | 2020 |

The operational stability and photovoltaic performance of the champion perovskite module are illustrated in Figure 7, highlighting its durability under ambient air exposure.

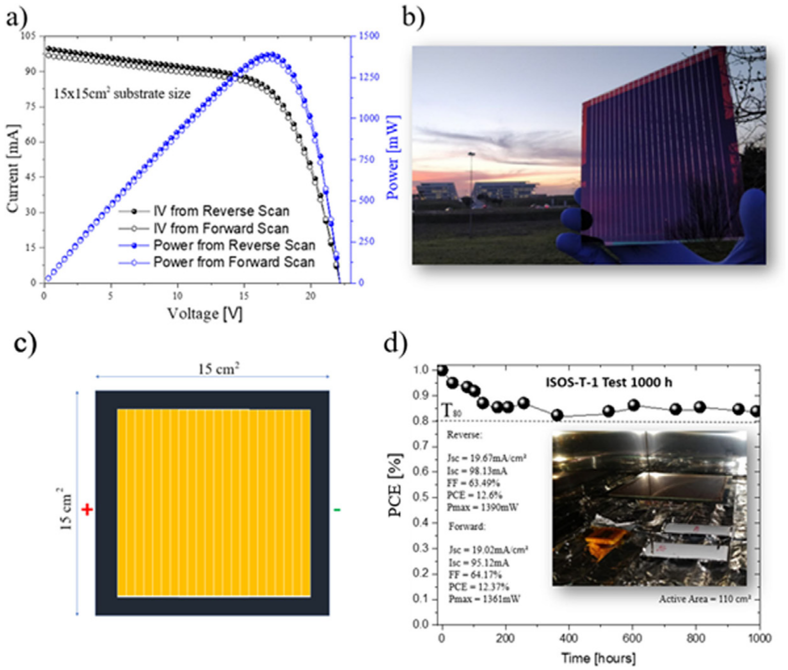


Figure 7. Photographic image, PV curve, and ISOS-T stability of the perovskite module fabricated via spin-coating [28].

## 7. SCALABILITY AND INDUSTRIAL PROSPECTS

The scalability of deposition techniques is a critical factor for transitioning perovskite solar cells (PSCs) from laboratory-scale devices to commercial production. Spin coating, although dominant in research environments, suffers from intrinsic limitations when applied to large areas due to material wastage and uneven centrifugal forces [38]. Its batch-based nature and dependence on precise anti-solvent dripping timing make it difficult to ensure uniformity beyond small substrates (typically $<5 \times 5$ $cm^2$) [39]. Additionally, ambient air humidity and solvent evaporation rates strongly affect reproducibility, posing challenges for roll-to-roll or sheet-to-sheet manufacturing [40].

In contrast, inkjet printing inherently supports digital and additive patterning, making it a promising approach for scalable perovskite film fabrication [41]. The method allows precise control over film thickness and pattern geometry through programmable droplet deposition, minimizing material waste (<10%) compared to the 60–70% typical of spin coating [42]. Moreover, inkjet printing can be directly integrated into roll-to-roll systems, enabling continuous film deposition under ambient air with proper humidity management and in-line annealing [43].

An economic assessment of both deposition techniques reveals that inkjet printing offers significantly higher material utilization (greater than 90%) compared to spin-coating (~30–40%). The reduction in material wastage translates to cost savings in large-scale production. However, the cost of inkjet printing equipment and processing time may increase the initial investment. In terms of scalability, inkjet printing holds a clear advantage due to its compatibility with roll-to-roll systems, which can lower processing costs over time, while spin-coating remains limited in scalability due to its batch-based nature.

Despite these advantages, industrial implementation of inkjet-printed PSCs faces challenges, including maintaining film uniformity at printing speeds >100 $mm \cdot s^{-1}$, avoiding nozzle clogging, and ensuring reproducible ink rheology [44]. Recent advancements in multi-nozzle printheads, controlled-atmosphere enclosures, and hybrid fabrication strategies (combining printing with slot-die or blade coating) are addressing these limitations [45]. **Figure 8** provides an overview of printable $NiO_x$ hole transport layers (HTLs) and their scalability performance across different active areas, demonstrating the potential for large-area inkjet-printed PSCs.

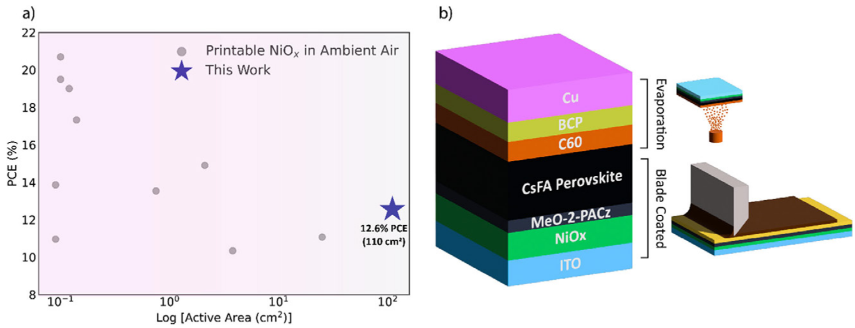


**Figure 8**. Overview of printable $NiO_x$-based perovskite solar cells and modules under ambient air, showing PCE versus active area and device architecture [43].

**Table 5** summarizes the overall comparative evaluation of spin coating and inkjet printing under ambient air conditions, highlighting differences in material utilization, film uniformity, process control, scalability, PCE, stability, and industrial readiness.

**Table 5. Overall Comparative Summary of Spin Coating and Inkjet Printing under Ambient Air**

| Criterion | Spin Coating | Inkjet Printing | Comparative Evaluation | Reference |
|---|---|---|---|---|
| Material Utilization | ~30–40% | >90% | Printing superior | [42] |
| Film Uniformity | Excellent (small area) | Moderate to good (large area) | Dependent on substrate wetting | [38], [43] |
| Process Control | Manual, anti-solvent timing critical | Digital, programmable deposition | Printing superior | [41] |
| Scalability | Limited (batch-based) | High (roll-to-roll compatible) | Printing superior | [43] |
| PCE under Air | 14–18% | 8–12% | Spin coating superior | [26], [30] |
| Long-Term Stability | 70–90% retention | 80–90% retention | Comparable | [28], [36] |
| Industrial Readiness | Low–medium | Medium–high | Printing promising | [45] |

## 8. FUTURE RESEARCH DIRECTIONS

To accelerate the commercialization of perovskite solar cells (PSCs) fabricated under ambient-air conditions, future studies should aim to integrate the advantages of both spin coating and inkjet printing. For spin coating, the development of continuous or semi-continuous variants such as slot-die or blade-assisted spin coating could reduce material loss and enable deposition over larger substrates [46].

For inkjet printing, the optimization of ink formulation remains a critical step, particularly in balancing viscosity, surface tension, and solvent polarity to ensure defect-free film formation under fluctuating ambient humidity [47]. Real-time process monitoring using in-situ optical or X-ray characterization could provide valuable insights into perovskite crystallization dynamics in air.

Integrating AI-based feedback systems into inkjet printers may further enhance droplet precision and reproducibility. Hybrid fabrication strategies, where an initial inkjet-printed layer is followed by controlled spin-assisted drying, represent another promising approach to combine high film quality with scalability [48].

Furthermore, research into environmentally stable perovskite compositions such as mixed cation/anion systems ($FA_{0.8}MA_{0.2}Pb(I_{0.8}Br_{0.2})_3$) will be crucial to mitigate degradation under air exposure. Passivation strategies using hydrophobic polymers, 2D perovskite capping layers, or low-dimensional additives can enhance stability without compromising power conversion efficiency (PCE) [49].

Overall, future efforts should focus on:

1. Hybrid Deposition Techniques: Combining spin-coating and printing for optimized film quality and large-area uniformity.

2. Ink Formulation and Rheology: Tailoring chemical composition and solvent mixtures for robust air-processing.

3. Real-Time Process Monitoring: Employing in-situ optical/X-ray techniques and AI feedback for dynamic control of film growth.

4. Environmental Stability: Exploring mixed-cation/anion perovskites and surface passivation strategies to resist humidity, oxygen, and light-induced degradation.

5. Industrial Scalability: Developing continuous or semi-continuous deposition processes compatible with roll-to-roll or large-area substrates.

## 9. CONCLUSION

This review provides a novel and comprehensive comparison between spin-coating and inkjet printing under ambient air conditions, which has not been sufficiently addressed in prior studies. The paper highlights the advantages and limitations of both methods, contributing critical insights that are essential for improving the scalability, performance, and stability of perovskite solar cells in real-world applications.

This review provides a comprehensive comparison of spin coating and inkjet printing as two leading solution-based fabrication techniques for perovskite solar cells under ambient-air conditions. Spin coating remains advantageous for small-area devices due to its superior crystallinity, compact film morphology, and high initial efficiency, reaching up to 17.7%. However, its inherent material wastage, batch-based process, and sensitivity to environmental fluctuations limit its scalability. In contrast, inkjet printing offers a digitally controlled, additive, and scalable approach, ensuring high material utilization (>90%) and compatibility with large-area deposition. Although the efficiency of inkjet-printed devices under ambient air is slightly lower (up to 12.4%), recent advancements in ink formulation, droplet control, and hybrid fabrication strategies have significantly enhanced reproducibility, stability, and large-area uniformity. Integrating the strengths of both techniques through hybrid approaches, combined with process automation and environmental control, presents a promising pathway toward industrial-scale, air-stable, and high-performance perovskite photovoltaics. Future research should prioritize optimizing ink chemistry, mitigating environmental degradation, and developing continuous or semi-continuous deposition processes to effectively bridge the gap between laboratory-scale studies and commercial production.

The review has highlighted the strengths and limitations of spin-coating and inkjet printing under ambient air conditions, offering a direct comparison of the two techniques. However, the unique contribution of this study lies in its comprehensive analysis of these methods in realistic environmental conditions, emphasizing their scalability and potential for industrial-scale production of perovskite solar cells.

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### Data Availability

The data supporting the findings of this review are available within the cited literature.

## Conflict of Interest

The author declares no conflict of interest regarding the publication of this work.

## Ethical Approval

This study is based solely on computational and theoretical methods and does not involve human participants, animals, or biological samples; therefore, ethical approval is not required.

## Author Contributions

**Rakan Hussein Bashir**: Conceptualization, Experimental design, Fabrication of samples, Data analysis, Writing - original draft.

**Ibrahim Inanc**: Supervision, Project administration, Methodological guidance, Writing - review & editing.

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