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Research Paper

Superiority of Inkjet-Printing Technology For Perovskite Solar Cells

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Abstract
Perovskite-solar cells (PSCs) are now the most promising area of research in the field of new-generation photovoltaic technology due to their exceptional power conversion efficiency (PCE). PSC fabrication can be accomplished by either a one-step or two-step deposition technique. The primary benefit of this deposition process, in comparison to others, is its ability to pattern without the need for masks and its cost-effectiveness, providing unmatched design flexibility. Inkjet printing is a newly developed method for depositing materials onto perovskite solar cells (PSCs). It offers precise patterning, efficient material usage, and cost-effectiveness. The minimal manufacturing expenses are the primary benefit of inkjet printing for solar cell production. This analysis article discusses the composition, operating method, and functional layers of PSCs, which include an electron-transport layer, a hole-transport layer, and a perovskite-active layer. The study also focuses on analysing specific procedures employed in producing PSCs, with particular emphasis on highlighting the advantages of the inkjet printing process. The study also investigated inkjet-printing methodologies, ink processing, ink characteristics, and the research development of manufacturing PSCs utilising the inkjet-printing process. After conducting a thorough literature study, it was determined that the inkjet printing process is superior to other deposition procedures that have been used. Nevertheless, the utilisation of inkjet printing technology for commercial perovskite manufacturing is currently limited to research and laboratory experiments.

Keywords: *Perovskite-solar cells, Inkjet-printing, Superiority, Deposition Techniques*

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I. Introduction

The dilemma of electricity costs, the security of supply, and anthropogenic climate change drive the transition towards development and the use of renewable, non-polluting energy sources that can also attain lower costs. Solar energy is one of the most abundant and sustainable forms of electricity, with no adverse environmental effects compared to other types, such as coal or nuclear oil. Solar energy already exceeds its storage and production capacity, prompting a drive to discover innovative technologies that can be used in the next generation of photovoltaic (PV) devices. During recent decades, the fabrication of solar cells has been seen as the most promising and potential way to meet the increasing demands of energy to support modern society's development and control the pollution produced by the combustion of fossil fuels.

In photovoltaic technology, a variety of solar cells, such as silicon-solar cells (Si), thin-film solar cells (TFSC), Cu-based chalcogenides, dye-sensitised solar cells (DSSC), organic-solar cells, and PSCs have been introduced. In exploring innovative ways to make solar energy more efficient, technology is continuously transforming into innovative, improved products. More recently, a PV group research concern has focused on organic-inorganic halide perovskites, while nowadays, perovskite solar cells (PSCs) have become an emerging form of photovoltaic technology. PSCs can significantly change clean solar energy output, as they are relatively easy to manufacture and have a high-power conversion capacity; thus, they have considerable potential for advancement in manufacturing low-cost, effective solar cells.

However, one of the main difficulties for the wider-scale application of PSCs is the high costs of manufacturing solar cells. For fabrication, the ETL layer is either spin-coated, spray- pyrolysed or evaporated (Peng et al., 2004). The spin coating has also been commonly used for depositing perovskite uniform and dense absorber layers, as well as different variations of this method intended to regulate the crystal formation of state-of-the-art perovskite (Bi et al., 2016). Nonetheless, as the cell size increases, spin-coating films become less constant and uniform, reducing performance and restricting the production of large-scale PSCs. Different deposition techniques, such as blade coating, spraying and roll-to-roll printing, have been tested (Barrows et al., 2014) for the fabrication of PSCs. Despite these developments, using PSCs for solar energy collection to ensure that the cells remain stable and functional for the desired 20-30 years (Peng et al., 2017) still presents particular key challenges. Therefore, the current research aims to assess the development of perovskite solar cells (PSCs) and establish an understanding of recent advances in inkjet printing as a deposition technique for PSCs.

The research will also contribute to the available literature by exploring in detail and providing a perspective on the superiority of the inkjet printing technique for flexible solar cells. The current research aims to investigate using a systematic literature review on what makes the inkjet-printing technique the most effective for producing perovskite solar cells. The following are the specific objectives: Assessment of perovskite solar cells (PSCs) development and Inkjet Printing. A systematic literature review was used to evaluate articles to understand the recent developments in inkjet printing with the deposition of different layers of PSCs. To explore several parameters of inkjet printing in increasing the stability of PSCs. To report the influence of these parameters on the working of inkjet-printed PSCs. New applications in building facades, wearables and garments involve semi-transparent and lightweight solar cells. Emerging printed PV, mainly organic photovoltaics (OPVs), can almost perfectly fulfil these demands. Similarly, the shift in photovoltaic applications enables a free option of solar cell colour and progressively appropriate shapes. Given that existing manufacturing methods, such as slot die coating, cannot satisfactorily match the requirements, new possibilities for solar module development need to be made accessible. As a possible solution to existing photovoltaic technology, inorganic and organic halide PSCs have evolved, enabled by the rapid growth of their power conversion efficiency (PCE).

Nevertheless, several challenges must be addressed before PSCs can be deployed on a Terawatt scale. These include chemical toxicity, lack of a clear understanding of material properties, poor stability and efficiency penalties in generating more giant cells. High-performance PSCs, including lead (Pb), raise a significant public health and environmental problem (Babayigit et al., 2016). The quantity of Pb, however, is low, while the existence of toxic elements in perovskites reduces the scope of its application and, ultimately, its commercial and competitive edge. Nonetheless, tin, the critical helpful ingredient for producing lead-free PSCs, could have an unstable oxidation state (2+), contributing to decreased cell efficiency and lattice vacancies (Bi et al., 2016).

Most research efforts centred on the production or processing method or essential compositional engineering of substances or materials in pursuit of greater efficiency without recognising the film-forming concept. In total, only a few studies on perovskite formation are available. Research, for example, suggests that colloids' dissolution in perovskite solution is caused by a shift in acidity rates that results in crystallisation and super-saturation (Nayak et al., 2016). Meanwhile, several other research studies based on colloids in perovskite's precursor solution have considered the film-forming process, although no consensus has been reached at this stage (Gheno, 2018). In this context, drop-on-demand (DOD) inkjet printing is promising, as it offers the possibility of practically waste-free printing of arbitrary shapes at throughput speeds of more than 1000 m^2 / h. Digital printing of whole solar cells and modules helps unlock the path for printed photovoltaics to reach highly customised consumer-driven applications, consequently inspiring the current research.

The current research is focused on reviewing articles through a Systematic Literature Review (SLR) to determine the superiority of inkjet printing in fabricating Perovskite Solar Cells. To achieve this, the following research questions are posed:

- What widely available articles are validly suitable for this research? The first approach in undertaking this systematic analysis is to search the related articles in the literature comprehensively.
- Is there established empirical evidence from the selected articles that validate the superiority of inkjet printing over other related technologies?
- What factors and parameters have been used in determining the superiority of inkjet printing over other related technologies for the fabrication of PSCs?
- What are the alternative printing and processing options for PSCs compared to IJP?

II. Research Methodology

This section contains how the survey on inkjet-printing-based perovskite and different fabrication techniques for Perovskite solar cells (PSCs) systems were conducted through critically reviewed studies. To effectively analyse to ascertain the superiority of the inkjet-printing technology for perovskite over other

technologies, a systematic review of literature on inkjet-printing based on ink preparation, characterisation of inks, and inkjet printing of the perovskite is systematically reviewed. To accomplish the specific objectives and research questions, a thorough, analytical, systematic literature review would be undertaken, including how and when particular sources were searched; years searched; search terms; inclusion and exclusion requirements with a theoretical and scientific rationale; what concerted attempts were made to acquire and incorporate both existing and unpublished work on the superiority of the inkjet-printing technology for perovskite solar cells fabrication. The PRISMA flow diagram that describes the identification, screening, eligibility and inclusion stages, with the number of studies included and excluded at each stage, along with reasons for exclusion during the eligibility, was used (Moher et al., 2009). PRISMA is a minimum set of reporting items in systematic reviews and meta-analyses based on evidence that focuses on reporting studies that review randomised experiments, which may also be seen as a framework for coverage on comprehensive assessments of certain forms of testing, especially experiment evaluations (Moher et al., 2009).
The following articles, as shown in Table 1 below, were selected and screened for the structured review.

Table 1: Synthesis Matrix of Selected and Screen Articles for the SLR

Research Title: Superiority of Inkjet- Printing Technology for Perovskite Solar Cells Preferred Materials	**Database** (Source)/Publisher/Date	**Work** (CrossRef/Web of Science *Citations*) SJR Ranking (Q1, Q2, Q3, Q4)	**Article Title (Description)**
Perovskite solar cells (PSCs) systems and different fabrication techniques.	Science (11/08/2020) Direct	Angmo et al., 2013 (***144)*** Q1	Scalability and stability of very thin, roll-to-roll processed, large area, indium-tin-oxide free polymer solar cell modules
	Nature Scientific Reports (09/08/2020)	Babayigit et al., 2016 (***183***) Q1	Assessing the toxicity of Pb- and Sn-based perovskite solar cells in model organism Danio rerio.
	Royal Society of Chemistry Journal (RSC) (11/08/2020)	Barrows et al., 2014 (***421***) Q1	Efficient planar heterojunction mixed-halide perovskite solar cells deposited *via* spray-deposition
	Google (11/08/2020) Scholar	Beatriz, 2016 (***2***) (**unpublished thesis**)	Inkjet Printing as an Enabling key Technology Printed Electronics for
	Google (11/08/2020) Scholar	Bi et al., (**1434**) Q12016	Efficient luminescent solar cells based on tailored mixed- cation perovskites.
	Google (11/08/2020) Scholar	Farawar, 2015 (**unpublished thesis**)	Perovskite Solar Cells: Stability, design architecture, photophysical properties, and morphology of the film in organometal halide Perovskite-based photovoltaics

Google Scholar (10/08/2020)	Gheno, 2018 (**unpublished thesis**)	Printable and printed perovskites photovoltaic solar cells for autonomous sensors network. Micro
J. Mater. Chem. A (11/8/2020)	Hashmi et al., 2017 (**54**) SJR-0	High-performance carbon-based printed perovskite solar cells with humidity-assisted thermal treatment.
Royal Society of Chemistry Journal (RSC Advances) (11/08/2020)	Mahmood, Sarwar, & Mehran, 2017 Q1 (***107***)	Current status of electron transport layers in perovskite solar cells: materials and properties.
Iowa State University Digital Repository (14/08/2020)	Hossain, 2018 (unpublished thesis)	Performance and stability of perovskite solar cells
Science Direct (Solar Energy Materials and Solar Cells)	Krebs, 2009 (***650***) Q1	Polymer solar cell modules are prepared using roll-to-roll methods: Knife-over-edge coating, slot-die coating, and screen printing.
American Chemical Society (Nano Letters)	(H. Li et al., 2017) (***112***) Q1	Carbon Quantum Dots/TiOx Electron Transport Layer Boosts Efficiency of Planar Heterojunction Perovskite Solar Cells to 19%.
Journal of the American Chemical Society (ACS Nano)	Z. Li et al., 2014 (***294***) Q1	Laminated Carbon Nanotube Networks for Metal Electrode-Free Efficient Perovskite Solar Cells.
Nature 12/08/2020	Hui-Seon et al., 2012 (***4667***) Q1	Lead iodide perovskite sensitised all-solid-state submicron thin film mesoscopic solar cells with efficiency

		exceeding 9%.
Journal of the American Chemical Society 12/08/2020	Kojima, Teshima, Shirai, & Miyasaka, 2009 (**9585**) Q1	Organometal halide perovskites as visible-light sensitisers for photovoltaic cells.
Journal of the American Chemical Society 12/08/2020	Liu et al., 2014 (**463**) Q1	A dopant-free hole-transporting material for efficient and stable perovskite solar cells.

PubFacts 15/08/2020	Maisch, P. 2019 (Unpublished thesis)	Process Development for Inkjet Printing of Organic Photovoltaics
Elsevier (Science Direct) 12/08/2020	Mathan, P. K., Abinash, D., Lalu, S. and Ranjith, 2018 (Book)	Fabrication and Life Time of Perovskite Solar Cells.
Nature Communications 12/08/2020	Nayak et al., 2016 (**114**) Q1	The mechanism for the rapid growth of organic-inorganic halide perovskite crystals.
Nature 12/08/2020	Burschka J, Pellet N, Moon SJ, 2013 (**6289**) Q1	Sequential deposition as a route to high-performance perovskite-sensitised solar cells
Elsevier (Science Direct) 12/08/2020	Can Şener, Sharp & Anctil, 2018 (**34**) Q1	Factors impacting diverging paths of renewable energy: A review
Royal Society of Chemistry Journal (RSC) 19/08/2020	Cao et al., 2015 (**51**) Q1	Efficient mesoscopic perovskite solar cells based on the CH3NH3PbI2Br light absorber.
Journal of the American Chemical Society 12/08/2020	Christians, Fung, & Kamat, 2014 (**862**) Q1	An inorganic hole conductor for Organo-lead halide perovskite solar cells. improved hole conductivity with copper iodide.
Royal Society of Chemistry Journal (RSC) 19/08/2020	Deng et al., 2015 (**359**) Q1	Scalable fabrication of efficient organolead trihalide perovskite solar cells with doctor-bladed active layers
Science Direct Progress in Quantum Electronics 17/08/2020	Djurišić et al., 2017 (**77**) Q1	Perovskite solar cells - An overview of critical issues. Progress in Quantum Electronics
Nature Communications	Docampo, Ball, Darwich, Eperon, & Snaith, 2013 (**1209**) Q1	Efficient organometal trihalide perovskite planar-heterojunction solar cells on flexible polymer substrates.
PubMed (Science) 18/08/2020	Dong, 2015 (**182**) Q1	Solar cells Electron-Hole diffusion length >175 nm.

Nature Communications 18/08/2020	Edri et al., 2014 (**404**) Q1	Elucidating the charge carrier separation and working mechanism of CH 3 NH 3 PbI 3-x Cl x perovskite solar cells
Royal Society of Chemistry Journal (RSC) 19/08/2020	Galagan, Coenen, Verhees, & Andriessen, 2016 (**49**) Q1	Towards the scaling up of perovskite solar cells and modules.
Royal Society of Chemistry Journal (RSC) 19/08/2020	Gao et al., 2017 (**20**) Q1	A TiO2 nanotube network electron transport layer for high-efficiency perovskite solar cells.
Nature Materials	Grätzel, 2014 (**1284**) Q1	The light and shade of perovskite solar cells
Iowa State University Digital Repository 20/08/2020	(Hossain, 2018) Unpublished article (Thesis)	Performance and stability of perovskite solar cells
Scopus 20/08/2020	Huang et al., 2017 (**64**) Q1	Effect of the Microstructure of the Functional Layers on the Efficiency of Perovskite Solar Cells.
Springer Link (Emergent Materials) 20/08/2020	Hussain et al., 2018 (**20**) Q1	Functional materials, device architecture, and flexibility of perovskite solar cells.
Nature (Nature Energy) 18/08/2020	Jeon et al., 2018 (**1030**) Q1	A fluorene-terminated hole-transporting material for highly efficient and stable perovskite solar cells.
Nature Materials 18/08/2020	Jeon et al., 2014 (**3923**) Q1	Solvent engineering for high-performance inorganic-organic hybrid perovskite solar cells.
Springer 18/08/2020	Kajal, Ghosh, & Power, 2018 (**1**) Q2	Manufacturing Techniques of Perovskite Solar Cells.

Nature 18/08/2020	M. Liu, Johnston & Snaith, [illegible] (**5183**) Q1	Efficient planar heterojunction perovskite solar cells by vapour deposition.
Nature Photonics	D. Liu & Kelly, 2014 (**1876**) Q1	Perovskite solar cells with a planar heterojunction structure prepared using room- Temperature solution processing techniques. Nature Photonics

RSC (Energy & Environmental Science)	J. Liu et al., 2014 (**463**) Q1	A dopant-free hole-transporting material for efficient and stable perovskite solar cells.
PubMed (Science) (12/08/2020)	Michael M. L., Joël T., Tsutomu M., 2012 (***7829***) Q1	Efficient Hybrid Solar Cells Based on Meso-Super structured Organometal Halide Perovskites.
Science Direct (Current Applied Physics) 16/08/2020	Minemoto & Murata, 2014 (***46***) Q2	Impact of the work function of back contact of perovskite solar cells without hole transport material analysed by device simulation.
Royal Society of Chemistry Journal (RSC) (Journal of Materials Chemistry A) 19/08/2020	Niu, Guo, & Wang, [illegible] (***1006***) Q1	Review of recent progress in chemical stability of perovskite solar cells.
NREL	NREL, 2020	NREL-Led Research into Perovskite-Silicon Tandem Cells Shows New Path to Take.
Journal of the American Chemical Society (Journal of Physical Chemistry Letters) 18/08/2020	Park, 2013 (***991***) Q1	Organometal perovskite light absorbers toward a 20% efficiency low-cost solid-state mesoscopic solar cell.
Royal Society of Chemistry Journal (RSC) 19/08/2020	Wu, Y., Islam, A., Yang, X., Qin, C., Liu, J., Zhang, K., … Han, L., 2014 (**604**) Q1	Retarding the crystallisation of PbI2 for highly reproducible planar-structured perovskite solar cells via sequential deposition.
Iopscience (Nanotechnology)	Ponseca, Tian, Sundström, & Scheblykin, 2016 (***24***) Q1	Excited state and charge-carrier dynamics in perovskite solar cell materials.
Nature Communications 17/08/2020	Qin et al., 2014 (***550***) Q1	Inorganic hole conductor-based lead halide perovskite solar cells with 12.4% conversion efficiency.
APL Materials 19/08/2020	Razza, Castro-Hermosa, Di	Research Update: Large-area deposition, coating, printing,

	Carlo & Brown, 2016 (***94***) Q1	and processing techniques for the upscaling of perovskite solar cell technology.
Science Direct (Dynamics of Curved Fronts) 21/08/2020	SAFFMAN & SIR GEOFFREY TAYLOR, 1988 (***3463***) Book	The penetration of a fluid into a porous medium or Hele-Shaw cell containing a more viscous liquid
Royal Society of Chemistry Journal (RSC) Nanoscale Journal 19/08/2020	Seo et al., 2016 (***171***) Q1	An ultra-thin, un-doped NiO hole transporting layer of highly efficient (16.4%) organic-inorganic hybrid perovskite solar cells.
ScienceMag.org (Science)	Sessolo & Bolink, 2015 (***51***) Q1	Perovskite solar cells join the major league.
PubMed (J Phys Chem Lett.) 15/08/2020	Savenije et al., 2014 (***378***) Q1	Thermally Activated Exciton Dissociation and Recombination Control the Carrier Dynamics in Organometal Halide Perovskite.
Google Scholar (Scientific Research Journal) 18/08/2020	Sharma, Jain, & Sharma, 2015 (***153***) Q-0	Solar Cells: In Research and Applications—A Review.
Google Scholar (Applied Physics Letters) 16/08/2020	Shi et al., 2014 (***334***) Q1	Hole-conductor-free perovskite organic lead iodide heterojunction thin-film solar cells: High efficiency and junction property.
Royal Society Publishing 18/08/2020	Stow, C. D. & Hadfield, 1981 (**579**) Q1	An experimental investigation of fluid flow resulting from the impact of a water drop with an unyielding dry surface.

ScienceMag.org (Science)	Stranks et al., 2013 (***6495***) Q1	Electron-hole diffusion lengths exceeding 1 micrometre in an organometal trihalide perovskite absorber.
Wiley Online Library (Advanced Materials)	Sutherland et al., 2015 (***117***) Q1	Perovskite thin films via atomic layer deposition.
Springer Link 19/08/2020	Wang, Chen, Wu, & Li, 2016 (***14***) Q1	Optimal design of efficient hole transporting layer free planar perovskite solar cell

Wiley Online Library 17/08/2020	Y. Wang, Luo, Nie, & Deng, 2016 (***206***) Q1	Planar Perovskite Solar Cells using CH3NH3PbI3 Films: A Simple Process Suitable for Large-Scale Production.
Royal Society of Chemistry (Energy and Environmental Science) 18/08/2020	Xiao et al., 2014 (***888***) Q1	Efficient, high yield perovskite photovoltaic devices grown by interdiffusion of solution- processed precursor stacking layers
ScienceMag.org (Science) 17/08/2020	Xing et al., 2013 (***4788***) Q1	Long-range balanced electron- and hole-transport lengths in organic-inorganic CH3NH3PbI3.
American Chemical Society (ACS Nano) 17/08/2020	You et al., 2014 (***1082***) Q1	Low-Temperature Solution- Processed Perovskite Solar Cells with High Efficiency and Flexibility
Wiley Online Library (Advanced Materials) 17/08/2020	Zhang, Wang, Chen, & Jen, 2017 (***145***) Q1	A Promising Inorganic Hole- Transporting Material for Highly Efficient and Stable Perovskite Solar Cells.
Hindawi.com (Journal ofNanomaterials) 19/08/2020	Zhou, Zhou, Tian, Zhu, & Tu, 2018 (***44***) Q2	Perovskite-Based Solar Cells: Materials, Methods, and Future Perspectives.
Science Direct (Journal of Power Sources) 18/08/2020	Y. Zhang, Liu, Tan, & Gu, 2015 (64) Q1	The essential role of the poly(3- hexylthiophene) hole transport layer in perovskite solar cells
Science Direct (Solar Energy Materials and Solar Cells) 16/08/2020	Zheng et al., 2017 (36) Q1	Spin-coating free fabrication for highly efficient perovskite solar cells.
Science Direct (11/08/2020)	Bag, M.; Jiang, Z. W.; Renna, L. A.; Jeong, S. P.; Rotello, V. M.; Venkataraman, 2016 (**55**) Q1	Rapid Combinatorial Screening of Inkjet-Printed Alkyl-Ammonium Cations in Perovskite Solar Cells.
Journal of Materials Chemistry (13/08/2020)	Karunakaran et al., 2019 (**14**) SJR-0	Recent progress in inkjet- printed solar cells
Researchgate.com (11/08/2020)	Sridhar, Blaudeck, & Baumann, 2011(**27**)	Inkjet Printing as a Key Enabling Technology for Printed Electronics

NCBI (12/08/2020)	Beedasy & Smith, 2020 (**4**) Q2	Inkjet Printing as a Key Enabling Technology for Printed Electronics
Cambridge Core -MRS Online Proceedings Library(Materials Research Society Symposium – Proceedings) 19/08/2020	Reis & Derby, 2000 (***85***) Q-0	Inkjet deposition of ceramic suspensions: Modelling and experiments of droplet formation.
Journal of Applied Physics	Nuno Reis, Ainsley, & Derby, 2005 (***189***) Q2	Inkjet delivery of particle suspensions by piezoelectric droplet ejectors.
PubMed (12/08/2020)	J. Perelaer, C. E. Hendriks, A. W. M. de Laat, 2009 (**253**) Q3	One-step inkjet printing of conductive silver tracks on polymer substrates.
Journal of Imaging Science and Technology 13/08/2020	Le, 1998 (**1063**) Q3	Progress and Trends in Inkjet Printing Technology. *Imaging Sci. Technol.*, 49–62.
IEEE 12/08/2020	Maisch et al., 2016 (**4**) Q1	Inkjet printing of highly conductive nanoparticle dispersions for organic electronics
Journal of Materials Chemistry A 16/08/2020	Mathies et al., 2016 (47) Q1	Multipass inkjet printed planar methylammonium lead iodide perovskite solar cells.
Advanced Functional Materials 17/08/2020	Peng et al., 2017 (**50**) Q1	Perovskite and Organic Solar Cells Fabricated by Inkjet Printing: Progress and Prospects.
Google Search	(Philipp, 2019) Doctoral	Process Development for Inkjet

(ResearchGate) 18/08/2020	Thesis	Printing of Organic Photovoltaics.
Journal of Materials Chemistry A 16/08/2020	Shao-Gang, L., Ke-Jian J., Mei- Ju, S., Xue-Ping, C., Jin-Hua, H., Qian-Qian, Z., Xue-Qin, Z., Lian-Min, Y., and Yan-Lin, 2015 (106) Q1	Inkjet printing of CH3NH3PbI3 on a mesoscopic TiO2 film for highly efficient perovskite solar cells.

Wiley online (Angewandte Chemie - International Edition) 17/08/2020	Wei, Z., Chen, H., Yan, K. &, & Yang, S., 2014 (**349**) Q1	Inkjet printing and instant chemical transformation of a CH3NH3PbI3/nanocarbon electrode and interface for planar perovskite solar cells.
Annual Reviews 18/08/2020	Basaran, Gao, & Bhat, 2013 (**194**) Q1	Nonstandard inkjets. Annual Review of Fluid Mechanics
Science Advances16/08/2020	Bi et al., 2016, (***1436***) Q1	Efficient luminescent solar cells based on tailored mixed-- cation perovskites
Wiley Online Library16/08/2020	de Gans, Duineveld, & Schubert, 2004 (***1219***) Q1	Inkjet printing of polymers: State of the art and future developments.
Web of Science 19/08/2020	Derby, 2010 (***743***) Q1	Inkjet printing of functional and structural materials: Fluid property requirements, feature stability, and resolution.
Wiley Online Library 20/08/2020	Eggers et al., 2020 (***23***) Q1	Inkjet-Printed Micrometer- Thick Perovskite Solar Cells with Large Columnar Grains
IEEE	Fromm, 1984 (***515***) Q1	Numerical Calculation of the Fluid Dynamics of Drop-on- Demand Jets
Wiley Online Library 16/08/2020	Alexandre Gheno et al., 2018 (***16***) Ranking (Unpublished)	Toward Highly Efficient Inkjet- Inkjet-printed perovskite Solar Cells Fully Processed Under Ambient Conditions and at Low Temperature.
J. Mater. Chem. A (12/8/2020)	(Hashmi, Tiihonen, et al., 2017) (***45***) SJR-0	Long-term stability of air-processed inkjet infiltrated carbon-based printed perovskite solar cells under intense ultra-violet light soaking.

American Chemical Society (Journal of Physical Chemistry C)	Koh et al., 2014 (***412***) Q1	Formamidinium-containing metal-halide: An alternative material for near-IR absorption perovskite solar cells.
Wiley Online Library (Advance Materials) 19/08/2020	Kuang, Wang, & Song, 2014 (***210***) Q1	Controllable Printing Droplets for High-Resolution Patterns.
Imaging.com (Journal of ImagingScience and Technology)	Le, 1998 (***1065***) Q3	Recent Progress in Ink Jet Technologies
RSC (Journal of Materials Chemistry A)	Li, S. G. et al., 2015 (***107***) Q1	Inkjet printing of CH3NH3PbI3 on a mesoscopic TiO2 film for highly efficient perovskite solar cells.
Google Scholar	Nandakumar & Paramasivam, 2006 Unpublished Thesis	Gravure, Flexography & Screen Printing. Sivakasi.
RSC (Journal of Materials Chemistry A) 19/08/2020	Noh et al., 2013 (***198***) Q1	Nanostructured TiO2/CH3NH3PbI3 heterojunction solar cells employing spiro-OMeTAD/Co-complex as hole-transporting material.
PubMed 18/08/2020	Beedasy & Smith, 2020 (***4***) Q1	Printed Electronics as Prepared by Inkjet Printing
American Chemical Society 18/08/2020	Soltman & Subramanian, 2008 (***580***) Q1	Inkjet-Printed Line Morphologies and Temperature Control of the Coffee Ring Effect
Wiley Online Library (12/08/2020)	Hoath, 2015 (Book)	Fundamentals of Inkjet Printing: The Science of Inkjet and Droplets.
RSC (Journal of Materials Chemistry A)	Li, S. G., Jiang, K. J., Su, M. J., Cui, X. P., Huang, J. H., Zhang, Q. Q., … Song, Y. L., 2015 (***128***) Q1	Inkjet printing of CH3NH3PbI3 on a mesoscopic TiO2 film for highly efficient perovskite solar cells.

From the selected and screened articles, as shown in Table 1, a thematic review of all the articles was undertaken. As illustrated in Table 1, the synthesis chart elucidated common factors and some differences between the articles in each theme; each theme discussed and compared the papers in the group. In the end, Table 1 was used to summarise the reviewed studies. The following sub-sections will present how the systematic literature review was conducted and how the screened studies have been summarised and explained in Table 1.

III. The Systematic Literature Review (SLR) Methodology

The current study was performed in compliance with recommendations for the systematic literature reviews to accomplish the research objective. SLR identifies the role and thesis research subject within the targeted subject area. It also assists in the determination and delimitation of the research scope. The SLR presents a comprehensive approach for selecting bibliographic references based on systematised and precise methods, looking for maximum findings and providing scientific evidence (Ramos, 2014). It is also necessary to answer the questions formulated clearly, collecting all accessible publications and previously studied and developed PSCs and inkjet-printing technology (Can et al., 2018). The first step is problem identification and definition of the research problem identified in Chapter One. The process of SLR methodology in this study is discussed below, and a summary is provided in Figure 1.

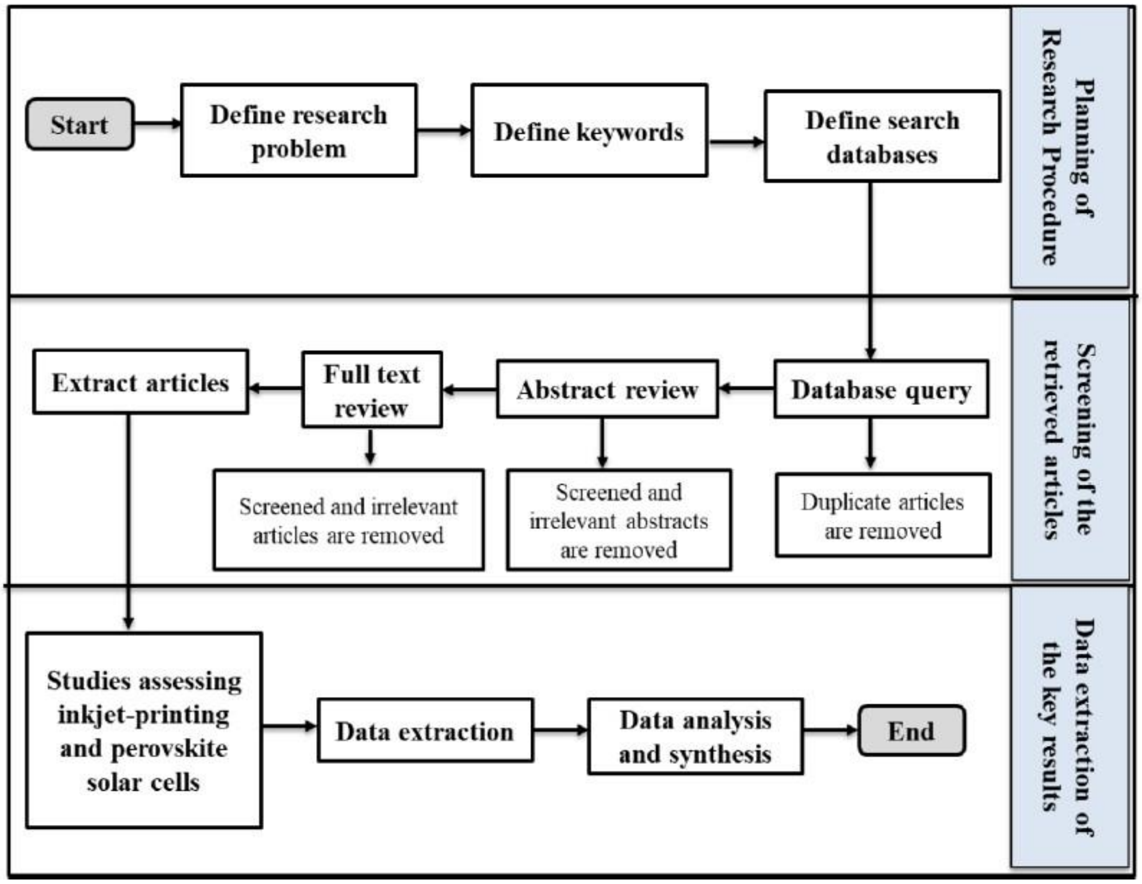

Figure 1: Summary of the Systematic Literature Review

3.1 Keywords and Search-string

The key terms or main words related to the research question were identified to conduct the current study: "How is inkjet printing technology superior for perovskite solar cells than other deposition methods?" The keywords searched for the study were defined as: "inkjet- -printing";' "perovskite solar cells"; "solar cells"; "efficiency of perovskite solar cells"; and "deposition methods." Following that, keywords were used on the repositories of various scientific articles to examine which bases constitute the study area. Several Boolean operators, such as 'OR' and 'AND' were used in-between these keywords to define the appropriate search strings, e.g. "perovskite solar cells" OR "solar cells"; "perovskite solar cells" AND "inkjet-printing technology"; "inkjet-printing technology" OR "fabrication methods" OR "deposition methods" AND "perovskite solar cells", etc.

3.2 Search Databases

The search method employed for the current research includes the selection of appropriate repositories to conduct the search process and locate existing works. ScienceDirect, Web of Science, Scopus, Google Scholar, IEEE, and PubMed are the repositories selected for this work. Considering the rankings of the journals and their publications in these repositories, they were chosen to select current works related to the subject area. This method is called the planning of research procedure.

3.3 Inclusion and Exclusion Criteria

The criterion for exclusion or inclusion of the retrieved articles was formulated. The critical rationale was to include only papers explicitly focused on PSC and inkjet printing. The search results were applied following the exclusion or inclusion criteria listed in the table below, which occurred before the actual conduct of the systematic analysis. The current study, using the Scimago Journal and Country Rank(Scimagojr, 2019) to validate the ranking and impact factor of the articles, collected the articles from selected databases as published in higher-ranking journals and with higher impact factors. The SCImago Journal & Country Rank is a publicly accessible portal with journals and country scientific research indicators developed from the Scopus ® database (Elsevier BV). (Scimagojr, 2019) These indicators could be used for the assessment and analysis of scientific articles. Journals can be individually compared or analysed(Scimagojr, 2019).

The impact factor was created in the 1960s to measure the value of journals by calculating the average number of citations per article over a specific period (Garfield, 2005). This research was not limited to reviewing articles from published journals but included articles from unpublished works(thesis) and books. As such, one prominent feature of the systematic review approach is a deliberate attempt to look for and include applicable, unpublished work (which meets the requirements for inclusion and exclusion) to minimise the impact of publishing bias(Siddaway, Wood, & Hedges, 2019). Publication bias defines the likelihood of published studies being available to rely on the findings. (Siddaway et al., 2019)

Table 2: Exclusion and Inclusion Criteria

Inclusion criteria	**Exclusion criteria**
Articles available only in the English language	Articles available in different languages other than the English
Studies directly related PSCs and inkjet-printing technology	Studies not directly related to PSCs and inkjet-printing technology
Research work which was carried out after 2007	Research which was carried out before 2007
Research which was published in peer-reviewed journals	Studies published in newspapers and in journals that are not peer-reviewed

IV. Test Significance of Retrieved Articles

The significance of the identified papers was assessed by analysing them against both the inclusion and exclusion criteria that follow the three-step procedure, as provided by Saltikov (2010). In the first step, all the titles of the papers were assessed; only the evaluation of titles provides the benefit that documents which do not fulfil the analysis criteria can be discarded or excluded within a relatively short period. Additionally, the title, which contained information too limited to determine its importance, was included. In the second step of screening, the abstracts of all remaining articles were read, identified and evaluated against both the exclusion and inclusion criteria. The whole paper was screened and systematically presented in a PRISMA flow chart in the third screening phase.

4.1 Assessment of Retrieved Articles

The quality evaluation is critical in determining correct paper results (Popay et al., 2006). Peer-reviewed papers have been included in the current study, which includes the requirement for more quality evaluation.

4.2 Critical Review

The step of critical review involves three different processes detailed in the following subsections.

4.3 Data Extraction

The selected and searched articles extracted appropriate data related to the defined goals and research question in light of our inclusion and exclusion criteria. It included:

I. The title and reference of the articles, including PSCs and inkjet-printing technology;
II. A summary of how much the research focuses on the superiority of inkjet- printing in comparison to other deposition techniques for PSCs;
III. The short overview of the fabrication methods used for PSCs;
IV. Parameters of inkjet printing that influence efficiency, stability and performance of PSCs;
V. Properties and characteristics of ink-formation that affect the efficiency of the PSCs.

4.4 Data Analysis

Secondary data were collected from evidenced-based research findings through available pieces of literature. The collected data were analysed and evaluated to answer the critical research questions and sub-questions. To effectively analyse the superiority of the inkjet-printing technology for perovskite over other technologies, the PRISMA flow diagram was used in screening articles and other works (related books and thesis). PRISMA flow chart is a minimum set of reported items in systematic reviews and meta-analyses based on evidence. PRISMA focuses on reporting studies that review randomised experiments, which may also be seen as a framework for coverage of comprehensive assessments of certain forms of testing, especially experiment evaluations (Moher et al., 2009).

To further validate the superiority of the inkjet-printing technology for perovskite over other technologies, box plots from Excel Spreadsheet, which examines the means of two or more independent variables to determine whether there is statistical evidence that there is significance in the ranking of articles used for the evaluation of superiority of the inkjet-print technology, in comparison to other articles. Numerical data is split into quartiles in the box chart, and a row is drawn between the first and third quartiles, with an additional line drawn along the second quartile to mark the median.

4.5 Synthesis

Finally, the results and findings of the selected articles were summarised, as presented in the following chapter.

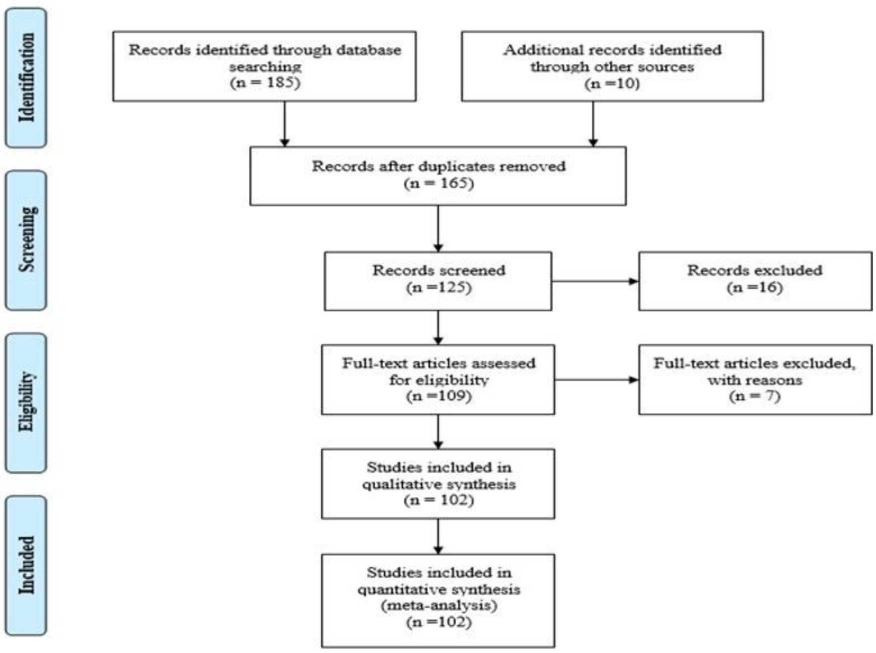

Figure 2: Prisma Flow Diagram (Adapted from Moher et al., 2009)

V. Results and Discussion

5.1 Results

To effectively analyse the superiority of the inkjet-printing technology for perovskite over other technologies, statistical analysis of the quality and ranking of the articles reviewed were conducted using Microsoft Excel 2016 Box Plots. The created box plots for ranking the articles (both published and unpublished) showed the distribution sets of data extracted from the Synthesis Matrix Table in Table 3.

Secondary data were collected from evidenced-based research findings through available literature to determine whether there is statistical evidence between the ranking of articles and the number of citations received. The Box Plot chart in Figure 4 shows a significant relationship between journal ranking and the frequency of citations. The chart in Figure 4 shows that the number of articles reviewed was higher than that of Q1 journals. The group of journal subjects is divided into four quartiles: Q1, Q2, Q3, and Q4. Q1 is in the top 25 percent of journals on the list; Q2 is in the 25 to 50 percent group; Q3 is in the 50 to 75 percent category, and Q4 is in the 75 to 100 percent category.

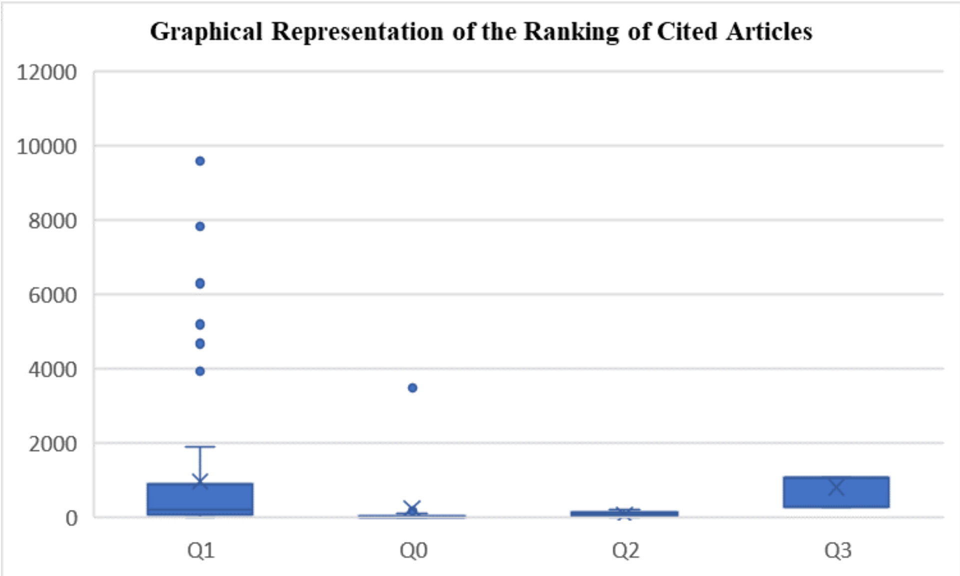

Figure 3: Citation Counts Retrieved for 102 Articles from Forty-Seven Journals and 22 Database for Inkjet and Perovskite Articles

In the chart and this study, Q0 represents journals and articles (like books and thesis) with zero (o) ranking and without citations.

One hundred eighty-five research papers were identified through database searching from Scopus, Wiley Online Library, ScienceDirect, Google Scholar, American Chemical Society, Hindawi, Nature, and others. Upon screening, 102 articles (in forty-seven journals) and unpublished works were included in qualitative synthesis and citation analysis. Unclear or incomplete analysis of the research questions and the primary result have not been correlated statistically substantially with the citation counts. An extended explanation of methodological techniques after correction for the journal had a favourable impact on the number of citations obtained. Figure 4 below elucidated that the journal ranking and the number of citations received were more from Q1 journals, which influenced the statistical study in this regard.

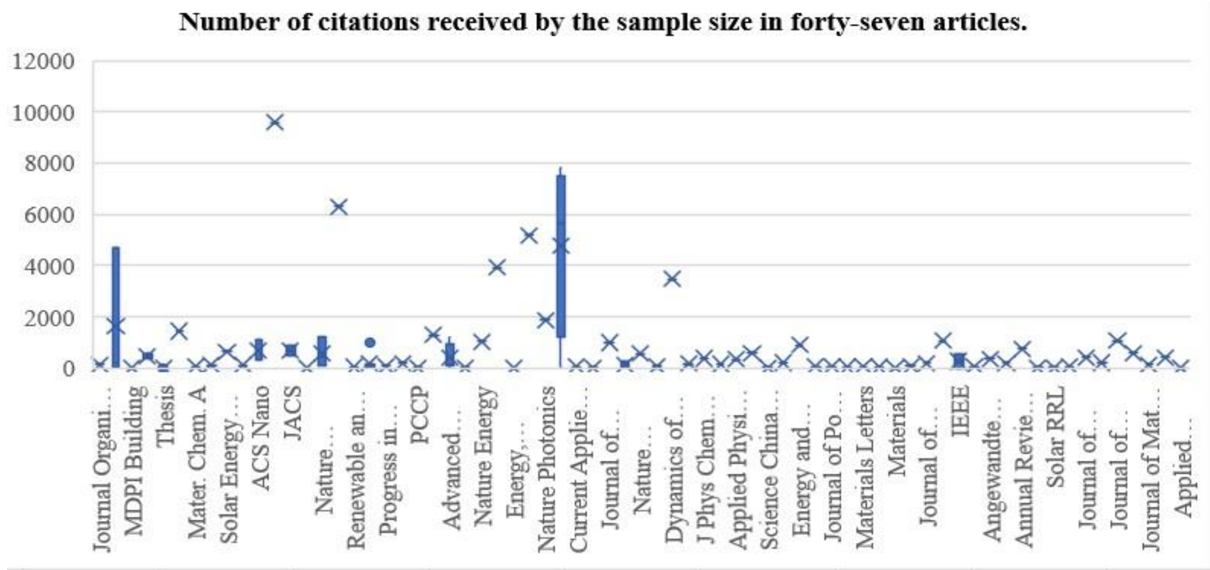

Figure 4: Screened Articles against Citation Counts from the Journals and other reports

The journal's quality and reputation are linked to accurate analysis of the critical study issue (superiority of inkjet printing), methodological methodology and key results. The box plots showed that the distribution of the number of articles screened (see Table 3.0) is highly positively skewed for Journal Ranking Q1, so we use the median as a measure of location.

5.2 Discussion

This research analysed the consistency of statistical reporting and analysis of one hundred and two (102) publications with several citations obtained to assess whether inkjet printing is superior to other traditional perovskite solar cell technology types. Failure to state (explicitly the superiority of inkjet printing) as essential details in this series of articles, such as the primary research question or the primary outcome variable, did not influence the number of citations the articles got. An adequate explanation of the different fabrication techniques and their effects on perovskite significantly raised the number of citations in the 102 publications, books and thesis screened. Quality reporting has been correlated with recognition and credibility in the journal due to the ranking of the journals and, as elucidated.

By assessing, systematically reviewing, and linking the findings of all the 102 related, high-quality published inkjet-printing and perovskite publications, it can be established that inkjet-printing possesses higher qualities in PSCs printing than other technologies. The article search was performed with support from the expert search engine on Google, Elsevier's ScienceDirect website, by using the parameters determined in the objectives and research questions for publications. Following the original goals, the critical areas of focus and sub-areas of concern on IJP and PSCs were grouped into three themes (Table 3) to promote the study's collection of relevant science articles. The table containing the lists of articles for the selected research areas was formed.

From the established review, it was discovered that inkjet research on PSCs has attained considerable interest over the years. There has been significant PSC growth in PCEs (i.e., from 3.9-22%), comparable to the Shockley-Queisser limit (Mathan et al., 2018). The inherent properties of inkjet printing, which include its efficient use of materials, highly controlled deposition, and operation under ambient conditions, make it an attractive tool in translating PSC fabrication from laboratory scale to mass production. However, even though inkjet printing has already been widely applied in the study of Organic Solar Cells (Li et al., 2015; Wei et al., 2014), its application in fabricating PSCs remains sparse (Bag et al.,2016; Wei et al., 2014). According to Peng (2017), this can be attributed to PSCs being a relatively nascent technology, with the research mainly focused on laboratory-scale devices without further consideration for scale-up.

Despite this, as significant advancements are reported in solving materials, stability, and film formation issues in lab-scale devices, interest has recently turned to large-scale processing (Peng et al., 2017). As deduced from the reviewed articles, inkjet printing has exhibited unique advantages in fabricating solar cells over conventional vacuum or solution methods. For instance, it does not require any mask or template during printing, coupled with the absence of material wastage, which enables a considerable reduction in device processing and material usage. Nevertheless, tremendous progress has been made regarding applying inkjet printing in the fabrication of solar cells, earning it a viable deposition technique for both academic research and industrial applications. The technological developments in ink formulation, strategies, and inkjet printing applications for different layers of various types of solar cells have been successfully reviewed in earlier sections.

VI. Conclusions

The main objective of the current research has been to assess the superiority of inkjet- printing over other conventional forms of technology for perovskite solar cells by expanding knowledge on inkjet printing (IP), exploring affordable new possibilities, and starting with previous knowledge of printing technologies as a basis. To achieve this aim, a distinction was made during the current study between a proven and an already proven, stable system already well-accepted in the industry, SP, and a rising-up strategy that is pressing fast into the electronic market of inkjet-printing. Screen-printing, as with other similar evaluated technologies, is an established and conventional technique that uses a mask or template to print, involving exhausted and laborious pre-processing of template output. Specifically, screen-printing is compatible with highly viscous materials, which include conductive pastes and even dielectric adhesives. Screen-printing pastes are typically suitable for high concentration and high- temperature substrates, such as ceramic technology. The current study has not only been an analysis of the IP methods, principles, and functional content production for PSCs, but also the study of the actual deployment functionality of the different technologies for PSC applications. The general conclusions on the superiority IP were drawn and listed below after the literature review of the various technologies and their applications in several fields, and especially on PSCs:

I. For inkjet printing the ink formulation is much more rigid and dynamic than the formulation of pastes (Beatriz, 2016). For this purpose, a thorough control of the physical parameters, and also the scale of the nanoparticles, is important for high quality printing for PSCs. Nevertheless, non-particulate precursor inks can be produced even better than screen printing pastes, owing to the probability of handling without binder and other proponents of rheology (Beatriz, 2016).

II. Inkjet-printing is a reasonable alternative for PSCs and some other devices to the screen-printing method, particularly those whose rapid prototyping may provide key details in the development and corroboration of performance simulations (Beatriz, 2016; Peng et al., 2017).

III. IP is suitable for the fabrication of devices, such as PSCs, which require less than a few microns of very thin layers. Screen-printing cannot tolerate this sort of deposition of thickness (Beatriz, 2016).

IV. Given the rapid achievement of high performance, PSCs faced many challenges, including improving poor reliability through reproducibility during manufacturing, particularly during scaling to industrial level (Bag et al., 2016; Li et al., 2015). This demonstrated manufacturing under fully vacuum-free conditions, and reduced the high production costs associated with high-cost materials, such as spiro-MeOTAD (Beatriz, 2016; Liu et al., 2014; Wu et al., 2014).

VII. Recommendations

Inkjet printing is rapidly becoming a popular technique for the solution-based manufacture of solar cells' perovskite. Replacing the vacuum phase with ambient processes significantly decreases the expense of assembling solar cells and modules. Digital printing, such as inkjet printing, enables module manufacturing without scribing. In the current study, the literature review shows that inkjet printing is suitable for the fabrication of perovskite solar cells with the correct positioning and precise volume decrease of practical substrate microliters. This offers the possibility of printing very near conductive tracks (tens of microns) and extremely thin layers ($< 0.3\mu m$), thus minimising the device size and manufacturing costs, owing to the reduced amount of material waste.

Conflict of Interest

This manuscript's authors declare no conflicts of interest any form or capacity.

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