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Facilitating Photovoltaic Cell Performance Improvement through Deployment of Engineered Organic Nanomaterials

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Abstract

This research work provides concise insights into fossil fuel consumption challenges, and the factors contributing to global warming, and evaluates the significance of photovoltaic (PV) materials in achieving net-zero-CO_2 emissions. The article categorizes constraints in the development of PV cells into four main areas: technical factors, leadership impact, political instability, and financial aspects. Primarily, the study delves into technical factors, focusing on the power conversion efficiency (PCE) and power density of PV cells. Theoretically, approximately 67% of solar energy is dissipated in various forms: - 47% as heat, 18% as photons, and 2% in local combination loss. Commercially available mono-crystalline silicon (c-Si) and poly-crystalline silicon (poly-c-Si) PV cells typically demonstrate a range of PCEs between 15%-22% and 13%-18%, respectively, presenting an efficiency considerably lower than the potential maximum of 100%. The study highlights organic photovoltaic cells (OPVs) as promising third-generation PV modules due to their relatively high power conversion efficiency (HPCE) and eco-friendly attributes. However, their commercial feasibility is under scrutiny owing to constraints such as a limited lifespan, high production costs, and challenges in mass production. Ongoing research and development (R&D) in PV cell technologies aim to enhance PCE and power density, establish cost-effective production methods, and create more reliable and sustainable supply chains. Additionally, the study explores the role of nanotechnology in developing high-power conversion efficiency cells, identifies research gaps and priorities in engineered organic material PV cells, and discusses the potential of OPVs in the R&D of high-efficiency, cost-effective, and environmentally friendly PV cells.

Keywords: *Power conversion efficiency, Photovoltaic cell materials, Organic photovoltaic cell, Nanotechnology, Renewable energy materials.*

1. Introduction

Solar photovoltaic (PV) energy stands out among renewable resources due to its widespread availability and accessibility. The potential of solar energy is substantial, and its conversion into electricity using PV modules is a straightforward, quiet, and low-maintenance process. Consequently, PV modules have gained significant traction for electricity generation, not only in rural and remote areas but also within urban settings, with expectations of significantly replacing fossil fuels. However, commercially available PV cells [1] such as monocrystalline silicon (mono-c-Si) and polycrystalline silicon (poly-c-Si) exhibit attributes that fall short of satisfaction. These limitations encompass the power conversion efficiency (PCE), cost-effectiveness, and energy density of PV cells. Typically, the PCE range for mono-c-Si and poly-c-Si cells falls between 15%-22% and 13%-18%, respectively [2, 3]. Research and development (R&D) of PV cell materials is rapidly advancing due to the quest for solutions to address identified functional gaps. These shortcomings hinder the widespread deployment of PV systems, and consequently, lead to heavy reliance on fossil energy. Even today, the importance of fossil fuels in sustaining the global economy remains significant, despite resolutions by the United Nations (UN) and various countries to reduce the use of polluting fuels [4-7]. This significance is due to the indispensable role of energy in human existence and socioeconomic development. Insufficient energy supply hampers socioeconomic growth and jeopardizes people's well-being [8, 9].

Several energy concepts including energy justice, energy trilemma, and energy for all have been proposed to mitigate the compromises associated with fossil fuel use and the resulting harmful emissions. The success of these contemporary energy concepts heavily relies on breakthroughs in the R&D of energy materials. The availability of materials exhibiting higher PV PCE, increased energy density, enhanced storage capacity, lower production costs, and reduced levelized cost of energy (LCOE) will facilitate the realization of these concepts. Achieving Sustainable Development Goals (SDGs) related to energy for all and a net-zero-CO_2 emissions economy will be unattainable without significant breakthroughs in renewable energy materials, especially in PV cells' R&D. Responding to this call to action, materials engineering studies and developments are ongoing in several areas including energy generation materials, energy storage materials, energy conversion materials, and energy efficiency and sustainability. Other research areas encompass advanced characterization techniques, computational materials design, emerging materials, environmental impact, and safety, as well as scale-up and commercialization.

This study briefly explores the evolution and implications of oil and gas consumption and the role of renewable energy in mitigating climate change. It examines how material advancements and nanotechnology contribute to achieving modern energy attributes and identifies research gaps requiring attention in the development of PV cells. To fulfil the objectives of this paper, it will provide a concise history of fossil fuel usage and CO_2 emissions, identify barriers to the development of renewable energy materials, and emphasize the importance of materials in addressing technical challenges in PV cell development. Additionally, it will overview emerging PV cell nanomaterials and organic photovoltaics (OPVs), recount recent R&D breakthroughs in renewable energy materials, and project outlooks for PV cell energy materials. The study recognizes the enhancements in PV cell performance through the utilization of engineered organic materials and acknowledges the ongoing efforts to address various research gaps.

3. Methodology

The study is based on the latest information from the recent research papers, conference presentations, and reports from credible sources within the domains of solar energy and materials science. This study presented short briefs on the use of fossil fuels, the growth of CO_2 emissions, the challenges that come with fossil fuel usage, and the causes of global warming. The paper x-rayed the role of RE in reducing net-zero-CO_2 emissions and the limiting barriers to RE development and deployment. This was followed by taking an overview of the critical role of engineering materials, especially the emerging organic nanomaterials, in tackling PV cell technical challenges and the identification of research priorities and gaps for further exploitation. The study relied on secondary sources of quantitative information, obtained from verified websites, government documents, textbooks, published articles, and local and international organisations' reports and prospects. Some of these international organisations are the World Bank and UN and their subsidiaries, and the International Renewable Energy Agency. Others are the United States National Renewable Energy Laboratory, the International Energy Agency, the Renewable Energy Policy Network for the 21st Century, and the World Energy Council. The information garnered will be used to offer insight and to establish the outlooks of OPVs. The focus is on the significance of new materials for PV cells that will facilitate the production of adequate, affordable, and clean energy to replace fossil fuels in powering socio-economic activities. The systematic approach and structure of the various issues considered in this study are represented in figure 1.

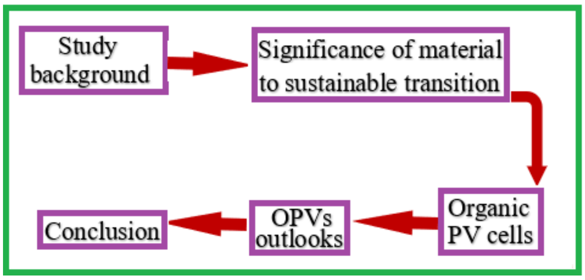

Figure 1. The systematic structure of the study.

4. Background study: How did we get here?

4.1. Carbon dioxide build-up: a product of socioeconomic development

The growth of fossil fuel consumption has been massive before and after World War II, and it is still very high in contemporary consideration, despite its strong link to climate change. It was a scenario of the more fuel burnt the greater the socio-economic activities. Unarguably, the world's two largest economies, the USA and China, consume the highest fossil fuel and contribute about 40% of the global CO_2 emissions in 2020

[10]. The challenges accompanying CO_2 emissions are critical and intimately connected to global warming; CO_2 emissions have been identified as one of the primary drivers of the Earth's warming climate [11-13]. The Earth's atmosphere contains GHGs, consisting of CO_2, methane (CH_4), and others. These gases naturally trap some of the sun's heat, creating a beneficial greenhouse effect that maintains Earth's temperature within a habitable range. Human activities, particularly the burning of fossil fuels (coal, oil, and natural gas) for energy, deforestation, and industrial processes have significantly increased the concentration of CO_2 and other greenhouse gases in the atmosphere. These increased concentrations of CO_2 and other GHGs lead to a rise in global temperatures. This warming is associated with a range of effects including more frequent and severe heatwaves, shifting weather patterns, melting glaciers and ice caps, rising sea levels, and disruptions to ecosystems and biodiversity.

The term "global warming" is often used interchangeably with "climate change." While global warming specifically refers to the increase in average global temperatures, climate change encompasses a broader range of changes including shifts in precipitation patterns, ocean acidification, and extreme weather events—all of which are influenced by increased CO_2 emissions [14, 15]. To address the impacts of global warming and CO_2 emissions, countries are working to reduce GHG emissions. This involves transitioning to renewable energy sources (solar, wind, hydroelectric), improving energy efficiency, reforestation efforts, and adopting sustainable practices in agriculture and industry. The UN through international cooperation reached an agreement, called the Paris Agreement, that emphasises on the reduction of CO_2 emissions and combat climate change. The Paris Agreement, a global accord within the United Nations Framework Convention on Climate Change (UNFCCC) aims to limit global warming to well below 2 ℃ above pre-industrial levels, with efforts to limit it to 1.5 ℃ [16]. The global aspiration of using alternative energy sources to drive a net-zero-CO_2 emissions economy is high. The 26th UN Conference on Climate Change (COP26), held in Glasgow, United Kingdom, in 2021, re-echoed cutting down fossil fuel consumption and increasing the use of alternative energy sources [17]. The deployment of affordable, clean, reliable, and sustainable electricity has been enshrined in the Sustainable Development Goals (SDGs), as item seven. Access to an adequate supply of clean energy has been portrayed as a right; therefore, the seventh item of SDGs declares clean energy for all by 2023. As a part of decarbonisation measures, electric-powered vehicles are expected to form a 30% share of the cars on the road.

4.2. Pursuit of RE and impediments

Elimination or reduction of the consumption of fossil fuel as one of the responses to climate change challenges is no longer debatable; it is now a necessity. The only possibility to kick fossil fuel out of the economic equation is to adequately develop and deploy clean, reliable, affordable, and sustainable energy alternatives [18]. In addition to solar, hydro, tidal, geothermal, and wind energy, an available alternative source of electricity to fossil fuels is nuclear energy. While other renewables are regarded as clean, compact, reliable, competitive, safe, and inexhaustible sources of electricity, there are sceptical issues about the use of nuclear energy [19]. Many nations described it as unsafe because of the perceived complex safety measures and the side-effects it generates if safety measures go wrong.

Despite decades of R&D and the upward surge in the recent global deployment of RE technologies, limitations still exist. Apart from the socio-political impediments, technical challenges such as energy intermittency and low power conversion efficiency (LPCE) are associated with PV systems, and are influenced by location, weather, and season. The study classifies solar PV development constraints into four categories, as presented in table 1 - technical factors, leadership influence, political instability and crisis, and finance. The use of combined systems, called hybrid renewable energy systems (HRES) [20], was introduced to ameliorate energy intermittency and LPCE. A power bolster, a diesel or petrol generator, is always added to the HRES to cushion the effect of supply fluctuations, and this negates the net-zero-CO_2 emissions drive. Hence, the need to develop and deploy HPCE and high energy-density storage materials is a clarion call.

Table 1. Photovoltaic materials development impediments.

Technical	Leadership influence	Political instability and crisis	Finance
Energy availability intermittency, low generation capacity, low PCE, inadequate business models, high cost, inadequate technical personnel and research capacities in RE development.	Corruption and rigid bureaucracies, inadequate developmental framework and policies, lack of technology acceptance and community awareness	Vandalisation and stealing of installed equipment, lack of continuity of power schemes	Huge upfront capital is a requirement; Expensive storage costs, lack of funding, non-cost reflective energy tariffs

4.3. Place of PV technology in 100% renewable energy power supply

The global energy challenges are deeper in the global south, and responses to these issues should be adaptive and based on peculiarities. The peculiarities should be in terms of PV technologies R&D, policy formulation, and effects of PV materials improvement on HRES. Solar PV stands out among the RE technologies because of its pattern of distribution and potential. Solar PV is at the epic of RE deployment to the proposed 100% RE power, and therefore, occupies special space in HRES. A study has hypothetically opined that energy trilemma accomplishments will be facilitated by breakthroughs in the ongoing R&D studies on PCE and low-cost flexible thin-film PV modules [21]. The HRES performance is a function of the average efficiencies of all the subsystems that formed the HRES [22]. Hence, the improvement of RE materials PCE will enhance the performance of HRES.

According to some studies, the planet's energy requirements would be met if just 0.1% of the Earth's surface is covered by PV cells with PCE of 10% efficiency [23, 24]. However, space limitation is a hindrance in countries on the islands such as Singapore, Malta, Maldives, Barbados, and Bahrain. Hence, the development of HPCE PV cells will facilitate greater deployment of PV systems in these countries. Present research on PV modules is driven by PCE and reliability improvement, cost reduction, and the creation of more secure and sustainable supply chains.

4.4. Fundamental and classification of photovoltaic cells

Solar energy is considered a clean and renewable source of power because it relies on abundant and freely available energy from the sun, and does not produce greenhouse gas emissions or air pollutants during electricity generation. It is widely used in both residential and commercial settings to generate electricity, reduce energy costs, and contribute to a more sustainable energy future. A solar or PV cell is a device that converts sunlight into electricity through a process known as the photovoltaic effect. Solar cells are a key component of solar panels, which are used to capture and harness solar energy for various applications including generating electricity for homes, businesses, and remote power systems. Solar cells are typically made of semi-conductor materials such as silicon. When sunlight (photons) hits the surface of the solar cell, it excites electrons in the semi-conductor material.

4.5 Type of solar PV cells

Solar panels consist of multiple interconnected solar cells to produce the desired amount of electricity. Solar cells can come in various types including mono c-Si, poly c-Si, thin-film solar cells, and many more, each with its own characteristics and efficiency levels. The PV cell technology has evolved over the years and the technology is classified into three, as presented in table 2 – first generation (crystalline silicon solar cells); second generation (thin-film solar cells - amorphous silicon (a-Si:H), cadmium telluride (CdTe), gallium arsenide (GaAs), and copper indium gallium selenide (CIGS)) [25]; and third generation. Third-generation PV cells are emerging technologies, and less commercially advanced compared with PV cells of first and second generations. This PV cells generation is ambiguous as it encompasses technologies that include, perovskite solar cells (PSCs), copper zinc tin sulfide (CZTS), organic photovoltaics (OPVs), quantum dot solar cells (QDSCs), and dye-sensitized solar cells (DSSCs) [26, 27]. Others are non-semiconductor (including polymer-based cells and biomimetic), tandem/multi-junction cells, hot-carrier cells, and up-conversion [28].

Table 2. Comparison of commercial PV cell materials [29].

Cell type	1st Generation: Crystalline silicon		2nd Generation: Thin film		
	Mono-crystalline	**Poly-crystalline**	**Amorphous silicon**	**Cadmium Telluride**	**CIGS**
Max. Efficiency	25%	20%	13%	21%	20%
High temp. effect on PCE	15% drop	20% drop	0% drop	0% drop	0% drop
Temperature coefficient P_{Max}	−0.5%	−0.5%	−0.25%	0%	0%
Low irradiance performance	Power output reduction	Power output reduction	Low impact on power output	Low impact on power output	Low impact on power output
3rd Generation PV cells [30]					
	OPVs	**DSSCs**	**PSCs**	**CZTS [26, 27]**	**QDSCs**
PCE range (%)	2.5 – 18.2	6.5 - 13	14.1 - 25.5	7.4 - 13	2.9 - 18.1
Open-circuit V_{OC} range (V)	0.583 - 0.897	0.711 - 1.04	1.007 - 1.986	0.7306 - 0.4598	0.525 - 1.14

where V_{OC} is the open-circuit voltage.

4.6. Electrical characteristics of PV cell

The energy from the absorbed photons causes electrons to be freed from their normal positions in the atoms of the semi-conductor material. This creates electron-hole pairs, where an electron is negatively charged, and the hole left behind is positively charged. The presence of these electron-hole pairs allows for the movement of electrons, creating an electric current. This flow of electrons is what generates electricity. The solar cell is designed with electrical contacts on its surface to collect the electrons and route them through an external circuit. This creates a flow of electricity that can be used to power electrical devices or stored in batteries for later use. The schematic diagram in figure 2 illustrates the illuminated solar cell's I–V characteristic. The fundamental traits of a solar cell encompass the short-circuit current (I_{SC}), the open-circuit voltage (V_{OC}), the fill factor (Ff), and the efficiency of converting solar energy (η) [31].

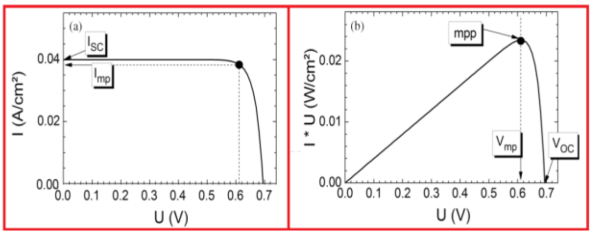

Figure 2. A I–V characteristic of a solar PV cell [31].

where P_{mpp} is the maximum power point, and V_{mp} and I_{mp} are the voltage and current density at the maximum power point, respectively.

There exists a specific pairing of current and voltage at which the solar cell achieves its highest power (I_{mp} and V_{mp}, respectively). This juncture on the I–V characteristic of an illuminated solar cell is termed the maximum power point (P_{mpp}), expressed mathematically as:

$$P_{mpp} = I_{mp} * V_{mp} \quad (1)$$

There are key parameters for determining the correct installation and PV system performance electrically, and these include [32]:

The PV system's annual electricity generation (E_{ann}) in kWh:

$$E_{ann} = A_{pan} * eff_{pan} * I_{irr} * PR \quad (2)$$

where A is the total solar panel Area (m^2), I_{irr} is the annual solar radiation (kWh/m^2), eff_{pan} is the panel PCE (%), PR is the performance ratio (losses coefficient, which ranges between 0.5 and 0.9).

The estimation of the real-time PR of the PV system is obtained from expression (1)

$$PR = \frac{PV_{OUT} * I_{stc}}{GTI * DC_{cap}} \quad (3)$$

where PV_{OUT} is the power output (W), I_{stc} is the irradiance at STC (1000 W/m^2), GTI is the global tilted irradiance, and DC_{cap} is the direct current (DC) capacity (W) of the PV system.

The temperature of the PV cell is a key performance variable; at elevated temperatures, the PV system output drops. The derating factor η_t accounts for the PV system's temperature effect and is estimated as follows:

$$\eta_t = 1 - \gamma * (T_c - T_{stc}) \quad (4)$$

where γ is the coefficient of power temperature (γ for c-Si PV panel is about 0.005), and T_c and T_{stc} are ambient and standard testing condition PV panel temperatures, respectively.

The fill factor (F_f) is a parameter that serves as a crucial metric for assessing the efficiency of solar cells. To determine the fill factor, one must divide a solar cell's real power output by its maximum potential power output, yielding a measurement that aids in evaluating the solar cell's performance [33].

$$F_f = \frac{P_{\max}}{V_{oc} * I_{sc}} = \frac{V_{mpp} * I_{mPP}}{V_{oc} * I_{sc}} \quad (5)$$

Typically, commercial PV cells are expected to possess an F_f exceeding 0.7. Cells with factors lower than this threshold are generally not advisable for practical utilisation in larger-scale electricity generation projects.

the fill factor (*FF*) and the efficiency of converting solar energy (η) [31]. The significance of concentrated sunlight in augmenting efficiency becomes evident. Evaluating resistive losses in practical solar cells introduces acceptable series and parallel resistances as assessment criteria.

A solar cell transforms solar power (P_{sun}) into electrical power (*P*), represented by the product of electric current (*I*) and voltage (*U*):

$$P = I * U \quad (6)$$

The rated capacity of a PV power plant (P_{inst}) is defined as the maximum power it can generate from P_{sun} (AM1.5) in the initial year post-installation.

$$P_{inst} = A * \eta * P_{sun}(AM1.5) \quad (7)$$

The electrical energy (P_{out}) obtainable from a PV power plant is determined mathematically expressed as:

$$PV_{OUT} = A * \eta * P_{sun} * t \quad (8)$$

where *A* is the area covered by the PV modules, η is the PV module PCE, AM 1.5 is air mass spectra, and *t* is the operational time.

4.7. Band gap and its significance to PV cells

The band gap or energy band gap represents the minimal energy necessary for electrons within a material's outermost shells to break free from the parent atoms, creating a vacancy termed a 'hole'. These liberated electrons are then involved in conduction. Good conductors possess zero band gaps, as they consistently offer available free electrons for conduction when exposed to even the smallest electric potential. Their valence and conduction bands overlap. On the other hand, insulators exhibit significantly high band gaps, requiring substantial energy to release their electrons from the parent atoms. Semi-conductors feature intermediate band gap energies measured in electron volts (eV). It's important to note that one electron volt (1 eV) is the energy required to reduce the potential of an electron by one volt [34, 35].

Regarding solar cells, silicon, the most prevalent semi-conductor, demonstrates a band gap energy of 1.11 eV at room temperature. Releasing an electron from a silicon atom at this temperature necessitates supplying an energy packet greater than 1.11 eV. For silicon-based solar cells to generate photovoltaic electricity, incident photons must carry energy higher than 1.11 eV. In contrast, solar cells manufactured from cadmium telluride (CdTe) exhibit a band gap energy of 1.44 eV [36]. The band gap directly influences the efficiency of a PV cell by determining the photons that can be absorbed and converted into electrical energy. Achieving the right band gap for solar cell materials is essential for optimal energy conversion and higher overall efficiency in harnessing solar energy. The band gap of a material is highly significant in the context of PV cells due to its role in the absorption of sunlight and subsequent energy conversion. The band gap determines the specific energy of photons that the material can absorb, affecting the efficiency and performance of the solar cell. For efficient energy conversion, PV materials require a band gap that balances both the absorption of a broad spectrum of sunlight and efficient electron-hole pair generation. Hence, selecting the right band gap for a specific application is crucial in maximizing the cell's efficiency. Different materials have various band gap energies, as shown in figure 3. Engineers and scientists continuously explore and develop new materials or material combinations to achieve ideal band gaps for better solar cell efficiency and performance.

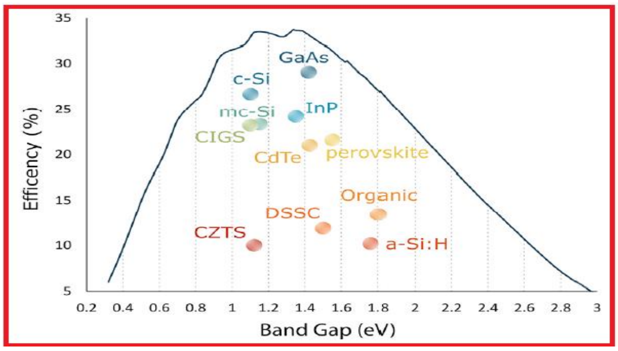

Figure 3. Band gap of different materials [36].

5. Role of Materials Engineering in Addressing PV Cells' Technical Challenges

The present global energy supply must satisfy the three "Es" of the energy trilemma: energy security, energy equity, and environmental sustainability. The attainment of the Es requires an increase in the use of clean, affordable, and RE sources; improving the PCE of RE technologies via R&D; increase in the deployment of clean energy in both urban and rural areas to ensure energy security. Materials engineering plays a crucial role in energy material R&D by enabling the creation of advanced materials that enhance energy generation, storage, conversion, and efficiency. This field focuses on designing, synthesising, characterising, and optimising materials for various energy applications. Some of the key aspects of materials engineering in energy research are presented in table 3.

Table 3. Key aspects of materials engineering in energy research.

Energy material research themes	Details of energy materials research interests and target	Reference
Energy generation materials	**Solar PV cells:** Researchers work on developing materials that have high energy density, are relatively cheap to produce, and efficiently convert sunlight into electricity such as thin-film solar cells, organic photovoltaics, and perovskite solar cells.	[37-40]
	Thermoelectric: Materials engineers design thermoelectric materials that can convert waste heat into usable electricity by utilizing the See beck effect.	
Energy storage materials	**Batteries:** Materials engineering contributes to the development of high-capacity and fast-charging battery materials including lithium-ion, solid-state, and beyond-lithium-ion battery technologies.	[41-43]
	Supercapacitors: Materials are optimized for high energy density and rapid charge-discharge cycles, enhancing the performance of supercapacitors used for short-term energy storage.	
Energy conversion materials	**Fuel cells:** Materials engineering plays a role in developing efficient catalysts and ion-conducting materials for fuel cells, which convert chemical energy into electricity.	[44-47]
	Thermoelectric generators: Researchers create materials that convert heat gradients into electrical power, enabling waste heat recovery and efficient power generation.	
Energy efficiency and sustainability	Materials engineers focus on improving the efficiency of energy production processes such as refining materials for better heat transfer, reduced energy losses, and enhanced durability.	[48-50]
	Sustainable materials development involves considering the life cycle impacts of materials, ensuring resource efficiency, recyclability, and reduced environmental impact.	
Advanced characterization techniques	Materials characterization methods such as electron microscopy, X-ray diffraction, and spectroscopy help researchers understand the structure, composition, and properties of energy materials at the nanoscale.	[51-55]
Computational materials design	Computational modelling and simulations are used to predict the properties of materials before they are synthesized, saving time and resources in the development process.	[56-59]
Emerging materials	The discovery of new materials such as 2D materials and nanomaterials opens up new possibilities for energy applications due to their unique properties.	[60-62]
Environmental impact and safety	Materials engineers consider the environmental impact and safety aspects of energy materials, ensuring that they are non-toxic, stable, and compatible with their intended applications.	[63-65]
Scale-up and commercialization	Developing energy materials at a laboratory scale is just the beginning. Scaling up production processes while maintaining material quality and performance is a significant challenge.	[66-68]

In recent times, the researchers have developed new strategies based on high-performance computing technologies to create nanomaterials. This has accelerated the discovery of new nanomaterials being applied in the RE sector. Materials, especially nanomaterials, have played a significant role in the past and present improvements recorded in RE technologies. They have gained notification in the recent years in the scientific and technological spaces. Nanomaterials' chemical, physical, and physicochemical properties differences are mainly responsible for their applications [69]. Nanoparticles (NPs) are materials with a size range of 1-100 nm, and they are grouped into different categories depending on their properties, shapes, and/or sizes. Nanomaterials are broadly categorised into four families - fullerenes, metal

NPs, ceramic NPs, and polymeric NPs nanomaterials. The reduction of particle size dimension to the nanometre scale enhances the electrical, electronic, optical, magnetic, chemical, thermal, and structural properties of materials. These properties form parts of the vital parameters that define the performance of energy materials. Details of properties influenced by size are presented in table 4.

Table 4. Impact of reducing particle dimension to nanometre scale on material properties.

Property	Influence of size reduction on material properties	Property	Influence of size reduction on material properties
Structural	Reduction of lattice parameter structure transformations	Thermal	Melting point reduction Phase transition temperatures Melting entropy reduction Phonon spectra softening
Mechanical	Hardness, fracture ductility, and strength improvement Ascending of superplasticity Wear resistance increase	Electronic	Band gap improvement Phonon generation evolvement Improving the conductivity under low temperatures in a semi-metal
Thermo-dynamical	Heat capacity increase thermal expansion increase Debye temperature decrease high-temperature phases stabilisation	Optical	Diffraction and interference Improvement of absorption in the ultraviolet range (blue shift) Oscillation of optical absorption Enhancement of nonlinear optical properties
Electrical	Conductivity for nanometals enhancement Conductivity for nanodielectrics improvement Dielectric inductivity improvement	Chemical	Increase in catalytic activity Increase of velocity of physiochemical interactions Swap of solubility

The nanomaterials are either used individually or sometimes combined, depending on the desired functional properties. The production techniques of these nanomaterials have moved away from traditional methods. Optical, toughness, reactivity, and other properties of NPs are dependent on their unique size, shape, and structure. Nanomaterials possess certain unique characteristics that make them deployable in the RE sector. Nanomaterials are thriving in their applications in the energy sector because of certain attributes, and these unique properties include the following [70]:

i. Quantum size effects - This influences the electronic, photonic, mechanical, and magnetic properties of nanomaterials and NPs.
ii. Chemical reactivity – pit has been observed that NPs are substantially different from their macroscopic form.
iii. Surface area per unit mass –rod the NPs have a surface area per unit mass of over 1000 m^2 per gram.
iv. New chemical formation – At the nanoscale, materials were observed forming new chemical compounds such as fullerenes, carbon nanotubes, zinc oxide, titanium oxide, and other layered compounds

Because of these characteristics, NPs have both domestic and commercial applications such as in medical, catalysis, imaging, energy-based research, and environmental applications.

5.1. Nanomaterials in renewable sector

Theoretically, for a standard solar cell, the upper limit for a single junction solar cell conversion of sunlight to electricity is 33% but the Carnot limit is about 95%. This solar cell conversion efficiency limit was first calculated as 30% for a silicon solar cell by William Shockley and Hans Queisser (SQ) in 1961 [71]. Theoretically, only about 33% of the energy from the sun is converted to electricity, while the remaining 67% is wasted as follows - 47% goes as heat, 18% of the photons that pass through the PV cell, and 2% of the energy is lost from local recombination [72]. The identified technical-based setbacks in Table 1 must be given attention constantly to overcome these barriers to pave the way for HPCE PV cells' emergence. Subsequently, nanotechnology has taken centre stage, and nanomaterials engineers, scientists, and other university innovators are working on developing newer PV cells that have the following attributes – low-cost, flexible, HPCE, compact, and lightweight. They are exploiting alternative chemicals, materials, and methods of synthesis in fabricating PV cells to harness solar energy. These materials include quantum dots, organic materials (polymers and conjugated polymers), and plastics. Some of the fundamental attributes of organic materials that offer very high possibilities for this purpose are molecular mass, charge generation, separation, bandgap, molecular energy levels, molecule-to-molecule interactions, and rigidity. Some ongoing trends and areas of exploration are presented in table 5.

6. Organic photovoltaics (OPVs)

Indeed, the development of engineered organic materials has played a significant role in improving the performance of PV cells [76]. The technology is rapidly gaining prominence in the PV landscape, marked by its progressively advancing cell efficiency, currently certified at 18.2% [77]. Moreover, OPV exhibits a promising performance lifespan of over 10 years without encapsulation, and it has showcased potential for cost-effective roll-to-roll manufacturing through solution processing. In the context of building-integrated PV applications, OPVs have gained attention due to their potential for low-cost, flexible, and lightweight solar energy conversion due to their unique attributes including the capacity to produce absorbers in a wide range of colours and create efficient, transparent devices. Some of the ways, in which engineered organic materials have contributed to the performance improvement of PV cells are presented in table 6 [78-80].

Table 5. Emerging PV cell nanomaterials ongoing areas of research exploration [73-75].

Areas of exploration	Description of research target
Nanomaterials in PVs	
Perovskite solar cells	Perovskite-based PVs have garnered substantial attention due to their remarkable efficiency improvements. Researchers are working on stabilizing perovskite materials, improving their scalability, and understanding degradation mechanisms.
Quantum dot solar cells	Quantum dots (QDs) exhibit tunable bandgaps, and can be integrated into various PV architectures. Ongoing research aims to enhance the stability, quantum efficiency, and size control of QDs for efficient light absorption and charge separation.
Nanostructured electrodes	Nanostructured materials such as nanowires and nanotubes are investigated for use as electrodes to improve charge extraction and enhance light absorption by increasing the effective surface area.
Advanced thin-film PVs	
CIGS and CdTe solar cells	Research continues to enhance the efficiency and reliability of thin-film PV technologies like copper indium gallium selenide (CIGS) and cadmium telluride (CdTe), with a focus on cost reduction and improved scalability.
Flexible and lightweight designs	Efforts are directed towards developing flexible and lightweight PV modules using nanomaterials and thin-film technologies, enabling new applications like wearable solar devices and integration into building materials.
Organic photovoltaics (OPVs)	
Material design and stability	Researchers are developing novel organic materials with improved charge mobility and stability to achieve higher power conversion efficiencies and longer device lifetimes.
Non-fullerene acceptors	The exploration of non-fullerene acceptors has led to notable improvements in OPV performance. Ongoing research aims to optimize their molecular structures and blend compositions for better charge separation and transport.
Tandem and multi-junction OPVs	Tandem and multi-junction OPV architectures are being explored to extend the absorption range and enhance overall efficiency by stacking cells with complementary absorption spectra.
Interface engineering and device architecture	
Interface optimization	Efforts are directed towards understanding and engineering interfaces within PV devices to minimize charge recombination, enhance charge extraction, and improve overall device performance.
Device architecture innovations	Novel device architectures such as inverted and semi-transparent designs are being investigated to improve light harvesting, charge collection, and stability.
Manufacturing and scalability	
Solution processing techniques	Researchers are developing scalable and cost-effective solution-based deposition techniques such as roll-to-roll printing to enable large-scale manufacturing of advanced PV technologies.
Encapsulation and environmental stability	Ensuring the long-term stability of PV devices under real-world conditions is a critical focus, involving the development of effective encapsulation methods and materials.
Sustainability and Circular Economy	
Recyclability	PV technology sustainability is being addressed by exploring materials and design strategies that facilitate easy disassembly and recycling of components, contributing to a circular economy approach.

Table 6. Some engineered organic materials contributions to PV cells performance improvement.

Attribute	Description
Light absorption	Organic materials can be tailored at the molecular level to absorb specific wavelengths of light. This allows researchers to design materials that can capture a broader range of the solar spectrum, enhancing the efficiency of energy conversion.
Tunable bandgap	The bandgap of a material determines the range of light it can absorb. Engineered organic materials can have their bandgaps tuned by adjusting their molecular structure. This flexibility enables the design of materials optimized for solar energy absorption.
Charge separation and transport	Efficient charge separation is crucial for generating electricity in photovoltaic cells. Engineered organic materials can facilitate the separation of electron-hole pairs created by absorbed photons and ensure their efficient transport to the respective electrodes.
Flexibility	Unlike traditional silicon-based solar cells, organic materials can be processed into flexible, lightweight, and even transparent substrates. This versatility allows for the integration of solar cells into a wide range of applications including wearable devices, building-integrated photovoltaics, and more.
Solution processing	Organic materials can be processed from solution, enabling cost-effective and scalable manufacturing methods such as printing and coating. This reduces production costs and opens up possibilities for large-scale deployment of solar technology.
Multi-junction cells	Engineered organic materials can be combined to create multi-junction solar cells. These cells consist of layers of different organic materials with varying bandgaps, allowing for efficient absorption of different wavelengths of light and higher overall efficiency.
Reduced energy payback time	The energy payback time refers to the time a solar cell needs to produce the same amount of energy it took to manufacture it. Organic materials often have a shorter energy payback time compared to traditional materials, making them more environmentally friendly.
Emerging materials	Ongoing research is focused on discovering new organic materials with improved properties such as higher charge carrier mobility and longer exciton diffusion lengths. These properties contribute to more efficient charge collection and reduced energy losses.

Current R&D efforts in PV cells are focused on harnessing the unique properties of nanomaterials and advancing organic photovoltaics (OPVs) to enhance the efficiency, cost-effectiveness, and environmental sustainability of solar energy conversion. The production of first-generation PV modules generates hazardous chemicals that influence the environment negatively. One of the merits of third-generation PV modules and their fabrication methods is that they deploy new green renewable composite materials to produce eco-friendly PV devices. The PV cells that are products of these natural or synthetic processes are sustainable materials, often called organic photovoltaics (OPVs). Many natural dyes such as chlorophyll and carotenoids are arranged in a special pattern to produce efficient photo-prompted charge separation and electron transfer. These dyes are components of natural photosynthetic systems, and the researchers are integrating them into functional OPVs producing PCEs up to 0.99% [81]. Studies have shown that chlorophyll derivatives can produce PCEs of about 2.1% while the combination of copolymers generated from isoindigo with fullerene C70 generates high PCEs of up to 8%. The copolymers generated from isoindigo and fullerene C70 serve as the electron-deficient and electron acceptor units in the OPVs active layers, respectively [81-83]. Organic photovoltaics are an attractive class of PV materials that are seen to be better than traditional silicon-based and inorganic thin-film PV cells. The OPVs are lightweight, eco-friendly, mechanically flexible, and exhibit free-shape properties, hence, they can be deployed as building-applied photovoltaics (BAPV) and building-integrated photovoltaics (BIPV) [84]. The conversion performance of OPVs has gradually improved from about 10% PCE in the 2000s to 10.8% [85], 20.1% [86], and 25% [30] in 2013, 2014, and 2021, respectively.

This PCE progression was a result of material and synthesis evolutions. The PCE of conventional fullerene-based OPVs (F-OPVs) between the 2000s and 2014 is less than that of organic-inorganic hybrid perovskite PVs (PePVs) between 2013 and 2021 [87]. Several OPV production methods developed to tailor NPs to meet the desired functional properties are still evolving. Options are being proposed for OPVs' mass production processes such as simple printing or roll-to-roll (R2R), spin coating, spraying, and vaporization [88, 89]. The roll-to-roll is a low-temperature process that is energy-saving and cost-effective used in fabricating OPVs. Nanostructured thin films consist of layers of semi-conducting organic materials such as oligomers or polymers used in PV devices that receive photons from the solar spectrum [90]. Solution-based methods such as inkjet and screenprinting, which enable rapid mass production and drive down production costs are used to manufacture these devices. Nanomaterials made from the combination of III-V materials [91, 92] such as InP, InAs, GaAs, GaN, and InSb are being used as solar cells, and they have shown high efficiency, surpassing the conventional technology by about 40%. This is because of their superior electronic attribute, which includes direct band gap, high electron mobility, and low exciton binding energy. Many polymeric materials have been developed for photovoltaics (PPVs) applications, and this includes MDMO-PPV: poly(2-methoxy-5-(3, 7,-dimethyloctyloxy)-1,4-phenylene-vinylene); PCBM(6,6)-phenyl-C61-butyric acid methyl ester; RR-P3HT: regioregular poly(3-hexylthiophene); PCPDTBT: poly[2,6-(4,4-bis-(2-ethylhexyl)-4H-nta[2,1-b;3,4-b]-thiophene)-alt-4,7-(2,1,3-benzothiadiazole)) [93]. In a study [94], the structures of three types of anthracene-based organic dyes for DSSCs were studied based on a push-pull framework. The donor and acceptor were considered as anthracenyl diphenylamine and carboxyphenyl or carboxyphenyl-bromothiazole (BTZ), respectively, linked together by acetylene bridge. The study observed from the simulation report that the energy gap was reduced by the anthracene-based dyes and produced a red shift; the light capturing and the electron injection capability, which aids PCE improvement.

Despite the striking merits of OPVs, they are yet to have a significant share of the market because of some limitations such as OPVs' lifespan, high cost, and mass production possibility. One of the biggest hurdles associated with OPVs is their practical application reliability, as most of the stable ones do not last longer than seven years; some last for a few weeks to nine months compared to the current c-Si PV cells that work for 20 - 25 years. The degradation of OPVs is attributed to light and heat effects [95-97]. The acclaimed low-cost fabrication method, R2R, is still on the laboratory scale, and there are challenges in translating the R2R production technique, "from lab to fab." Subsequently, the difference between the maximum PCE achieved from the laboratory and scaled-up demonstrations from the current state-of-the-art is not commercially competitive at present.

6.1. Organic PV cell stressors and the significance of encapsulation process

Generally, PV modules placed outdoors are subjected to several conditions that cause them strain or tension. These conditions, which include temperature, radiation, moisture (mainly oxygen), and ultraviolet (UV), are called stressors [44]. These stressors degrade and compromise the lifetime of the OPVs, and the degree of impact of these external elements depends on the effectiveness of the collective working conditions of the active components of the OPVs. The third-generation PV cells are influenced negatively by elevated temperatures. Perovskite solar cell is one of the emerging promising third-generation PV cells and an increase above room temperature decreases its PCE. The PCE of PSC declines from 16% to 9% at a temperature higher than 25 ^{0}C [98]. A temperature increase from 25 $^\circ$C to 125 $^\circ$C resulted in alterations, which led to a significant loss of GaInP/GaInAs/Ge cell PCE reduction of about −17%, V_{oc} by −15% and fill factor (*FF*) by −4.5% [99]. The reduction of temperature of a planner heterojunction QDSCs of FTO/TiO2/PbS-EMII/PbS-EDT/Au structure from 80 $^\circ$C to -20 $^\circ$C increases the short-circuit photocurrent density (JSC), VOC, and FF. At -20 $^\circ$C (253 K), the QDSCs PCE (9.78%) is 33% above the PCE at 25 (7.34%), the VOC, JSC, and FF are 0.63 V, 33.1 mA/cm^2, and 0.47, respectively [100].

Optimisation of protection solutions for OPVs from stressors led to a series of studies of encapsulation processes using ultra-high barrier materials. To increase the performance of OPVs, inorganic flexible thin-film barrier materials have been deployed for the encapsulation of OPVs against moisture permeation [101, 102]. Several studies are ongoing on the development of low-cost and HPCE PV cells. Massive R&D activities are ongoing to tackle the identified stressors and develop HPCE and low-cost materials for PV cells. Recently published articles on OPVs are presented in table 7.

7. PV Cells' Energy Materials Outlook

In an era of a global call for the abolition of fossil fuels coupled with the increasing energy demand, the development of HPCE and sustainable technologies for energy generation and storage is a necessity. According to Wade Adams of Rice University, humanity will be most challenged by energy needs in the next fifty years [113]. Success in the development of low-cost HPCE solar PV cells and energy-dense materials will change the energy space tremendously. This has provoked a series of material-based research in terms of functionality and production processes in the energy sector. To this end, nanotechnology (nanofibers and NPs) has been portrayed as a promising technology, and this has attracted research interests. Recently, the focus has centred on combining natural photosynthetic biomaterials extracted from various plants and inorganic nanomaterials to improve the PCE of hybrid solar cells. Fabrication of hybrid and multifunctional materials, combining more than two nanomaterials, has been demonstrated to enhance the performance of the individual components. Nanomaterials are already playing essential roles in developing more effective devices applied in PV systems, wind turbines, fuel cells, and storage of energy.

Table 7. Some recently (2018-2022) published articles on the R&D of OPVs.

Target	Result	Reference
This article discusses the different pathways for lead sulfide colloidal non-radiative recombination losses in quantum dot photovoltaics (PbS QD PVs). Strategies to reduce these losses by the passivation of the surface and interface defects.		[103]
The analysis of the cost of solution-phase ligand exchange for producing deposition-ready PbS QD inks, and the manufacturing cost of R2R solution-processed PV cells using these materials were studied in this work.	The study reported that: i. The present costs of QD synthesis are excessively high for PV uses with median costs between 11 and 59 $ per g for PbS QDs. ii. The preparation of QD ink adds 6.3 $ per g (0.09 $ per W) and QD materials add up to 55% of the total module cost. The R2R-processed QDPV modules substantially cost more than silicon PV modules.	[104]
The study demonstrates the appropriateness of combining a digital production tool such as inkjet technology to enhance the electrical functionality of thin-film-based CIGS PV cells.	The study reported the development of an industry-relevant micro-filling process and PV cells with improved PCE.	[105]
This work investigates the effect of titanium dioxide (TiO2) nanostructures on the overall optical performance of gallium arsenide (GaAs) solar cells. The optical properties of three different TiO2 nanostructure shapes namely, cubic, spherical, and pyramidal are studied to minimize the reflectivity of GaAs substrates.	The results indicate that the spherical nanoparticle with a radius of 25 nm gives a reduction of the reflectance down to 9.2 % (compared to the 37.2 % of uncoated GaAs). Furthermore, the pyramidal nanoparticle with both width and length of 50 nm has a nearly similar performance, achieving a 9.8% reflectance. However, the cubic nanoparticles with a width of 100 nm achieved the worst optical performance with a reflectance of 28 %.	[106]
This paper carried out the analysis of a cut cone nanowires (NWs) PV cell with an air gap, Lumerical finite difference time domain (FDTD), and Lumerical device software applications deployed for optical and electrical characterisations.	The study reports that the examined NWs possess: Optical ultimate efficiency of 42.74% and short circuit current density of 34.98 mA/cm2 with about 18.15% improvement over conventional conical NWs. 32.16 mA/cm2 short circuit current density, 0.66 V open circuit voltage, and 15.36 % PCE by the radially doped design.	[107]
A colloidal mercury telluride quantum dots (HgTe QDs) was synthesised, and their low-order non-linear optical properties were analysed using 1064 nm, 532 nm, and 10 ns pulses.	The study reported that HgTe QDs colloidal suspension has negative non-linear refraction and strong saturable absorption. Kerr and thermal influence in 1064 nm and 532 nm probe pulses, respectively, were said to be responsible for the negative nonlinear refraction.	[108]
A study demonstrated the effect of post-treatment on the relaxation of residual lattice strain in the imprint-assisted organic ammonium halide, along with perovskite grain growth/coalescence, defect repair, and crystallinity enhancement.	The following results were reported that the residual lattice strain was well released, leading to: The obtaining of 21.30% PCEs of nickel oxide-based FACs inverted with strain-free perovskite solar cells The encapsulation of devices, which retails 98% of their initial efficiencies at 45 °C, under 1-sun with maximum power point tracking in the surrounding environment for 1000 h.	[109]
The organic halide salt hexaneammonium iodide (HAI) aims growth at grain boundaries was demonstrated.	The study reported that: The PCE of the PSCs improved from 22.38% to 24.07% (23.59% certified PCE) with a voltage loss of 0.35 V. The PSCs' operational stability was improved by the surface treatment improved and 81.4% of the initial PCE was sustained for 200 h under continuous light radiation in the atmospheric nitrogen.	[110]
Dripping of 2-bromoethyltrimethylammonium bromide (BETAB) colloidal solution onto perovskite films was used to demonstrate a novel nanocrystal-pinning passivation.	The results showed that: The resulting product, FA1-xMAxPbI3 based planar devices impressively displayed a PCE of 23.04% (certified: 22.10%) with a voltage loss of about 390 mV. The BETAB nanocrystals increased perovskite films' hydrophobic	[111]

	properties and prevent the formation of 2D and reaction perovskites during device operation. The devices showed excellent stability under heating, moisture, and operational tracking conditions.	
Luminescent CdZnS/ZnS and CdZnSe/ZnS QDs were deployed for downshifting materials for nanostructured silicon in this study.	This approach was described as a reliable method of enhancing solar cell properties. The study shows that: QDs exhibit significant change capacity for the high energy in the ultraviolet zone to low energy. The cell efficiency improved from 10.4% to 13.5% by the energy transfer.	[112]

There are ongoing research investigations on nanostructures and natural dyes such as nanotubes, thin films, quantum dots, and NPs for PV cell applications [114]. This trend of PV cell research including exploiting nanomaterials in developing devices for collecting and converting solar and wind energies, harvesting fuel cells, and storage of energy will continue. As climate change effects get worse by the day, the search for alternatives to fossil fuels and the development of mitigation and decarbonisation processes will sustain the evolution and application of nanotechnology in the energy sector. Over the next decade, R&D of HPCE, low-cost, and environment-friendly PV cells will be cut across the three generations of PV cells, as presented in table 8. The ongoing research should identify effective restorative measures, mitigate climate change, and empower the community.

Table 8. Solar PV cells research priorities [115].

Generation	Research areas	Reference s
First-generation	Feedstock, crystallization and wafering; epitaxy, si-foils and sic deposition; characterization of process materials and silicon materials; doping and diffusion; surfaces - conditioning, passivation and light-trapping; metallization and structuring; high-efficiency silicon cell fabrication and analysis; pilot processing of industrial silicon solar cells; metrology and production control; technology assessment; silicon bottom cells for tandem photovoltaics; module technology.	
Second	These are thin-film technologies that are often commercially available as thin-film solar cells - amorphous silicon (a- Si: H), cadmium telluride (CdTe), gallium arsenide (GaAs), and copper indium gallium selenide (CIGS)).	[25]
Third	Perovskite solar cells and modules; organic PV cells and modules; perovskite silicon tandem PV.	

8. Conclusions

Power is the soul of socioeconomic development; as a result, it is a herculean task to provide an adequate alternative to fossil fuel without compromising the environment and human health. To respond appropriately to the global GHG emissions, energy need, and climate change, some of the following measures and practices should be integrated into the national orientation and infrastructure planning and development - deliberate increase in RE share through the deployment of RE technologies such as wind, hydro, solar PV, geothermal, and storage. Solar PV stands out among RE technologies because of its potential and spread. However, the development and deployment have been limited by certain factors, which this study has categorised into four - technical factors, leadership influence, political instability and crisis, and finance. The role of material engineering in tackling technical issues hindering the development and greater deployment of PV systems is the focus of this paper.

This study portrayed nanomaterials, especially OPVs, R&D as pivotal for advancing HPCE PV cells, and their low-cost production systems. Already, there are a series of ongoing R&D activities that are pushing the limits of PCE, fielded energy output, lifespan, and manufacturability of low-cost PV components. Nanotechnology has been identified as the present and future processing technology for the desired PV cells, especially OPVs. The following nanomaterials are expected to play an active role in the OPVs outlook - quantum dots, nanotubes, thin films, nanostructures and natural dyes, and NPs as they are currently being investigated. The ongoing OPVs R&D is geared towards pushing the boundaries of PV module's PCE, improving device stability, reducing manufacturing costs, and ensuring sustainable integration of PV technology development into our energy landscape. The study noted that although the engineered organic materials have shown significant progress, there are still challenges to address such as stability over time, efficiency under varying lighting conditions, and long-term durability. The researchers continue to work on overcoming these challenges to make organic PV technology even more viable for widespread solar energy adoption.

9. Research Gaps in OPV Cells for Future Study

Despite acknowledging that OPV's strength depends on the design and synthesis of organic materials for the acceptor, absorber, and interfaces, the need to scale up their PCEs and lifetime to large area modules is paramount. Although significant advancements have been achieved in the field of OPV, several research gaps presented in table 9 persist. Addressing these research gaps is crucial for furthering the development and widespread adoption of organic photovoltaics. Continued innovation, interdisciplinary collaboration, and investment in these areas are essential to overcome these challenges and unlock the full potential of organic solar cell technology.

Table 9. Some of the notable research gaps in OPV cells.

Research gaps	Description of research gaps
Stability and durability	Engineered organic materials often face challenges in terms of stability and durability over time, especially when exposed to environmental factors such as moisture, heat, and UV radiation. Research is needed to develop materials and encapsulation techniques that enhance the long-term stability of organic photovoltaic cells.
Efficiency under low-light conditions	Organic PV cells typically exhibit lower efficiency under low-light conditions compared to traditional silicon-based solar cells. Finding ways to improve their performance and maintain efficiency in varying lighting environments remains a research challenge.
Device scale-up and manufacturing	While solution processing and printing techniques offer scalability, there is a need to optimize these manufacturing methods further to ensure consistent and reliable production of high-performance organic photovoltaic cells at larger scales.
Material diversity and optimisation	The variety of organic materials available for PV applications is vast, and optimising material properties to achieve higher efficiency and stability is a complex task. Researchers need to identify and tailor materials with the most suitable properties for specific applications.
Charge transport and recombination	Efficient charge transport and minimal charge recombination are essential for high-performance PV cells. Investigating ways to improve charge carrier mobility and minimise loss due to recombination is an ongoing challenge.
Multi-junction device integration	While multi-junction organic PV cells hold promise for improved efficiency, integrating and optimising multiple layers of different organic materials is a complex task that requires further research.
Understanding interface effects	Interfaces between different organic layers and between organic and inorganic layers in hybrid solar cells can significantly influence device performance. Research is needed to better understand and control these interface effects.
Standardisation and characterisation techniques	Developing standardised methods for characterising and evaluating the performance of organic photovoltaic materials and devices is important for enabling accurate comparisons and accelerating advancements.
Environmental impact	As the field progresses, it's essential to assess the environmental impact of engineered organic materials, both in terms of their production and end-of-life disposal, to ensure their sustainability.
Integration with existing infrastructure	Integrating new PV technologies including those based on engineered organic materials, into existing energy infrastructure and grid systems presents technical and regulatory challenges that require further investigation.
Economics and commercial viability	While organic materials offer potential cost advantages, further research is needed to optimize production processes, reduce material costs, and assess the economic viability of large-scale manufacturing and deployment.

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Authors' Contributions

WSE conceptualised the study and drafted the manuscript, and PYT supervised and proofread the manuscript. All authors have read and approved the manuscript.

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Declarations

Conflict of Interests

The authors declare that they have no conflict of interest.

10. References

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