

## Photovoltaics for indoor applications: Progress, challenges and perspectives

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### ABSTRACT

Indoor photovoltaics has received much interest lately due to its applications in the daily human life in the small scale device applications like Internet of things, human-interactive machines based actuators, wireless sensors to name a few. Nevertheless, these devices possess light weight, low cost, less power for charging and environmental friendliness leads appropriate devices for indoor light applications. Thus, recent enormous progress in indoor photovoltaics prompts us to highlight the applicability of all three generations of solar cells i.e., crystalline silicon, amorphous silicon and thin films, and organic/dye-sensitized/perovskites working under indoor conditions, challenges and market perspectives in this review.

### 1. Introduction

The floodgate has opened on the research centering on clean renewable energy by the researchers to overcome the extreme dependence on non-renewable energy resources for the past couple of decades particularly [178,135]. With increase the standards of living of a human being along with rapid industrial transformations, modernization and population growth globally, required energy consumption also increases tremendously Santamouris and Vasilakopoulou [166]. Hence it is of paramount importance that necessary energy is produced, in this regard the existing fossil fuels like oil, coal and natural gas are prime source for energy harvesting [2,56]. Fossil fuels already at the stage of extinction; it can be used for mere couple of more decades Niall and Mark [139]. In spite of that, usage of fossil fuels has created havoc in environmental apprehension, particularly, global warming, climate change and acid rains etc. [15], Kibert [92], Donald and Atul [42]. Consequently, it is high time for everyone to focus on alternate sources for energy production which can produce sufficient energy for current and future generation. To put a break on consumption of fossil fuels and to move towards green energy, majority of the nations agreed to formulate a significant contribution to reduce the global environmental challenges for the betterment of the future generation when they participated in the United Nations Climate change conference (COP21) in the year of 2015 Le Quéré [102]. Policy makings concerning renewable energy and energy efficiencies were the key highlights of the summit. European Union has set a target of reducing global house gas emissions by at least 40 % by 2030 and 80 % by the end of 2050. As expected, Out of total energy,

30 % perhaps produce from renewable energy resources by 2030 and estimates further 100 % by 2050. Hence, renewable energy gained attention from energy policy makers, power producing companies and governments [140].

In this view, researcher's main focus is on solar energy which is the most plentiful energy source which can fulfill energy demands. In this context, Sun is the major source to produce solar energy [159,84,164]. Literature states that, at an instant  $1.8 \times 10^{11}$  MW power solar radiation is received onto the earth, nevertheless the total global energy consumption necessity is far too less than the energy we receive from the Sun Anju and Rahul [6]. Hence solar energy is been highly valued as an alternate source of energy by the government organizations and investors due to both environmental and economic benefits. Solar energy is used in our daily life in various circumstances right from heating water to producing electricity [161]. Conversion of solar energy into useful electrical light by semiconducting materials is termed as photovoltaics (PV) and the device involved in conversion is called as photovoltaic cell. Main component and building block of a PV is a solar cell. A cell which converts energy of photons into electricity i.e., direct current (DC) is coined as solar cell. Solar cell technology is broadly classified into three generations. First generation (1G) comprises of crystalline silicon wafer based solar cells that includes mono-crystalline silicon (c-Si), poly crystalline silicon (poly-Si), micro-crystalline silicon (mc-Si) and hetero-junction with Intrinsic thin layer (HIT) with efficiency in the range of ~25 % [130]. Whereas second generation (2G) solar cells which contain thin film technology. For example, cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), single junction

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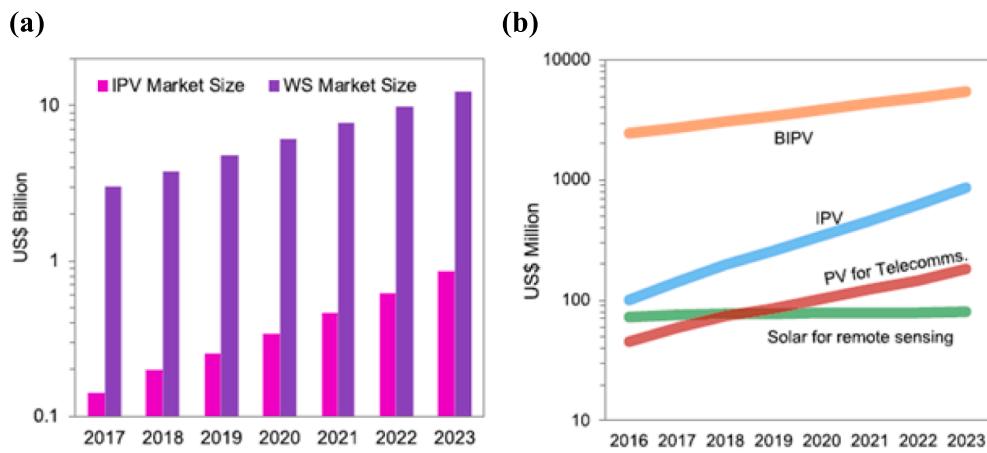


Fig. 1. a) Estimated market growth of ipvs and wireless sensors. b) predicted size of the market for pv technologies. (mathews et al., Copyright 2019 Elsevier).

gallium arsenide (GaAs) and amorphous silicon (a-Si) are major materials for solar cells fabrication (Mathews et al., 2014) [182]. Subsequently, third generation solar cells (3G) are emerging cell technologies that made out mainly organic materials and tandem or multi junction devices fabrication. [96,49,39].

Electricity which is generated by the solar photovoltaic system in turn connected to utility grid is called as grid connected PV system. It contains several items like panels, inverters, power unit and grid connector. These grids based PVs can be used in small residential purpose to large commercial rooftop systems. For house hold purpose, rooftops which are grid connected can generate up to 10 kW which can meet the load of many consumers. Installed capacity of the global solar energy by the end of 2020 was off 728 GW and it is expected to reach 1645 GW by 2027. In addition to grid connectivity, there are many small applications particularly under low-light/artificial light conditions. The present review highlights the applications of all three generation solar cells towards indoor photovoltaics [129].

### 1.1. Indoor photovoltaics

Indoor photovoltaics (IPV) emerged in PV technology in present scenario due to the ease of power generation under simple indoor light conditions and also serve the fastest energy supplements for growing

technologies like Internet of Things (IoT). Moreover, an IPV system allows the realization of self-power-driven electronic devices in Internet of Things because it compensates the fluctuation in voltage drop. Hence, IPVs have shown remarkable applications in the area of wireless sensors, actuators and communication devices. Indeed, there is an evolution in PV technology from outdoor applications to indoor with long term stability and improved photo conversion efficiency leads high demand in this area. Therefore, advantages in IPVs and their remarkable PCEs and durability generate huge market in PV technologies in future. Formula used to calculate PCE remains same for both indoor and outdoor conditions and it is presented in the equations. [128] (Li, M et al., 2020).

$$\eta = J_{sc} \cdot V_{oc} \cdot FF \cdot P_{in} \quad (1)$$

where  $\eta$  is conversion efficiency,  $V_{oc}$  = open circuit voltage,  $J_{sc}$  = short circuit current density, FF = fill factor,  $P_{in}$  = Intensity of the incident light.

$$ff = \frac{J_{max} \times V_{max}}{J_{sc} \times V_{oc}} \quad (2)$$

where,  $J_{max}$  and  $V_{max}$  are the photocurrent and photo-voltage for maximum power output and  $J_{sc}$  and  $V_{oc}$  are the short-circuit photocurrent density and open-circuit photo-voltage [112].

**Market cap of IPV:** Over the years, IPVs have shown incredible

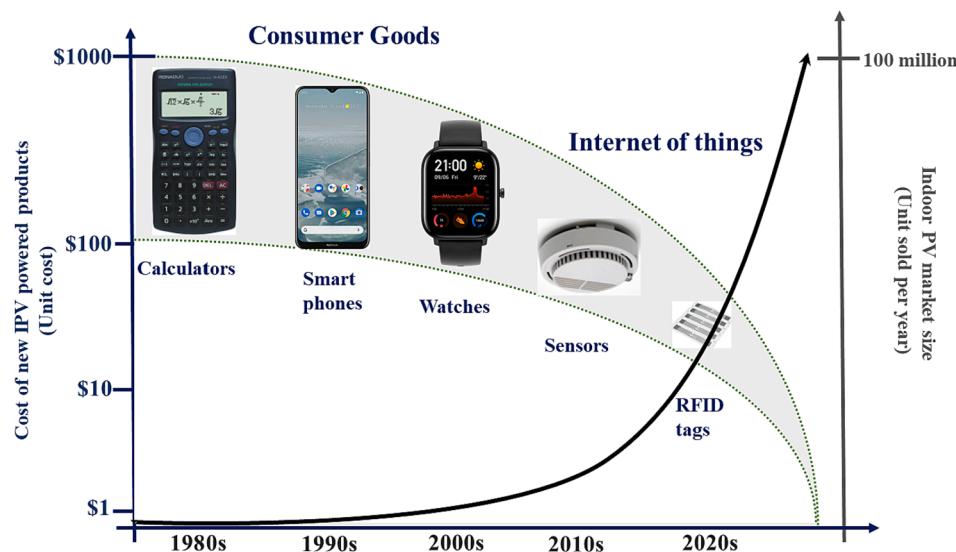
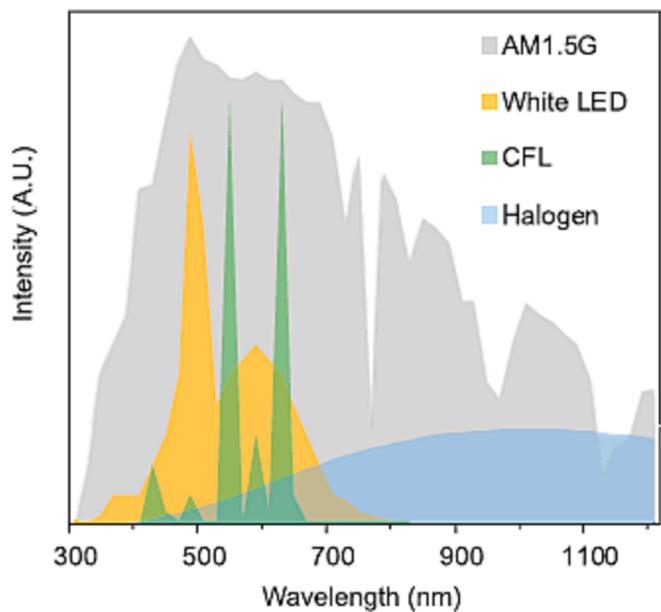


Fig. 2. Summarizing the cost of new IPV powered products for the past few decades and anticipated IPV market size (Unit sold per year). (Li et al., Copyright 2021 Wiley-VCH).



**Fig. 3.** An overview of the light spectra from different sources: standard solar spectrum (AM 1.5G), white LED, CFL and Halogen. (Matthews et al., Copyright 2019 Elsevier).

growth in market size. i.e., solar modules and panels (Fig. 1a). Currently, the global market worth is \$140 million, which is significantly less because solar modules (\$100 billion) are more expensive. Thus, the projections promotes the building integrated PVs (BIPV) and IPVs exhibit higher market worth and will continue to do so compared to standard PVs, already using in wireless sensing and telecommunications etc. It is projected IPVs will reach \$850 million by the end of 2023 and in subsequent years it will hit billion dollar mark (Fig. 1) [189,75,111].

**Commercial applications:** As known, PVs have been used to mini portable devices such as sensors, calculators, wrist watches and so on. This is achievable because the cost of such PVs is continuing to fall, and their performance in low-light circumstances is improving. Although mini devices attract consumer attention, however, our lives are dependent on significant sectors like agriculture, healthcare, industrial, security, infrastructure, energy, education, and so on, all of which require sensitive and highly complicated indoor operations. So, IPVs play major role in the development of these fields. PV technologies based on silicon and dyes have experienced actual commercialization but large scale industrial production for indoor applications hitherto unknown. In this field, Solems, WSL Solar, Gcell, Ricoh, and 3G Solar are well-known companies in solar modules market. They specialized in generating the amorphous silicon and organic dye based solar cells and modules for the application mini devices like calculators, sensors and watches under <20 lx LED illumination. However, these technologies is not reached expected outcome, thus, improvement of performance and reduce the production cost of PVs by development of various organic/inorganic materials to reach the global demand are necessary (Fig. 2) [75,111].

## 1.2. Indoor photovoltaic perspectives

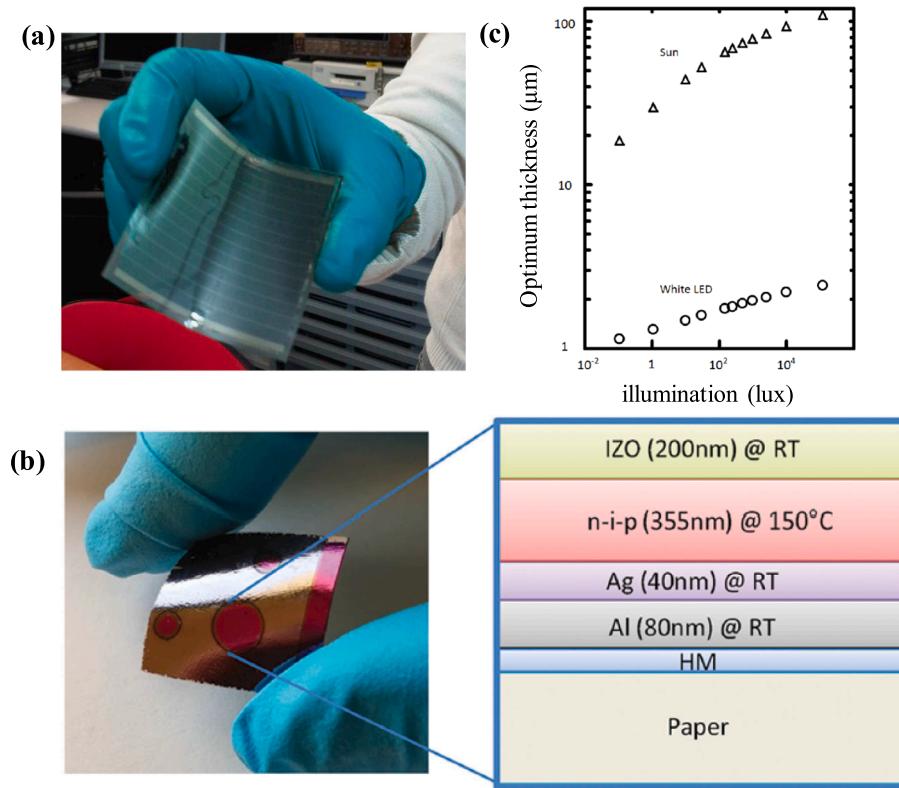
In today's fast moving generation indoor photovoltaics have emerged as the front runner in powering small devices with IoT. Connected with internet, a system which communicates among various devices wirelessly and automatically is termed as Internet of Things (IoT). IoT collects the real time data and exchanges digital information data with electronic devices which is further applied to various applications like aerospace, smart-home, indoor wearable technology and alarm systems. IPVs act as power source required in IoTs which can be used in wearable electronic devices, wireless antennas, and biomedical

applications and so on. In IPVs the factor of indoor light used and its characteristics plays a huge role, in case of 1 Sun simulation AM1.5 source is used commonly to evaluate the PVs performance in the laboratory. But it's not necessary with various reason desired sunlight is met factors varying from weather, environment and time. Hence, artificial lighting sources such as halogen lamp, CFL, incandescent bulbs and LED with regulating temperatures and intensity of light are needed to improve the performance of a PVs. (Fig. 3). When a device based IPV can generate output power of  $15 \mu\text{W}$  with the input power of  $0.521 \text{ mW cm}^{-2}$  with a PCE of 30 %, which can power small devices like wrist watches, calculator, RFID tags and standby devices, what is the need for electricity generated by non-renewable routes of energy or by any other means [150]? For the years, key energy resource for mini modules like sensors, calculators, and watches from IPVs because its stable power output and high performance at dim light. Apart from that to create a huge market IPVs shows great potential for indoor renewable energy. With light intensity of 20 lx, amorphous silicon and organic dyes based DSSCs can provide power mini portable devices. As seen, abundant advantages from IPVs for indoor applications, there is prediction that billions of IoT devices will be installed in coming ten years. [220].

Although IPVs have some difficulties but it has an excellent development prospect. Alongside, the major concern is the stability of devices to sustain long run and utilizing toxic materials like cadmium, lead and arsenide in devices leads environmental damages, thus, manufacturing of PVs is banned in few areas. Interestingly, progress of manufacturing IPVs has made significant contribution in recent years due to the vast applications in indoor devices. Moreover, IPVs can be fabricated on a large scale and flexible substrate it plays a crucial role to meet the market demands. Although IPVs have been rapidly developing in research scale, commercialization of IPVs lags behind compared to development of solar modules. To replace something which already exists by a new thing it should have advantages both in terms of cost and performance in that way IPV can be lot improved. Based on recent development on indoor light photovoltaics, IPVs can be broadly classified into four categories with the materials used in it, namely inorganic, organic, DSSCs and PSCs.

## 1.3. Inorganic materials based solar cells for indoor applications

First generation of solar cells contained inorganic semiconducting materials, where silicon (Si) assisted solar cells was reported in 1941 Ohl [144]. Later to enhance durability, applicability, lifetime and PCE of silicon based solar cells, various research groups have come forward with different techniques Green [64]. With great efforts, on date 26 % highest PCE has been achieved under 1 Sun condition Green [65], Green [66]. In 1970's, where the indoor photovoltaics were in budding stage, amorphous silicon was used in solar cell to harvest indoor light energy to power devices like calculators and watches Hamrick [70]. But the PCE was poor and the production cost was high. Keeping this in mind, researchers were forced to deviate their attention in developing low cost, efficient and environmentally stable photovoltaic material for fabricating the efficient solar cells for indoor applications. With some special techniques, researchers have focused to enhance the efficiency and durability of Si-solar cells along with search of new inorganic materials. Foti et al. in 2014 have fabricated hydrogenated Si inorganic PV material for indoor applications on a polymer substrate [48]. Under fluorescent lamp with 100 lx condition they obtained PCE of 9 % which showed high flexibility and stability. Later, Águas et al., have reported a thin film Si on a paper substrate for indoor applications [3]. Further, Kao et al., enhanced the PCE to 9.6 % at 500 lx LED illumination by introducing amorphous silicon carbide in silicon based thin film devices [88]. Although Si based solar cells have achieved maximum PCE of about 26 % under 1 Sun condition due to its broad absorption spectra, under indoor light conditions, it cannot efficiently work owing to its low band gap of  $\sim 1.1$  eV. The PCE of c-Si solar cells is reduced is due to indoor capacitive effect results reduction in fill factor. Subsequently, real time



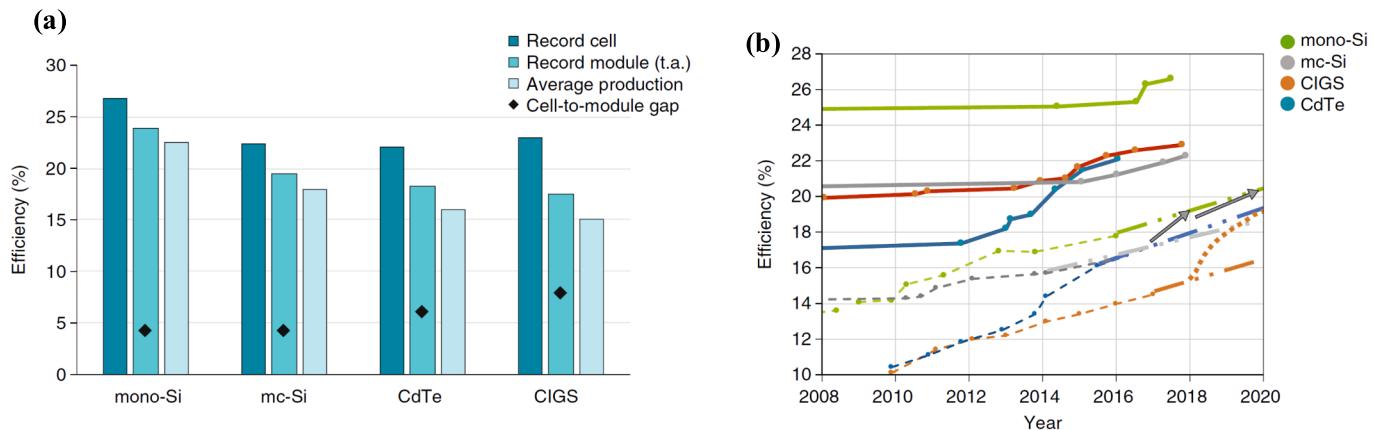
**Fig. 4.** (a) Image of elastic silicon module on polyimide. (Foti et al., Copyright 2014 Elsevier) (b) Pictorial representation of a-Si based PV device on the FS-2 paper and also shown the schematic view of various layers constituting in device. (Aguas et al., Copyright 2015 Wiley-VCH). (c) Graphical illustration of optimum thickness against the illumination using white LED (2700 K) and standard AM1.5G (Bahrami-Yekta et al., Copyright 2018 Optica).

one sweep method was utilized to eliminate the capacitive effect. Later, Yu group was demonstrated 76.6 % PCE with a-Si and they generated hybrid source from the co-operation of incident indoor lighting with vibrational energy [207]. It also has its own advantages like low temperature processing and light weight in nature. However, spectral mismatch and difference in performances with the device structure are the challenges faced, even with the advancement in research in this area. In Si solar cells efficiency is a function of device thickness whereas in other cases band gap and absorption coefficients play a role, Bahrami-Yekta and group calculated the optimum thickness for devices to get 29 % PCE under 250 lx LED is 1.8  $\mu\text{m}$  (Fig. 4) Bahrami-Yekta and Tiedje [10].

Apart from classical Si devices, researchers have also focussed on another set of inorganic materials for PVs such as CdS/CdTe, III-IV semiconductors, and CIGS in developing indoor cells. Having high and tunable band gap energy, III-V semiconducting materials are of special interest which makes them promising candidates for indoor solar cells. Also, these devices exhibit high efficiency in single junction PVs under 1 Sun illumination. By creating multiple junction structure which enhances the broadness of absorption wavelength of incident light, efficiency can be further improved. In powering indoor wireless sensors, III-V can act as strong competitor light harvesters as it has wide active band gap component [67]. Wide band gap generally yields higher voltage which matches with indoor light spectrum that decreases thermal losses and hence improving the efficiency which is evident in GaAs devices [1]. A low illumination intensities using LED and CFL under constant illumination, GaAs and GaInP based single junction solar cells shows significant better performances compared to a-Si and dye sensitized solar cells. Matthews and group have shown that the power density of GaAs solar cell is three times more than that of dye sensitized solar cells at indoor light levels [130,40] A GaAs solar cell of credit card sized can supply 4 mW power to a wireless sensor in a well lit office space ( $\sim 1000$

lx) (Mathews et al., 2014). Thionyl lithium chloride batter is used in detection system in international space station, which is an expensive, explosive, toxic and difficult to maintain is also proposed to replace by GaAs to overcome the challenges of the battery [31]. Teran and group have reported PCE of 21 % with  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$  solar cell under LED with 580 lx conditions, upon comparison of commercial c-Si, fabricated GaAs and  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$  in terms of theoretical and experimental efficiencies. The electrical performance under artificial light condition,  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$  demonstrated highest performance remarkably even GaAs also exhibited better performance compared to Si PV [181]. Prominent disadvantage of III-V solar cells lies with high fabrication cost which limits them to space exploration and production for wide area devices is not feasible with such cost [1,31]. In a cost effective manner, under 300 lx conditions a small sized GaAs PV system can generate  $>600 \text{ nW mm}^{-2}$ , it is with equal importance to scale up to large surface device in a cost effective manner as this will improve power conversion efficiency as PCE also depends on active cell area [1]. Small sized GaAs devices are also influenced by dark current, recombination and shunt leakage mechanism which effects to PCE [38]. Recently, Alta Devices Company which put efforts to produce these PVs industrially had to shut down due to bankruptcy and unavailability of suitable investors [170].

To bring down the production cost of III-V PV like GaAs solar cells, National Renewable Energy Laboratory has come up with a new approach and it is named as “germanium on nothing”. Idea involves the GaAs cells are grown on thin layer of germanium which is preliminarily deposited on reusable germanium substrate [46]. Along with III-V group materials, other semiconducting inorganic materials like CdS/CdTe and CIGS have been involved for indoor applications, but efficiencies for these devices were poor in indoor environments. Batzner and group reported a solar cell based on CdS/CdTe which exhibited PCE of around 22 % under 1 Sun condition but only 8 % PCE was obtained with same solar cell under indoor environment (halogen lamp) [12]. In case of



**Fig. 5.** (a) Reported efficiencies of first and second generation solar cells by utilizing various materials and modules. (b) Graphical representation of efficiency vs year of 1st and 2nd generation devices. (Bermudez et al., Copyright 2018 Nature Portfolio).

CIGS, it more worse, for instance, Bermudez and group reported solar cell with CIGS material showing PCE of 22 % under 1 Sun illumination whereas only 2.5 % PCE under LED light. (Fig. 5) Bermudez and Perez-Rodriguez [13].

To conclude on indoor applications with inorganic materials based solar cells, it is evident that III-V semiconducting materials are most preferable for indoor conditions because of it better efficiency and good spectral matching and stable to environment conditions. These inorganic materials can be further tuned to produce high efficiencies like tuning band gap energy and other properties like electrical conductivity, transparency, absorption spectra and surface morphology can be varied by addition of dopants. It is also necessary to design and develop a material to overcome the cost factor which is major drawback of this technology.

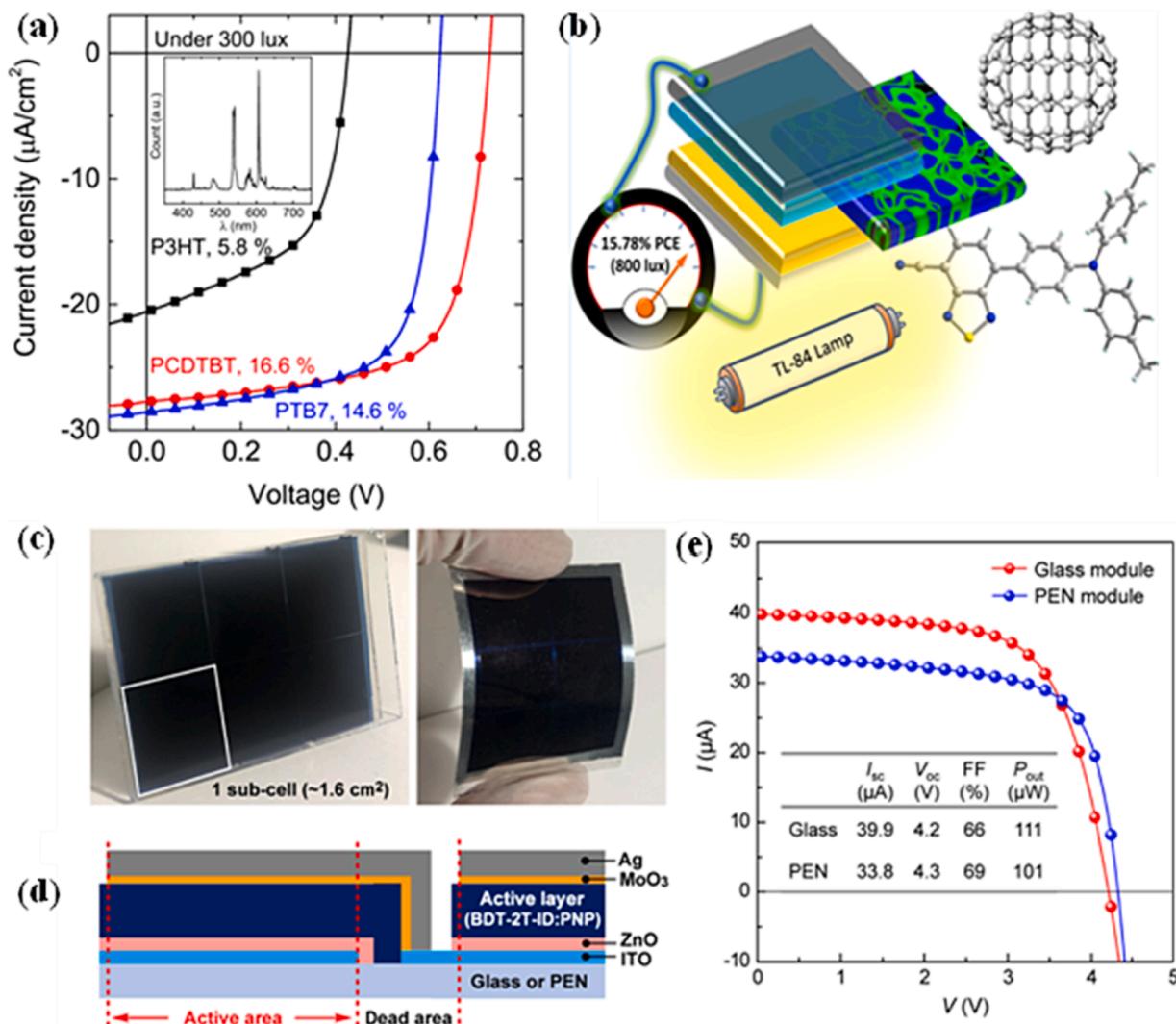
#### 1.4. Organic photovoltaics

Organic materials based solar cells fall into the third-generation solar cells, after inorganic materials being used in the first two generations of solar cells, in this organic materials are being used. Organic Solar Cells (OSCs) device architecture mainly contains six components like substrate, cathode, electron transport layer (ETL), active layer, hole transport layer (HTL), and anode. Each layer plays its own important role in proper functioning of the device. The active layer is a light absorber, formed by Bulk Hetero Junction (BHJ) having the blended materials of donor and acceptors, which absorbs photons and converts those photons into free charge carriers. Lately, with fine tuning of the device under outdoor conditions, PCE of almost 18 % has been achieved [120] (Zhang et al., 2021) [214,191,122]. Thanks to advances in research where it involved donor-acceptor materials molecule designing [117] (Yuan et al., 2019) [199,219,200], interfacial modifications, [198,194] device engineering [132], Morphology optimizations and several other factors [114]. But under indoor conditions its PCE dramatically increases. When compared to outdoor conditions as well as with silicon solar cells these cells show superior performances, better operational stability under LED or FC illuminating conditions [136,32,103]. Indoor light contains emitting spectra range only in between 400 and 700 nm compared to sun light illuminations contains much broader region, implying the optimum band gap region for organic solar cells lies in the scope of 1.8–3.0 eV. Keeping this in mind, synthesizing the molecules with wide band gap to identical with the spectrum of indoor light is the noteworthy. The first report of organic solar cells came to light in 2010 when Minnaert et al. shelled out applicability of OSC in indoor environment Minnaert and Veelaert [134]. Ten years down the lane, currently it has reached to almost 30 % PCE [127].

As per the reports stated by National Renewable Energy Laboratory

(NREL), a high efficiency of 26.1 % is achieved by the c-Si solar cells (ISFH, Germany) under 1 Sun conditions, where in similar condition organic counterparts achieves only 18 %. [67] Under indoor conditions, however this scenario reverses when light source is FC or LED suggesting Indoor Organic Photovoltaics (IOPVs) are better performers compared to silicon solar cells. When PTB7-Th:PC<sub>71</sub>BM (2-ethylhexyl 6-(4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)-6-methylbenzo[1,2-b:4,5-b']dithiophen-2-yl)-3-fluoro-4-methylthieno[3,4-b]thiophene-2-carboxylate (PTB7-Th): [6,6]-phenyl-C71-butyric acid methyl ester (PC<sub>71</sub>BM)) OSC and c-Si based solar cells where compared by Mori and group, outcome was 13.49 % of PCE was achieved by c-Si solar cells and PTB7-Th:PC<sub>71</sub>BM OSC recorded only 8.43 % PCE under 1 Sun condition [136]. Interestingly, when same cells where recorded under LED at 890 lx PCE of c-Si was reduced to 9.65 % and PTB7-Th:PC<sub>71</sub>BM OSC PCE was increased to 11.63 %. Upon further decreasing of intensity to 189 lx PCE of OSC was found to be 10.5 % whereas c-Si based cell showed further reduction is PCE of 6.92 %.  $V_{OC}$  of OSC was reduced to 0.56 from 0.78 as the illumination intensity get decreased, in the case of c-Si based solar cells  $V_{OC}$  severely decreased which might be the reason for decrease in PCE. Cutting et al., also compared PCE of Si solar cells and OPVs, in which a-Si based solar cell and c-Si solar cells showed PCE of 1.45 and 16.72 % respectively under 1 Sun condition, whereas under LED condition of 20.5mWcm<sup>-2</sup> a-Si showed 2.19 % and c-Si showed 20.19 % [35]. On the other hand, OPVs, P3HT:PCBM [3-hexyl-2,5-dimethylthiophene(P3HT), [6,6]-phenyl-C61-butyric acid methyl ester (PCBM)] and PCE10:PCBM [2-ethylhexyl 6-(4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)-6-methylbenzo[1,2-b:4,5-b']dithiophen-2-yl)-3-fluoro-4-methylthieno[3,4-b]thiophene-2-carboxylate (PCE10)] based OPVs showed 2.93 and 8.65 % PCE respectively under 1 Sun illumination. But under LED condition their performance was increased many folds where they showed efficiencies of about 12.83 and 21.04 % respectively. Such significant increase in PCE makes OPVs most suitable for indoor environment.

The maximum power conversion efficiencies of photovoltaics based on theoretical calculations according to detailed balance limit theory are calculated by the method of Shockley and Queisser Shockley and Queisser [169]. Here they assume the energy above the material is completely absorbed by different light sources and all carriers are completely extracted. Optimum bandgap for OPVs according to theoretical calculations for indoor conditions is 1.9 eV, its 1.34 eV for AM1.5 conditions [50]. The better indoor light spectra can be covered, when the band-gap of material is wider. The maximum theoretical efficiency for phosphor and 3-colour LEDs is close to 60 % with band-gap of 1.9 eV, but in case of AM1.5 the upper limit cumulative efficiency doesn't exceed 40 % at band-gap of 1.34 eV. High efficiencies are due to the narrowing of spectra of light sources in which irradiated photons are sufficiently used by active materials, once the spectra become narrower



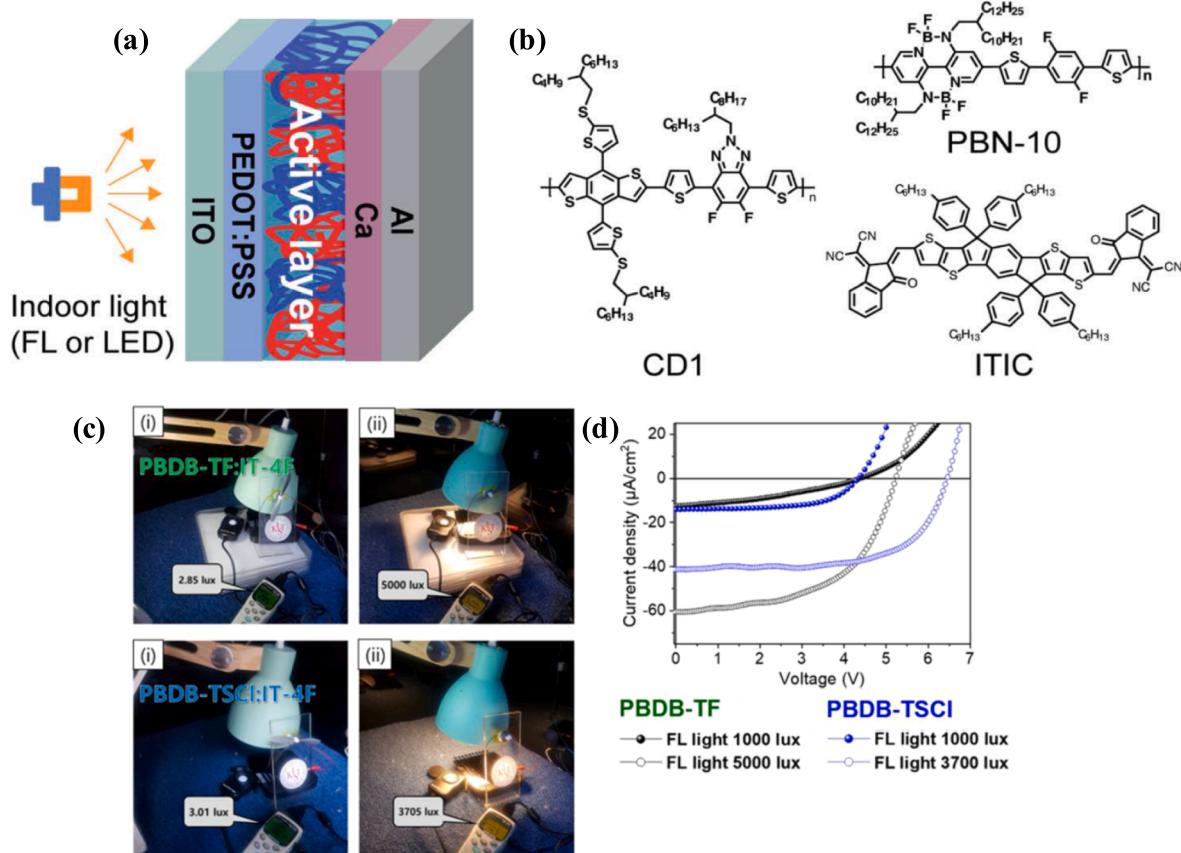
**Fig. 6.** (a) Current density ( $J$ )-Voltage ( $V$ ) spectra of three devices based on P3HT, PCDTBT and PTB7 with PCBM and PC71BM under standard conditions and under 300 lx fluorescent lamps. (Lee et al., Copyright 2016 American Institute of physics). (b) Schematic illustration of device with donor N,N'-aniline at indoor lamp conditions (Chen et al., Copyright 2019 ACS). (c) Images of modules connected in series on glass and flexible surfaces (d) Design of modules preparation. (e) Device performance of modules under white LED 200 lx illumination. (Arai et al., Copyright 2019 ACS).

transparency is reduced and thermalization losses are also lessened [181]. c-Si has band-gap of 1.1 eV which relates to the optimal band-gap under solar luminance so they achieve high efficiency under AM 1.5, once the bandgap is narrowed the PCE is also lowered under indoor conditions when compared to OPVs (Cui et al., 2019) [34,206].

Along with the spectral match and band-gap match there are few other golden points to keep in mind while designing OPVs like minimising  $V_{OC}$ , preventing recombination losses. For better PCE, the active material photoresponse should fully match with indoor light source. Next is,  $V_{OC}$  loss should be minimised to the maximum extent. Under indoor lighting  $V_{OC}$  reduces drastically when compared to 1 Sun condition and it is unavoidable due to drop in intensity of light. Minimizing the reverse dark saturation current can maximize the  $V_{OC}$ . For IOPVs to achieve high  $V_{OC}$  under indoor environment, a high  $V_{OC}$  under AM1.5 and a small  $V_{OC}$  loss in indoor environment are essential. In contrast, the carrier density, when the intensity is decreased from AM1.5 to indoor condition dramatic decrease in carrier density is noticed, trap assisted recombination considerably suppresses electrode to efficiently gather charge carriers, trap can impact on fill factor (FF) along short circuit current ( $J_{sc}$ ) and  $V_{OC}$ . Hence, there is a need to prevent trap assisted recombination for IOPVs in achieving better PCE [195].

**Fullerene based OPVs:** In 1995, methanofullerene was successfully

synthesized which was soluble in organic solvents and characterised and in same year similar fullerene derivative was used as acceptor for internal D-A hetero-junction OPV. From then a new era has started to fullerene beyond OPV and it has been utilised in several research directions involving solution-processability techniques involving fullerene derivatives. In recent times it has been utilized in perovskite solar cells, molecular electronics, organic thermoelectric and organic electrochemical transistors. It has fascinating properties like unique structural and electronic properties, high, electron affinity, small reorganization energy, excellent electron mobility, long lived-charge separated states which makes them to be a promising candidate. Along with this, electron mobility, better film morphology and structure ordering of fullerene make them more suitable for OPVs [8]. This fullerene also enhances the stability as it is hydrophobic in nature. Lee et al., in 2017 reported three different combinations of OPVs with material P3HT:PCBM (3-hexyl-2,5-dimethylthiophene (P3HT): [6,6]-phenyl-C<sub>61</sub>-butyric acid methyl ester (PCBM)), PCDTBT:PC71BM (Poly[N-9'-heptadecanyl-2,7-carbazole-alt-5,5-(4',7'-di-2-thienyl-2',1',3'-benzothiadiazole)]) and PTB7:PC71BM (Poly(thieno [3,4-b] thiophene-alt-benzodithiophene) (PTB7)): PC71BM with device efficiency of 2.4, 6 & 6.8 %, respectively under AM1.5 conditions [104]. Comparatively, when these devices were tested under 300 lx fluorescent illuminations, their PCE was enhanced to 5.8,

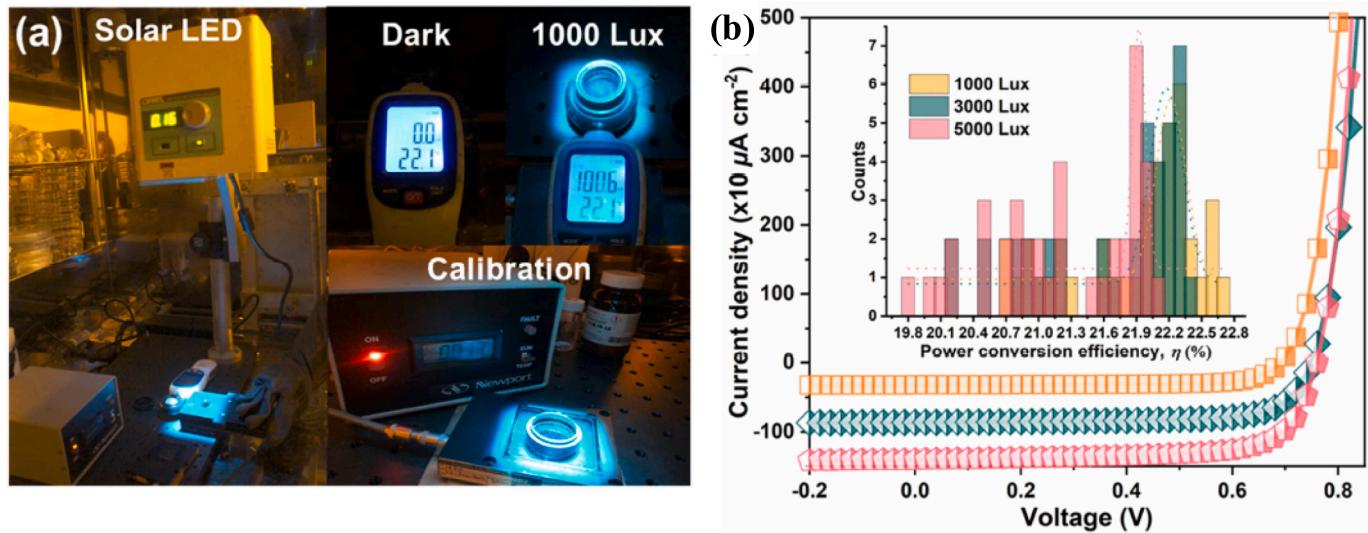


**Fig. 7.** (a) Schematic representation of the device fabrication under indoor light. (b) Molecular structures of ITIC, PBN-10 & CD1. (Ding et al., Copyright 2019 RSC) (c) Pictorial depiction of OSC modules based devices supported for power supply towards rotor spinning at before (i) and after fluorescent lamp illumination (ii). (d) Device performance evaluated by J-V graphs of champion organic solar cells (OSCs) modules under different indoor illuminations conditions. (Park et al., Copyright 2019 ACS).

16.6 & 14.6 % PCE for P3HT:PCBM, PCDTBT:PC71BM and PTB7:PC71BM respectively. Since emitting spectrum of FC lamp lies in the visible region and that matches well with these IOPVs they could perform well under indoor conditions. A high  $J_{SC}$  can be observed for fullerene-based devices since they will have high EQE. Arai et al., have synthesized two small organic donors namely, 1DTP-ID and 2DTP-ID ( $2,2'((4-(2\text{-octyldodecyl})-5\text{-oxo}-4,5\text{-dihydrodithieno}[3,2-b;2',3'-d]pyridine-2,7-diyl)bis(3,4'-dihexyl-[2,2'-bithiophene]-5',5-diyl))bis(methaneylylidene))bis(1H-indene-1,3(2H)-dione$ ) (1DTP-ID); and  $2,2'((4,4'\text{-bis}-(2\text{-octyldodecyl})-5,5'\text{-dioxo}-4,4',5,5'\text{-tetrahydro-[7,7'-bidi-thieno-[3,2-b;2',3-d]pyridine]-2,2'-diyl})bis(3,4'-dihexyl-[2,2'-bithiophene]-5',5-diyl))bis(methaneylylidene))bis(1H-indene-1,3(2H)-dione$ ) (2DTP-ID)), they had band-gap of 1.65 and 1.7 eV respectively Arai et al. [7]. Under 1 Sun illumination, 1DTP-ID:PNP (Nphenyl-2-phenyl[60]fulleropyrrolidine (PNP)) and 2DTP-ID:PNP based devices exhibited PCE of 2.6 and 2.9 % respectively. Surprisingly, there was dramatic increase in PCE when these devices were illuminated under 200 lx LED illumination. Upon illumination on white LED with a colour temperature of 2900 K they revealed PCE of 19.3 and 17.8 % PCE for 1DTP-ID:PNP and 2DTP-ID:PNP respectively. The absorption of two polymers lied in the range of 610 nm which matches with the incident light spectrum might be the possible reason for high efficiency. A semi-crystalline donor PPDT2FBT was reported by Shin et al., for IOPV [168]. Under 1 Sun condition, PCE of 7.5 % was noticed for PPDT2FBT: PC71BM, but same device under 1000 lx LED showed PCE of 16.6 %. OPV based on these devices even showed thickness tolerance where it maintained PCE of 12.5 % with thickness of 870 nm. Further Chem and group synthesized wide band-gap molecules in D-A-A fashion as donors, they are DTCBP, DTCTB, DTCPBO, DTCTBO (7- (4-(di-p-tolylamino)

phenyl)benzo[c][1,2,5]thiadiazole-4-carbonitrile (DTCBP), 7-(5-(di-p-tolylamino)thiophen-2-yl)benzo[c][1,2,5]thiadiazole-4-carbonitrile (DTCTB), 7-(4-(di-p-tolylamino) phenyl)benzo[c][1,2,5]oxadiazole-4-carbonitrile (DTCPBO) and 7-(5-(di-p-tolylamino)thiophen-2-yl)benzo[c][1,2,5]oxadiazole-4-carbonitrile (DTCTBO) [22]. Among the synthesized donors, device based on DTCBP:C70 showed PCE of 6.55 % under 1 Sun condition, reason for higher PCE lies in better exciton dissociation, and less germinated recombination which results in high FF. With TLD-840 fluorescent illumination of 800 lx illuminating intensity maximum PCE achieved was 15.78 %. Yin and group reported porphyrin based donor P1, which contain porphyrin ring with two rhodamine groups, when P1:PC71BM was compared with PCDTBT: PC71BM P1 devices showed better PCE under 1Sun illumination with PCE of 5.78 % [203]. At 300 lx illumination P1 device outperformed the other device with PCE of whopping 19.15 %. Further great thickness tolerance was shown by P1 device, at thickness of 200 nm it showed PCE of around 18 %. This is due to low electronic disorder of P1 device compared to PCDTBT device. Arai and group synthesized two novel organic donors, namely BDT-2T-ID and BDT-1T-ID and used them for organic solar cells  $2,2'((4,8\text{-bis}(5\text{-(2-ethylhexyl)}\text{thiophen-2-yl)})\text{benzo}[1,2-b:4,5-b']\text{dithiophene-2,6-diyl})\text{bis}(3,4'\text{-dihexyl-[2,2'-bithiophene]-5',5-diyl})\text{bis}(1H\text{-indene-1,3(2H)-dione}$  (BDT-2T-ID).

and  $2,2'((4,8\text{-bis}(5\text{-(2-ethylhexyl)}\text{thiophen-2-yl)})\text{benzo}[1,2-b:4,5-b']\text{dithiophene-2,6-diyl})\text{bis}(4\text{-hexylthiophene-5,2-diyl})\text{bis}(methaneylylidene))\text{bis}(1H\text{-indene-1,3(2H)-dione}$  (Fig. 6) [7]. Under 200 lx LED with a colour temperature of 8500 k BDT-2T-ID:PNP device showed efficiency of 16 % compared to BDT-1T-ID based device as its absorption strongly matches with the illuminating indoor source. With BDT-2T-ID



**Fig. 8.** (a) Photo of indoor measurement setup: Solar LED at dark and 1000 Lux conditions. (b) Device performance of PM6:Y6:Y-Th2 under three different illuminations such as 1000, 3000 and 5000 Lux, respectively. (Singh et al., Copyright 2020 Elsevier).

device they fabricated a module with active area of  $9.2 \text{ cm}^2$  under 200 lx LED illumination could generate  $111 \mu\text{W}$  power which was sufficient to power self-sustainable electronic devices. You and group designed and synthesised a polymer called PDTBTBz-2F<sub>anti</sub> with a wide bandgap of 2 eV and tried to match with PC71BM for IOPVs [115]. Unmatched PCE of 23.1 % was noticed for PDTBTBz-2F<sub>anti</sub>:PC71BM (poly[(5,6-bis(2-hexyldecyloxybenzo[c][1,2,5]thiadiazole-4,7-diyl)-alt-(5,50-(2,5-difluoro-1,4-phenylene)bis(thiophen-2-yl))]) device under 1000 lx white LED illumination benefitting for the superior absorption spectrum matching of white LED source, this device even outperformed interdigitated-back-contact Si based solar cells (16.3 %). Yang and group studied performance of three BHJ device combinations under indoor environment, P3HT:PC61BM, P3HT:ICBA and PBDDTTT-EFT:PC71BM (poly[4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)benzo[1,2-b;4,5-b0]dithiophene-2,6-diyl-alt-(4-(2-ethylhexyl)-3-fluorothieno[3,4-b]thiophene)-2-carboxylate-2-6-diyl]) (PBDDTTT-EFT)) [202]. They noticed PCEs of 3.68, 4.90 and 6.95 % under 1 Sun condition for P3HT:PC61BM, P3HT:ICBA and PBDDTTT-EFT:PC71BM devices respectively. Whereas under LED and fluorescent tubes illumination with intensity of 500 lx, 13.76 % PCE was obtained for P3HT:ICBA and outperformed other two devices due to its well match of absorption spectrum with indoor source. Singh and group studied performance of donor group based on BDT on fluorine substituted WF3F [171]. Three devices namely WF3:PC71BM, WF3S:PC71BM and WF3F:PC71BM achieved PCEs of 7.71, 7.91 and 9.11 % with DPE additive, but showed better PCE under 500 lx condition and PCE increased to 12.83, 14.32 and 17.34 % respectively.

**Non-Fullerene based OPVs:** Performance of fullerene-based devices has enhanced to different level in OPVs there is still some concerns regarding huge energy loss and intricacy in tuning energy level of fullerene [74,24]. On contrast great advantages have been shown by non fullerene acceptors (NFA) like modifying band-gap, low energy loss and so on [117,208,218,209]. Researchers have put lot of efforts to progress high performing NFAs for IOPVs. Cui and group reported a novel NFA in 2018 for OSC and compared performance in 1 Sun and indoor environments [33]. NFA called IO-4Cl with bandgap of 1.89 eV. IO-4Cl was blended with PBDB-TF to form a device and exhibited efficiency of 9.8 % under 1 Sun condition. Lowest energy loss of 0.6 eV was noticed when they calculated for the device. At different illuminating intensities like 200, 500 and 1000 lx intensities with white LED illumination of colour temperature 2700 K PCE was found to be 22.2, 24.6 and 26.1 % respectively for different illuminating intensities. They also reported

these devices are compatible for large scale processing. They also showed PBDB-TF:IO-4Cl device to be stable even for 1000 h maintaining initial PCE even under continuous illumination. Ding et al., in 2019 showed CD1:PBN-10 which is a polymer as a great potential in IOPVs Under 1 Sun condition it achieved  $V_{OC}$  of 1.29 eV and PCE of 7.93 % [41]. Similarly, under 1000 lx and 2000 lx at FL illumination it achieved 26.2 % and 27.4 % repetitively for different intensities which was of highest achieved intensity for IOPs. They also studied device performance for material on CD1:ITIC, which showed inferior performance compared to other device due to unmatched absorption spectrum. Cui and group studied the performance of ITCC, PC71BM and IT-4F in IOPVs (Cui et al., 2019). At AM1.5G illumination PBDB-TF:ITCC, PBDB-TF:PC71BM and PBDB-TF:IT-4F devices showed PCE of 8.43, 10.3 and 12.2 % respectively. They performed studies at varied illuminations with 200, 500 and 1000 lx at warm white LED for PBDB-TF:IT-4F device. PBDB-TF:ITCC device outperformed the other two devices under white LED illumination and displayed equivalent PCE under various indoor sources, low  $E_{loss}$  and matched absorption spectrum could be possible reason. Under weak illumination they found it has good photostability. Park et al., have synthesized a donor PBDB-TSCI for OSC (Fig. 7) [152]. PBDB-TSCI:IT-4F showed slightly better PCE of 13.13 % compared to PBDB-TF:IT-4F which showed PCE of 12.12 % under 1 Sun condition. But under 500 lx FL illumination PBDB-TSCI:IT-4F showed much improved PCE of 21.53 % to PBDB-TF:IT-4F of 15.57 %. It was seen that more balanced charge transporting and improved charge mobility in case of PBDB-TSCI:IT-4F leading to higher FF further leading to better PCE. Even it showed great resistance to thermal test where it was stable at 100 °C maintained 95 % of PCE. Je and group studied the substitution of chlorine on thiophene substituted benzodithiophene unit in photovoltaic performance [81]. Three devices, PBDB-TS:IT4F, PBDB-TS-3Cl:IT4F and PBDB-TS-4Cl:IT4F PCEs were calculated under 1 Sun condition and were found to be 8.7, 12.6 and 12.7 % respectively, on the other hand under 500 lx illumination PCEs were found to be 5.3, 20.4 and 21.7 %. This result showed chlorination plays key role in increasing  $V_{OC}$ . Yin and group involved a low driving force P3TEA:FTTB-PDI4 unit for making thick films in IOPVs [204]. It showed 8.3 % PCE under 1 Sun condition and its PCE increased by 3 folds under the illumination from 170 to 1650 lx. Device maintained PCE of 21 % even at thickness of 200 nm. Kwon and group used copolymers for IOPVs, P(BDBT-co-NDI2T) based OSC demonstrated better PCE compared to P(BDBT):P(NDI2T) (without copolymer) which showed PCE of 6.22 % under 1 Sun condition [98]. Whereas under LED illumination of 500 lx P(BDBT-co-NDI2T)

exhibited PCE of 12.7 % outperforming to 6.8 % of P(BDBT):P(NDI2T). This result could lead to the whole new direction of OSCs.

**Ternary and quaternary devices based OPVs:** To overcome the disadvantages for the binary devices adding third and fourth components to the active layer is a wise idea. When compared to the binary devices, ternary and quaternary devices shows better performance due to enhanced carrier mobility which are helpful in increasing FF which broadens the absorption spectrum thanks to complimentary absorption which further enhances  $J_{SC}$ , high  $V_{OC}$  [215,216,5,55,121,196]. Yin and group added PDTSTPD as the third component into the PCDTBT: PC71BM blend and studied device performance with both binary and ternary components [32]. Under 1 Sun condition binary device exhibited PCE of 5.3 % and ternary exhibited 6.0 % PCE. In case of indoor lighting at FK illumination of 2700 K ternary device achieved 19.8 % PCE compared to 16.5 % of binary device, PCE could be further improved to 20.8 % with solvent vapour annealing. Singh and group employed EP-PDI as third component to enhance the device accomplishment of PTB7:PC71BM (Singh et al., 2019). At white LED illumination of 500 lx intensity when EP-PDI was used in the ratio of 40 % ternary device achieved PCE of 15.36 %, whereas binary device showed PCE of 8.85 % [62]. Cho and group employed a series of wide band-gap acceptors namely PM:Y6:Y-Th2 studied their device performance under 1 Sun condition and obtained PCE of 16.01 %, which outperforms the binary device which showed PCE of 15.04 % [27]. Under 1000 lx LED illumination ternary device exhibited excellent PCE of 22.7 %. Farhat and group used PDI as a third component in the device of FBT:PC61BM and studied the performance [47]. PCE of 7.7 % was achieved with slot-die coated method and achieved 7.9 % with the spin coated method under 1Sun condition. FBT:PC61BM:PDI gave excelled PCE of 15.5 % under white LED illuminations. Singh and group chose different NFA as third component like PDI2, PDI4, IDT and IDDT into the binary device of OD:PC71BM. These devices have showed PCEs of 8.61, 10.48, 8.92, 11.38, and 9.32 % for OD:PC71BM, OD:PC71BM:PDI2, OD:PC71BM:PDI4, OD:PC71BM:IDT and OD:PC71BM:IDDT respectively, under 1 Sun condition (Fig. 8) [172]. In contrast, under indoor source of 1000 lx environment IDT ternary device showed 21.3 % PCE that showed best at its morphology and outperformed other devices. Tan and group used PM7 as third component which has wide band-gap in J52F:BTAA3 device exhibited PCE of 20 % under indoor lighting with  $V_{OC}$  of 1 V [11]. The third component played an important role in enhancing the PCE by reducing  $E_{loss}$  and by suppressing the carrier recombination. Nam and group employed four component method to make a device with PBDB-T, PTB7-Th, PC71BM and ITIC-Th being components [138]. Quaternary device showed PCE of 9.46 % PCE under 1 Sun illumination and exhibited 14.29 % PCE under indoor lighting This device showed excellent semi-transparent property with average visible transmittance of 48 % and PCE of 13.7 %.

**Other methods:** Along with the above said methods few other techniques are also used to enhance the performance of OSC device like interfacial engineering [60,99,205], tandem devices [17], electrode engineering [60,61], solvent vapour annealing [106], introducing metal nanoparticles [76,180], and so on.

**Challenges for IOPVs:** Although high performing IOPVs have been reported at lab scale it needs long way to go for reaching commercial stages, there are few problems to be taken care off like standardising the performance measurements of IOPVs, the light needs to be calibrated, theoretical bandgap of 1.9–2.2 eV should be targeted to achieve which enhances the  $V_{OC}$  that in turn helps to increase PCE [9]. While going for commercialisation, stability of devices should be given prime importance, there is still a scope to increase thermal stability, photostability, air stability and mechanical stability. When compared to small area IOPVs, large area-based devices showed inferior performance and this needs to be addressed while going for commercialisation. On the whole, for indoor environment, IOPVs have outperformed Si- based devices if these above-mentioned challenges are addressed this will be seen in commercial applications soon.

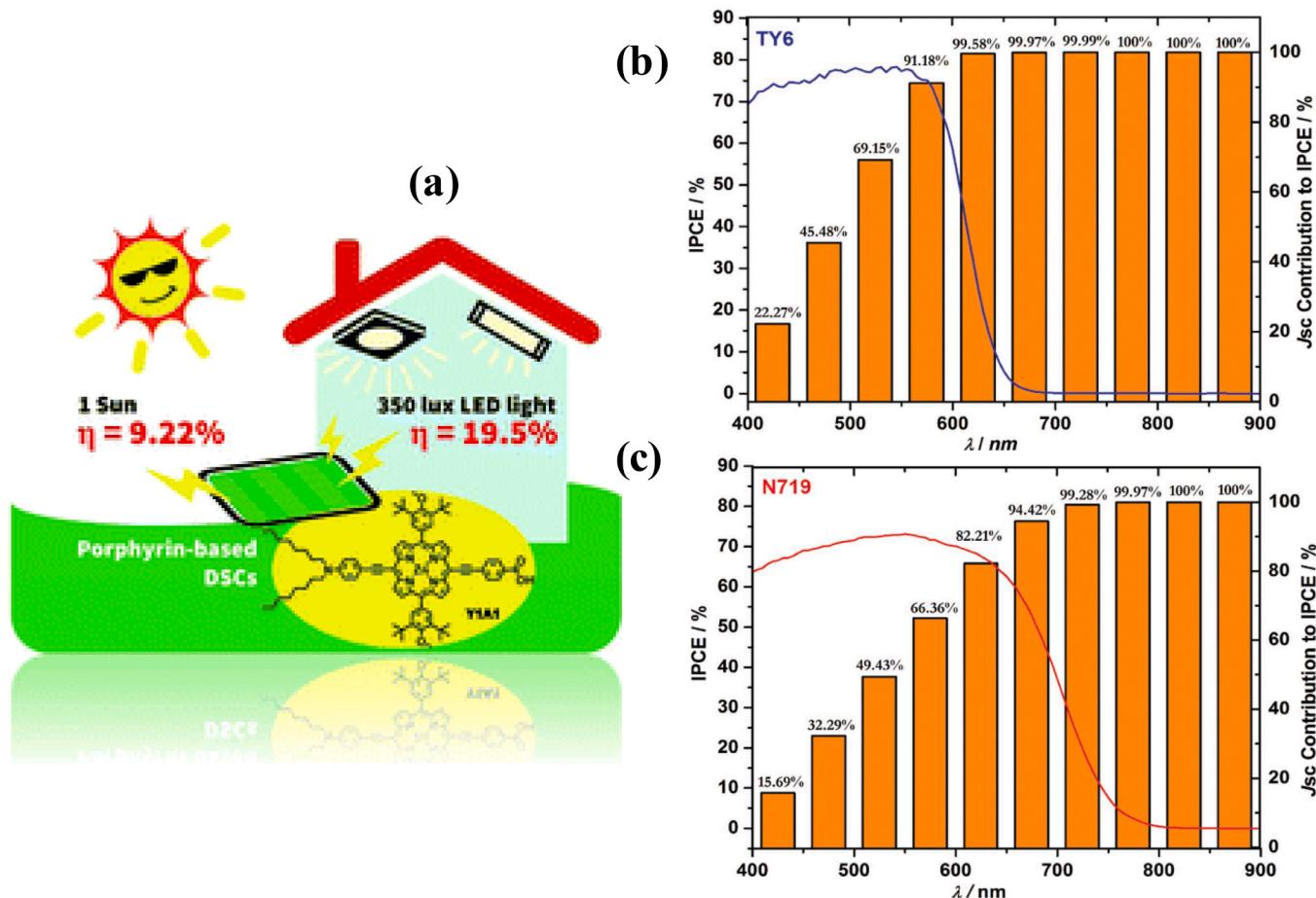
### 1.5. Dye sensitized solar cells

Dye sensitized solar cells (DSSCs) belongs to the third generation of solar cells, which is well explored owing to their high PCE, low cost and ease of fabrication. O'Regan and Grätzel first reported DSSC with over 7 % in 1991 O'regan and Grätzel [148]. Since last three decades, DSSCs have shown tremendous progress in terms of device stability, certified efficiencies over 12 % and low production cost [86]. DSSC working principle is stated briefly: Dye molecules get excited upon solar illumination and the photo-generated electrons from dye rapidly diffused into the conduction band of  $TiO_2$ , which further get diffused into FTO layer and finally pass through the external circuit to the counter electrode. Excited dye molecules goes back to the ground state by oxidizing the electrolyte and the electrolyte further gets the electron from the accumulated electrons at the counter electrode [69,59 51 156,46]. In recent years DSSCs have performed well under indoor light and PCEs have shown remarkably well compared to one Sun condition. With excellence performance shown by DSSC under artificial light sources, DSSC have a bright prospect for portable electronic equipment. First report on indoor based DSSC was reported by Kawata and co-workers for which they obtained 0.61 V,  $78 \mu A cm^{-2}$ , 0.78,  $V_{OC}$ ,  $J_{SC}$  and FF respectively. PCE of 11.2 % was found under 1000 lx illumination with obtaining  $37 \mu W cm^{-2}$  power output [91]. De Rossie and group have obtained PCE of 12.4 % under 200 lx illumination with CFL lamp based on flexible DSSC device [39]. These results explained the importance of development of i-DSSC. In the field of machine learning, Michaels et al., have used DSSC as to generate power supply [133]. Both materials and device architecture play a crucial role in achieving high efficiency of the device under low-light conditions. [58].

### 1.6. Sensitizer

Sensitizer plays a crucial role in DSSC to harvest light exclusively under indoor light condition [30,87]. To enhance power conversion efficiency, capturing enough light is an essential criteria. The  $\pi$ -conjugated molecule, which absorbs maximum photons in visible and near IR region is considered as an ideal dye. Among the natural dyes, chlorophyll is of utmost important which can absorb sun light to perform its function, tetrapyrrolic (porphyrin) ring present in it helps to absorb light. Henceforth porphyrin based organic dyes have been thought to be ideal sensitizers for DSSC and have been extensively reported. A simple porphyrin dye Y1A1 was reported by Liu and group for i-DSSC, under illumination of 350 lx found PCE of 19.5 %, whereas under AM1.5 condition PCE was showed 9.22 % [124]. An alternative porphyrin dye SK7 bearing two N,N-diaryl amino groups at beta positions was reported by Reddy and group for i-DSSC [162]. Along with that with one N,N-diaryl amino group at meso position porphyrin was also synthesized (YD2) to compare the photovoltaic performance. Under 6000 lx illumination T5 light YD2 based dye showed PCE of 20.0 % whereas SK7 based dye showed PCE of 19.7 % under the same condition.

Metal-free organic dyes are another class of sensitizers that widely used as dye for DSSC due to well established synthetic protocols, easy to tune its optical and electronic properties. Among various organic scaffolds, anthracene based scaffold is highly attractive for i-DSSC applications due to good thermal stability and show unique photo physical properties, for instance good fluorescence quantum yields, small radiative lifetimes, high red shifted absorption, transition dipole [163]. A series of organic dyes based on anthracene was reported by Wang et al., i.e., AN1, AN3, AN5, AN7 and AN8. The fabricated DSSC modules with these dyes, the module based on AN3 dye with  $36 cm^{-2}$  area showed 5.45 % PCE at T fluorescent lamp under 1000 lx illumination [186]. They also tested the device stability and found only 3 % overall efficiency was dropped even after 2000 h, which suggests AN3 a promising candidate for indoor applications. Tsai and group reported another set of 3 anthracene dyes for i-DSSC named as AN-11, AND-12 and AN-14 [124]. As a result of panchromatic absorption of visible light AN-11

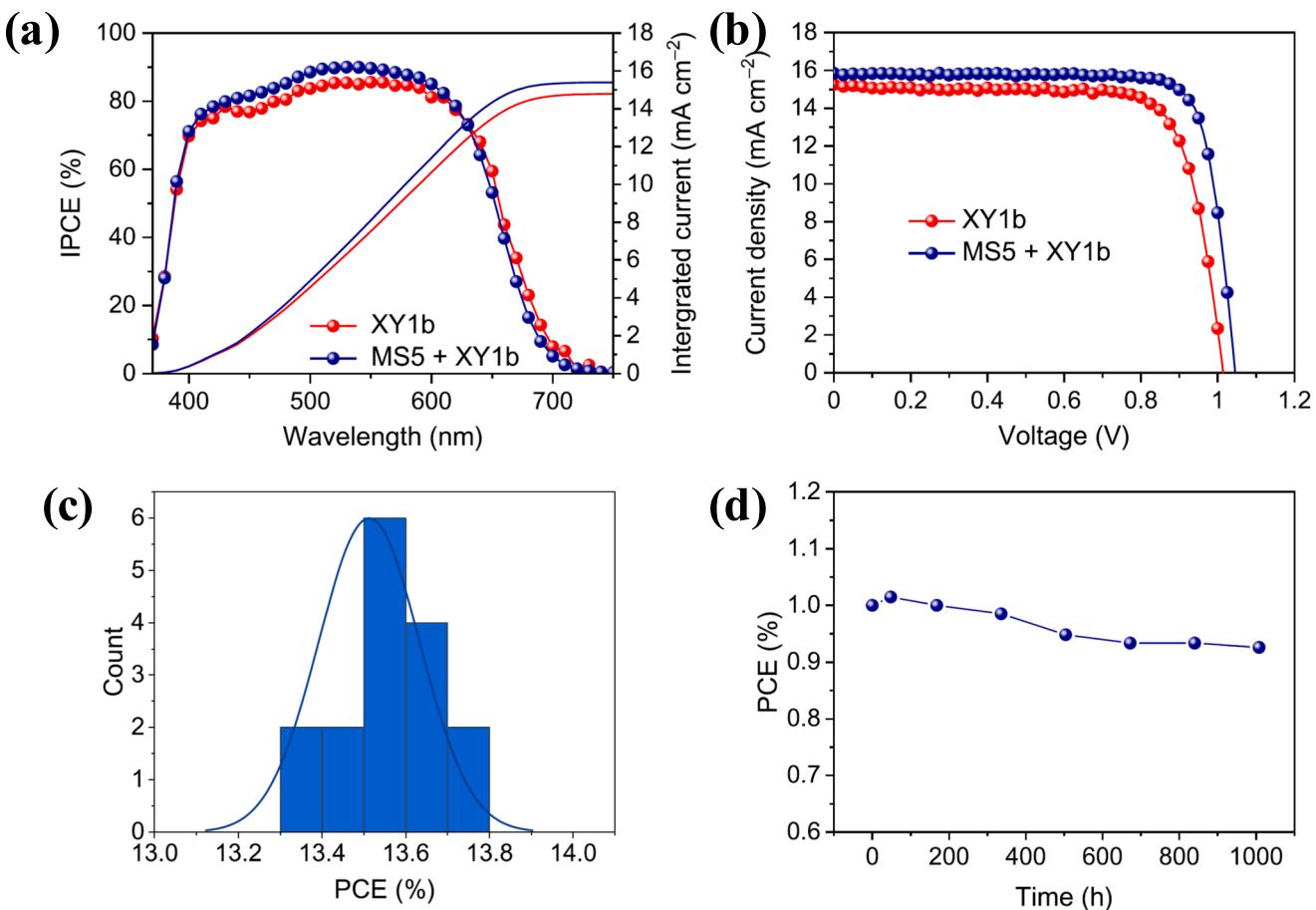


**Fig. 9.** (a) Comparison between 1 sun and at LED with 350 lx LED light on porphyrin based DSSCs. (Liu et al., Copyright 2016 RSC). (b,c) IPCE of TY6 and N719 based devices and also shown the percentage of accumulated current production at different wavelengths (Tingare et al., Copyright 2017 Wiley-VCH). (d) IPCE spectra of DSSCs co-sensitized with XY1 and D35 at various dye and D35 at various dye ratios. (Freitag et al., Copyright 2017 Nature portfolio).

based i-DSSC showed superior performance compared to the other two dyes. With active area of  $26.80 \text{ cm}^{-2}$  AN-11 based device showed 11.26 % PCE under 1000 lx illumination. They compared Z709 with same area device and obtained PCE of 10.91 % under similar conditions. Further, the sensitizer AM-11 displayed good stability for weather stress test. Tingare and co-workers have synthesized three anthracene based organic dyes for i-DSSC, in which they incorporated with alkoxy chains and electron deficient moieties to enhance the device performance [183]. The increase in charge recombination resistance with alkoxy chains which reduces the charge recombination rate and further increasing the electron lifetime. They chose benzotriazole electron deficient moiety over benzothiadiazole which resulted highest charge recombination rate due to deep LUMO energy which might have impacted in obtaining high  $V_{OC}, J_{SC}$  and FF values. They noticed red shift in absorption spectrum of the electron donating alkoxy on the aromatic amine donor, with the help of theoretical studies. This red shift endorsed the absorption of TY4 to completely fall on the emission range of T5 fluorescent source. Hence TY4 showed good performance in the indoor condition due to its good light collecting property. In contrast, the absorption spectra TY-6 revealed nice overlap between blue and red regions of LED emission. Apart from light collecting characteristic, energy levels also play a key role in dye regeneration and electron transfer in DSSC. In case of TY3, TY4 and TY6, their LUMO energy levels were significantly different which varied from  $-1.10$  to  $-1.21$  V and their HOMO lied between 1.15 and 0.95 V. Based on these energy levels TY-6 benefitted the most and delivered the PCE of 20.72 % under 6000 lx of LED and 28.56 % under fluorescent light.

Chou et al. reported metal-free organic dyes in D-A'-π-A fashion and

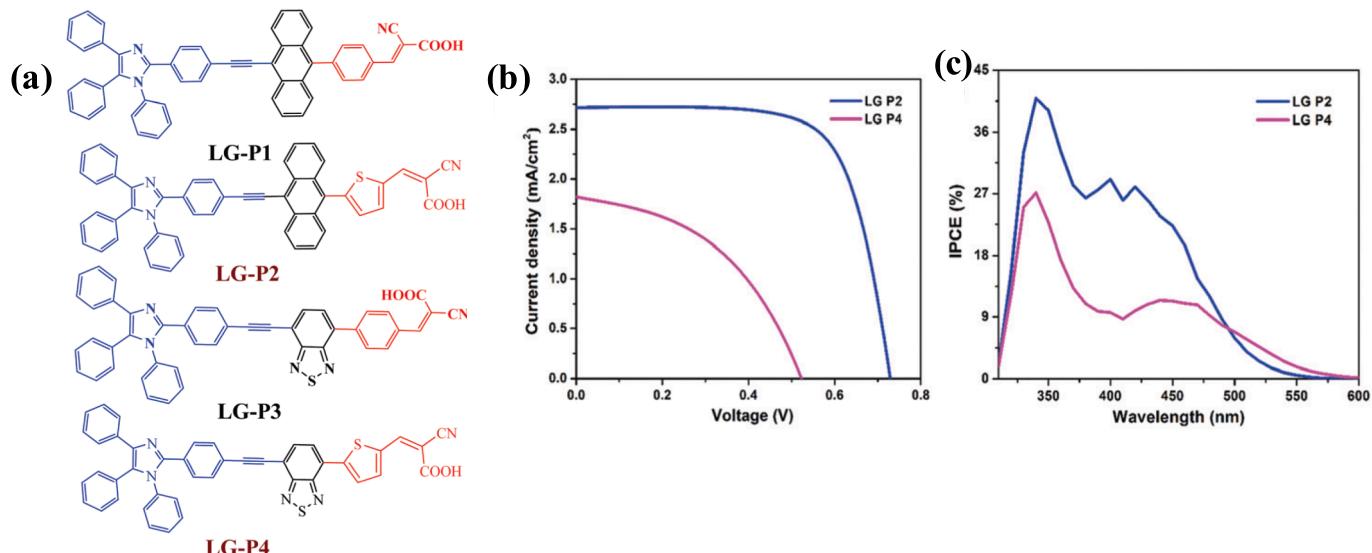
made GJ-x push-pull organic dyes by facile methods (Fig. 9) [29,133]. Under different illumination conditions, photovoltaic performance GJ dyes series was studied. In particular, GJ-BP dye showed highest PCE of 15.79 % with power output of  $0.28 \text{ mW/cm}^{-2}$  under 6000 lx light intensity. Desta et al., have developed four D-A'-π-A type sensitizers MD4, MD5, MD6 and MD7 bearing thieno [3,4-b] pyrazines (TP) and benzo [3,4-b] pyrazine (BP) as auxiliary acceptor for i-DSSC [40]. MD-7 based device showed PCE of 27.17 % under 6000 lx and 18.95 % under 300 lx intensities. From electrochemical impedance studies MD7 was the superior performing among the four dyes in suppressing the dark current due to its twist structure with the presence of alkoxy chains. Hegfeldt and co-workers in another report used two dyes to form a combined co-sensitized DSSC with D35 and XY1 dyes. Under 1 Sun condition D35:XY1 device a record PCE of 11.3 % was achieved (Freitag et al., 2018). Under indoor illumination of 1000 lx the device exhibited PCE of whopping 28.9 % with external quantum efficiency exceeding 90 % among the entire visible region. In an another study by Fretig and co-workers have co-sensitized XY1 dye with L1 using Cu(I/II) redox couple achieved device efficiency of 34 % under 500 lx light intensity [133]. Further Gratzel and co-workers by using co-sensitization concept with XY1b and MS5 using Cu(I/II) redox couple reached device efficiency of 34.4 % 1000 lx using white fluorescent light and this is champion data as on today (Fig. 10) [213]. Durability studies revealed that these devices are stable up to 1000 h. Jiang and group exhibited increase in the extinction coefficient with the introduction of quinoxaline and quinoxalinoid and a reported a series MM-1 to MM-6 in D-A-π-A approach [83]. MM-5 and MM-6 displayed red shift due to intra-molecular charge transfer when compared to other dyes. IPCE revealed that MM-5 and MM-6 have wider



**Fig. 10.** (a) XY1b and co sensitized XY1b based device's IPCE spectra. The corresponding current density against voltage curves for both devices under standard sunlight conditions. (c) MS5 + XY1b based device histogram of PCE. (d) Stability studies. (Zhang et al., Copyright 2021 Nature portfolio).

absorption bandwidth compared to other four dyes due to more number of long chain alkyl substituents. To reduce the rate of charge recombination deoxycholic acid (DCA) introduced as a coabsorbant, which helps in preventing the dye molecules from being aligned parallel to the  $\text{TiO}_2$  surface. The result showed enhanced FF and  $V_{OC}$  values. Under indoor

conditions PCE of MM-1 to MM-4 was found to be around 13 % due to narrow absorption region, whereas for MM-5 and MM-6 showed PCE of 19.88 % and 27.82 % respectively under 2500 lx illumination. Co-sensitized device with MM-6 and DCA yielded PCE of 28.95 % with  $303 \mu\text{Acm}^{-2}$ , 0.625 V and 0.7054 as  $J_{SC}$ ,  $V_{OC}$  and FF respectively under



**Fig. 11.** (a) Designed sensitizers for DSSC under ambient conditions. (b) Voltage vs current density spectra of P2 and P4 sensitizers and (c) IPCE profile with the  $[\text{Cu}(\text{dmp})_2]^{1+/2+}$  redox couple.

same illumination. Further, the co-sensitized MM-3 with MM-6 and this device showed PCE of about 30.45 %. Recently, Suraj and co-workers have reported two carbazole based sensitizers for DSSC namely YK 8 and YK 9 [71]. By using iodide/triiodide electrolyte under 1 Sun YK 8 and YK 9 showed PCE of 7.49 and 6.60 % respectively. They have studied device performance under various indoor light illuminations, in which under 1500 lx CFL illumination YK 8 showed 30.24 % PCE, whereas YK 9 showed highest PCE of 20.11 % PCE under 2000 lx CFL illumination.

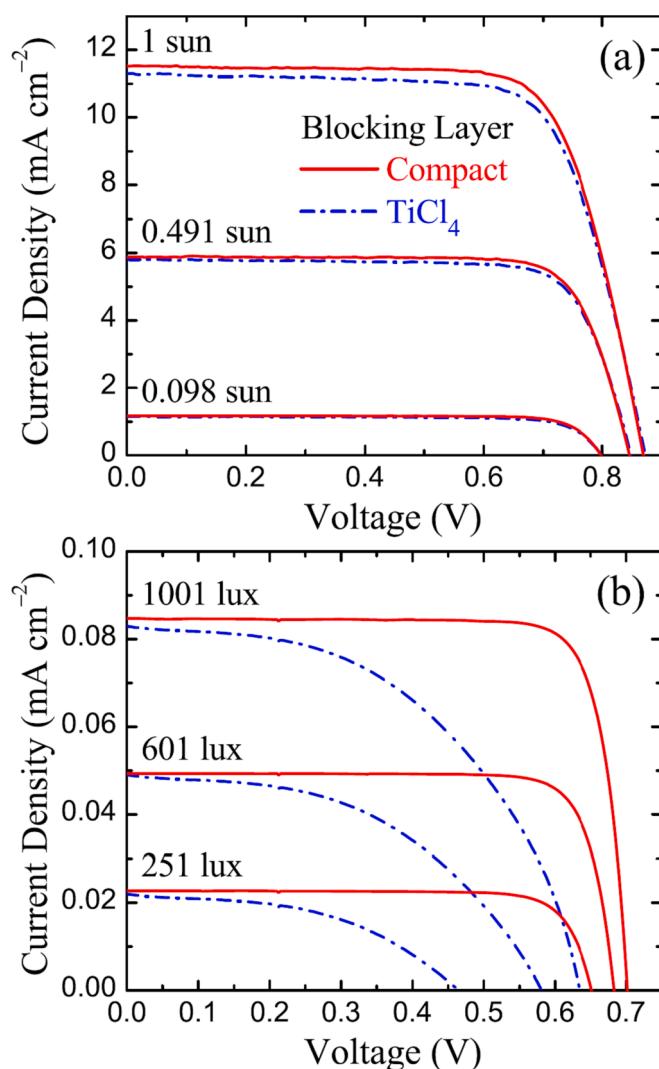
### 1.7. Electrolyte

Another important component of the device is redox couple in achieving high efficiency and durability of the device. The ingredients of a redox couple consists polar solvent and a soluble ion pair salt. Usage of the proper electrolyte in the DSSC widens the light absorption range to match the indoor light spectrum [57], Srivishnu et al. [177]. The electrolyte which is used in the DSSC under 1 Sun condition cannot be used for the devices under indoor environment as the indoor spectrum differs from solar spectrum [91,185]. Also when metal complex based redox couples such as Co(II/III), Cu(I/II) etc., mass transport and recombination problems exists when we go from test cell device to modules. Hence there is a need for specific design and synthesize the electrolytes suitable for indoor spectrum. Small molecular transition metal complexes with copper are widely used electrolytes for i-DSSC along with the few cobalt complexes. Recently, Giribabu and co-workers have used triphenylimidazole based sensitizers (LG-P1, LG-P2, LG-P3 and LG-P4) and compared their performance under 1000 lx using LED and CFL illumination with either Cu(I/II) or  $I^-/I_3^-$  redox couples and observed device efficiency of ~10 % (Fig. 11 [52–54]). Lan and group deliberated the influence of iodine on the PCEs of the indoor DSSC devices [101]. From the current-voltage performance and EIS results they showed that lower iodine content electrolyte exhibited superior PCEs at lower intensity light due to comparatively higher transparency and less electron recombination at the interface of photo-anode and electrolyte. Usage of liquid electrolyte always poses safety concerns. Hence the urge of solid state electrolyte is highly required and i-DSSC based solid state electrolytes have recently come to the light. Venkatesan et al. have fabricated a quasi solid-state DSSCs with the help of polymer gel electrolytes [185]. They found that the iodine concentration and the thickness  $TiO_2$  film had great impact on QS-DSSC. Upon optimization, QS-DSSC based devices obtained PCEs of 15.39 and 20.63 % under 200 and 600 lx illumination respectively. A sub module device active area  $11.21\text{ cm}^{-2}$  showed a relatively high PCE of 12.23 % under 200 lx conditions. Even after 1000 h QS-DSSC showed high stability and retained 97 % of its initial PCE. Using N719 and Z907 dyes, long term stability of QS-DSSC studies were studied and it showed that 95 % and 97 % of initial PCE was restored for N719 and Z907 based QS-DSSC devices respectively.

In another report by Suraj Soman and group reported the performance of copper redox shuttles under both indoor and standard conditions and they emphasized on mass transport in the electrolyte. They concluded that  $[Cu(tmby)_2]^{2+/1+}$  as best electrolyte for DSSC under both outdoor and indoor conditions compared to conventional iodide/triiodide or cobalt complexes. Even though metal complex is bulkier in nature authors suggest that it is limited by the mass transport. Since the regeneration of the dye ground state by  $Cu^I$  and the reaction of  $Cu^{II}$  at the counter electrode are comparatively faster processes, the efficiency of DSC involving  $Cu^I/Cu^{II}$  electrolytes under relatively high light intensities is largely governed by the diffusion of  $Cu^I/Cu^{II}$  species. They studied the devices with D35, XY1 and D35:XY1 dye based devices with the copper redox shuttle in both outdoor and indoor conditions [184].

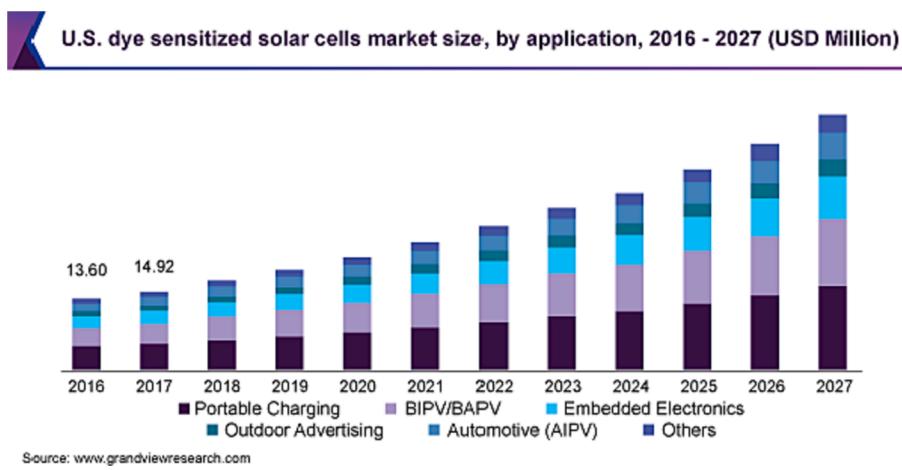
### 1.8. Device architecture

Currently the planar structure solar cells are primarily produced, in which problems like electrolyte leakage occurs, above that the



**Fig. 12.** MK-2 dye based device with Co electrolyte at different illumination conditions: (a) J-V curve under standard sunlight (b) J-V curves under T5 lighting conditions. (Liu et al., Copyright 2018 ACS Liu et al. [119].

performance of the device is dependent on the angle of the incident light Wu and Zhu [193]. In contrast to the planar structured DSSC, cylindrical DSSC (C-DSSC) have been introduced to overcome problems faced and they are relatively stable after being plugged with a copolymer called ethylene vinyl acetate [89]. It can cover any light falling onto it immaterial with incident angle to the electrical energy, which helps in the ease of solar cell installation. Kapil and co-workers first introduced the concept of cylindrical DSSC using ruthenium based N719 dye and D205, Y123 organic dyes as sensitizers [187,123,211]. Space can be used more effectively if the cells are installed in the cylindrical way. Under low light intensities of 1533 and 3333 lx, Ti-coil-based transparent conductive oxide-less C-DSSC performance was studied. To evaluate the device accomplishment a parabolic reflector was used to reflect the scattered light of fluorescent lamps during testing. C-DSSC could generate power only at the top surface under white light illumination and the bottom surface only to enhance the resistance of the solar cell in case of diffuse reflection. In case of crowded condition of an indoor environment cylindrical shape is desirable. Among the three C-DSSCs, J-V curve of N719 dye showed best performance. N719 based C-DSSC exhibited higher  $V_{oc}$  with 0.69 V compared to 0.62 V and 0.58 V of D205 and Y123 based C-DSSC at  $100\text{ mWcm}^{-2}$ . EIS measurements revealed that electron transfer resistance at the  $TiO_2$ /dye/electrolyte interface primarily causes the difference in the device reorganization.



**Fig. 13.** Market share of dye sensitized solar cells. (<https://www.grandviewresearch.com/industry-analysis/dye-sensitized-solar-cell-market>).

When compared to D205 and Y123 sensitizers N719 dye displayed lowest electron transfer resistance of  $72.11\ \Omega$  which might be another reason for higher  $V_{OC}$ . Cao and group prepared an advanced DSSC structure in which photoanode and photo cathode were directly connect without any spacer. EIS studies showed that when there is a direct contact between photoanode and counter electrode it can reduce the diffusion path of the electrolyte and results in decrease in Warburg resistance.

In DSSC to enhance the photovoltaic performance, blocking layers (BL) also plays a crucial role. It reduces the electron leakage and inhibit recombination pathways [153]. Liu et al. identified that for indoor lighting conditions traditionally used  $TiCl_4$  based BLs did not function well for hole blocking, so compact  $TiO_2$  BL was used as substitute to reduce electron leakage over a wide intensity range (Fig. 12) (Peng et al., 2018). This helps in achieving good performance under indoor conditions. Both devices with  $TiO_2$  and  $TiCl_4$  BLs showed similar performance under 1 Sun condition, whereas under 1000 lx environment  $TiO_2$  yielded PCE of 15.26 % and  $TiCl_4$  showed PCE of 8.56 %. It was seen in SEM images that surface with compact BL was more homogeneous than that of  $TiCl_4$ . Cyclic voltammetry results showed that compact BL has significantly better blocking function than of  $TiCl_4$ .

Zhai and group have reported ultra small and ultra fine quantum dots of  $TiO_2$  and they efficiently used  $TiO_2$  quantum dots as compact layer (CL) [212].  $TiO_2$ -QDs-CL based DSSC attained PCE of 18.3 % under 7000 lx intensity. Electron recombination was proficiently suppressed at the interface of electrolyte and FTO by  $TiO_2$ -QDs-CL which improves the photovoltaic performance. In another study by Wang et al., used Zn doped  $TiO_2$  film in the DSSC and they noticed increase in PCE to 23 % under low light intensity of 11 mW/cm<sup>2</sup> Wang and Teng [188]. Chen and group fabricated DSSC by using a blocking layer made of thin film of  $Nb_2O_5$  [23]. Under various intensities,  $Nb_2O_5$  thin film induced blocking layer effect on charge recombination was studied. From impedance analysis and open circuit voltage decay it was demonstrated that  $Nb_2O_5$  thin film can suppress the charge recombination on the photoanode effectively. They demonstrated PCE was increased from 10 % to 53 % when intensities were varied from 300 to 6000 lx.

Recently, Andrea Lamberti and group reported modified graphene based counter electrode device and tested under indoor conditions. Laser induced graphene (LIG) was used as counter electrode material which was integrated with a self powered storage system. Authors showed their LIG device outperformed Cu electrolyte based DSSC. Their flexible LIG device showed open circuit voltage of 0.94 V and PCE was found to be 4.96 %. [176].

Plasmonic Au nanoparticles embedded Ytterbium-doped titania nanocomposites photoanodes were employed in DSSC and were measured under indoor conditions by Sai Santosh Raavi and group. They

demonstrated efficient photoanodes incorporating gold (Au) nanoparticles embedded into ytterbium doped titania nanoparticles for IPV. This doping improved the electron hopping mechanism. This doped titania devices with Au nanoparticles exhibited PCE of 8 % under 1 Sun condition whereas under 1000 lx white LED it showed PCE of 13.9 %. [90].

Suraj Soman and group recently reported innovative  $TiO_2/ZnO$  bilayer architecture capable of delivering higher  $V_{OC}$  by carefully controlling the conduction band (CB) position and recombination losses. They have achieved record open circuit voltage of 1.27 V with MS5 dye and copper redox mediator under 1 Sun condition, 1.295 V under higher intensity white light. These bilayer devices also demonstrated impressive  $V_{OC}$  of 1.025 V under 1000 lx compact fluorescent light (CFL) and light emitting diode (LED) illumination and could autonomously power a temperature sensor using a single device of  $0.24\text{ cm}^2$  active area. [80].

In another report same group has modified the photoanode by surface texturing of  $TiO_2$ . To increase the light scattering  $ZnO$  microflowers were introduced into the  $TiO_2$  layer. Upon this modification light absorption was increased up to 13 and 85 % improvement in the PCE under 1 sun condition and indoor condition. Authors conducted detailed interfacial charge transfer studies in this work, by this modification this device led to semi-transparent and authors suggests these devices can be used as facades for building integrated photovoltaic applications. [167].

### 1.9. Challenges to overcome

Although DSSC is the go to technology in the future, it still has some drawbacks which need to be addressed before commercialization if it needs to reach to every door. Major concern lies in the cell stability and the efficiency. Even slight change in the chemical and physical properties will affect the long term stability [133]. Choosing proper electrolyte plays key role in terms of both stability and the efficiency. Other drawback is toxicity, since different layers are being used in the making of DSSC, each component may have different toxicity level. Especially the dye material used needs to be properly addressed, in case of Ru complexes they are toxic in nature, in QD sensitizers cadmium and lead are used both are chalcogenides and both have high toxic levels [187,123,211]. Generally organic dyes are non toxic in nature. Finally the manufacturing cost while making in the bulk scale is a concern, the materials and fabrication technique used matters a lot to economic viability.

### 1.10. Market perspective

The global market of DSSC was valued at USD 90.5 million in 2019 and it is likely to grow at CAGR of 12.4 % in the period from 2020 to

2027 (Fig. 13). [158] There are key companies which are ruling DSSC market like Dyesol Ltd, G24 innovation Ltd, Solaris Nanosciences Corporation, Solaronix, 3G Solar Photovoltaics Ltd etc. UK based GCell manufactures DSSC modules for Bluetooth keyboards, e-readers in the consumer electronics, washroom fragrance dispenser, smoke alarms, and other products which are used in retail sector. Solarprint is an Israel based company which makes indoor light based DSSCs which are useful in applications like in making sensors for thermosets and smoke detectors, in surveillance cameras, alarms, Internet of Things. Aisin Cosmos Company manufactures 4 cells module fabrication for indoor conditions. [159]

### 1.11. Perovskite solar cells

Perovskite Solar cells (PSC) is termed as the Emerging technology in the photovoltaics. Perovskite based solar cells have been attained tremendous interest in recent times as they are potential light harvesters [95,158,145]. Research interest among the researchers is growing as the steady increase in device efficiency is achieved very often. Perovskites are the one which have generalized formula of  $ABX_3$ , where A is an organic/inorganic cations like methylammonium $^+$ , formamidium $^+$ , Cs $^+$  and Rb $^+$  which is occupied at cubo-octahedral site, Divalent cation is occupied at octahedral B site like Sn $^{2+}$ , Pb $^{2+}$  and Ge $^{2+}$  and anions like halogens are filled at octahedral sites X i.e., Cl $^-$ , Br $^-$  and I $^-$ . This kind of molecules are highly rated owing to their excellent optoelectronic properties like tunable band-gap, high absorption coefficients, high charge carrier mobilities, long carrier diffusion lengths and low exciton binding energies. Initially perovskite was incorporated as sensitizer in the DSSC, later considered as the new efficient thin film light absorbers. Further many approaches were tied to deposit high quality of perovskite material later it emerged as solution based technology, and the next major task was to overcome its difficulties were its toxicity and stability Saliba et al. [165] (Rajeswari, R et al., 2017). But still the PSCs are in high demand and continuous efforts are being put in to address these challenges as they have peculiar properties like high external radiative efficiency, steep absorption edge, and high ratio of  $V_{OC}$  even theoretically predictable limit is attainable, its high voltage ratio is second highest among all other PV materials. Due to the inherent toxicity of the materials involved their commercialization has been held back, once the toxicity has been properly addressed PSCs are ready to make inroads for the commercialization and these materials have promising future if stability and safety factor is enhanced [82,94].

As per the reports of National Renewable Energy Laboratory, highest certified PCE of perovskite photovoltaics (PPV) is 25.5 % measured under AM1.5 condition by Ulsan National Institute of Science and Technology NREL [143]. Large PPV modules with area 802 cm $^2$  have achieved PCE of 16.9 % (Panasonic, Japan's NEDO and Panasonic Achieve the World's Highest Conversion Efficiency of 16.09 % for Largest-area Perovskite Cell Module, <https://news.panasonic.com/global/press/> (accessed: June 2021). Recently Utro Light have achieved record PCE of 20.5 % at 63.82 cm $^2$  cells and under indoor conditions PPVs have even achieved 40 % PCE [190]. Enabling novel materials incorporating into the PPVs, by a thriving passivation tactic has enabled to obtain PCE of 40.1 % for iPPV under 824 lx LED illumination and 38.2 % under 1000 lx LED light. In the recent past, flexible substrate PPVs under 1 Sun condition has achieved PCE of 19.5 % whereas under 400 lx illumination it achieved 22.6 % (He, X et al., 2021) [147,146,77,20].

To overcome the toxic nature of Pb in PPVs, hunt for Pb free PPV based materials are being explored and researchers have investigated Bismuthoxyiodide, Cs<sub>3</sub>Sb<sub>2</sub>I<sub>9</sub> and silver bismuth iodide as active layers materials but still research in this area is in the cradle stage [97]. Conventional Si PV processing is of 156 mm X 156 mm and this is compatible with Perovskite PV processing [4] (Lin et al., 2020). Keeping Si technology stability and high PCE, Si-PPV tandem cells are being closet to the commercialization. PPV/Si tandem technology was recently

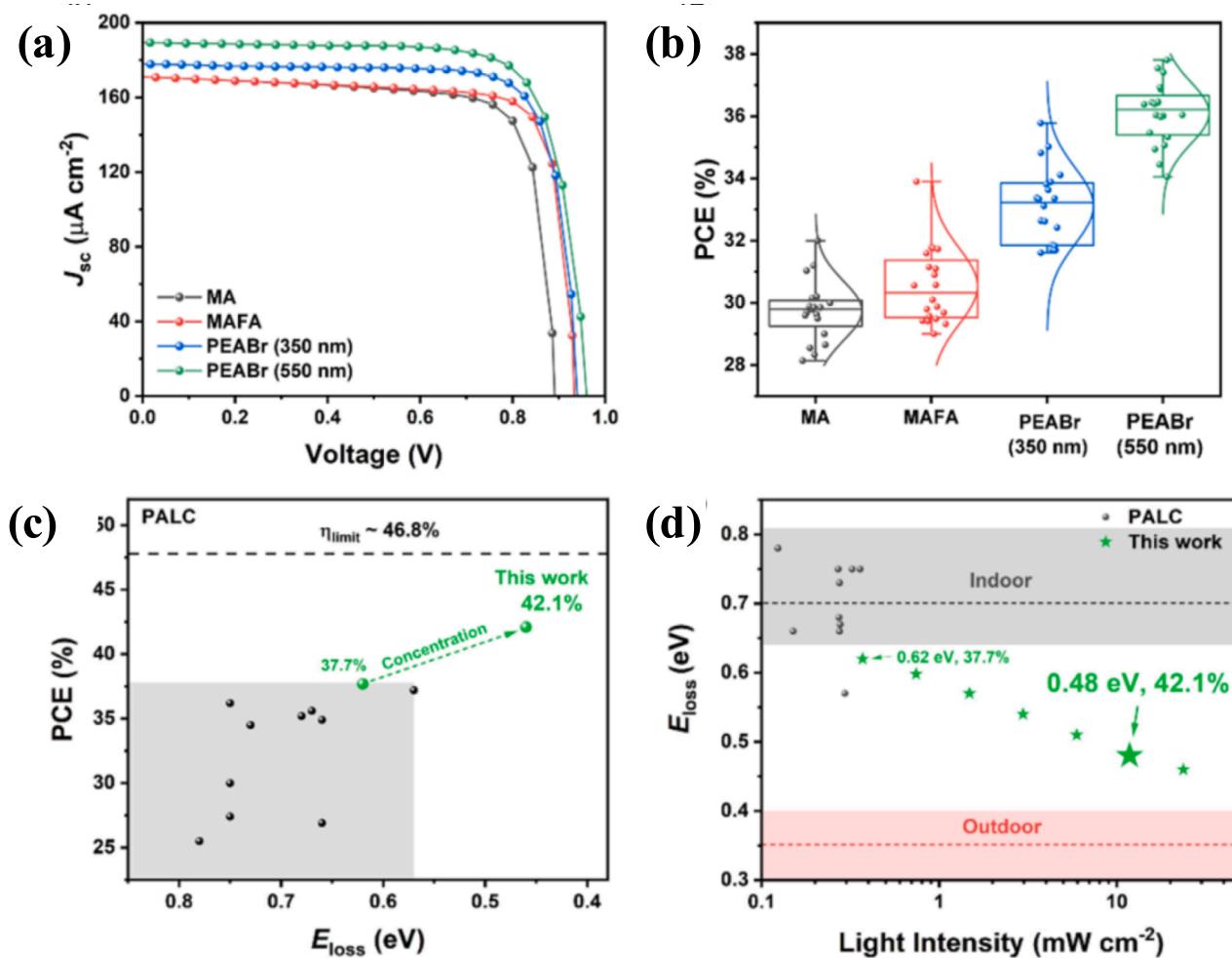
demonstrated by Oxford PV and Helmholtzzentrum of Berlin to show PCEs of 29.5 and 29.1 % respectively Oxford [149].

As we have seen in earlier sections also that in achieving high efficient PV device absorption spectrum of photoactive material should match the emission spectrum of the indoor source to the maximum extent. Similarly equal importance should be given to band-gap value of the material. Theoretically it has been calculated that the band-gap for an ideal light absorbers lie between 1.82 and 1.96 eV and illumination intensity ranging between 100 and 1000 lx and it is expected that PCE ranging in between 51 and 57 % [73] (Ding, Z et al., 2019).

### 1.12. Progress in high performing IPPV

Mainly the research is focused on tuning of doping and composition of light absorbing perovskite material. By tuning of perovskite materials the efficiency and the stability of the device has been increased owing to the change in physico-chemical and optoelectronic properties. Chou and group reported improved efficiency of Methylammonium Lead iodide (MAPbI<sub>3</sub>) perovskite by sequential doping of cesium Choi et al. [28]. Upon 10 % of Cs into MAPbI<sub>3</sub> doping they noticed around 40 % improvement in the efficiency and also increased the stability of the parent perovskite, it may be due to improved morphology, superior energetic alignment and good light absorption. Wu et al. have studied the effect of Br ion content within the mixed cation perovskite on the device performance [192]. When Br ion content increased they noticed widening in the band-gap of the perovskite film which is also accompanied by the steady blueshift in the absorption and photo luminance spectra. With 15 % Br content, under 1000 lx light intensity, device showed  $V_{OC}$  of 0.9 V and improved PCE of 26.4 % compared to the control devices in the absence of Br ion. On similar lines, Lim et al., tuned the parent perovskite MAPbI<sub>3</sub> by controlling the Br ion content in the stoichiometric ratios [115]. Improved morphology of perovskite films were observed at 10 % Br ion content with larger grain sizes and reduced non radiative recombination centers when compared to parent perovskite. This optimized perovskite showed PCE of 34.5 % under 1000 lx LED illumination. Singh and group studied the substitution of I $^-$  with Br $^-$  in MAPbI<sub>3</sub> [173]. Later in the study they concluded that for indoor applications pure crystalline phases of MAPbI<sub>3</sub> and MAPbBr<sub>3</sub> were more stable and efficient when compared to the pseudocubic MAPbIBr<sub>2</sub> and MAPbI<sub>2</sub>Br perovskite structure. Recently Sun and group achieved high PCE of 36.3 % and 33.2 % under white LED and FL illumination respectively by tuning the perovskite through cation and anion variation of Cs<sub>0.05</sub>MA<sub>0.95</sub>PbBr<sub>x</sub>I<sub>3-x</sub> along with the usage of Nb doped TiO<sub>2</sub> [26,179]. It could be concluded from these few results that proper tuning and engineering of perovskite layer has impacted the performance of the device under the indoor conditions. With the partial substitution devices showed better efficiencies but their stabilities were minimized due to halide segregation. Cheng and group came up with new methodology called triple halide approach to overcome the problem Cheng et al. [25]. By introducing the Cl anion they obtained band-gap of 1.8 eV with a low trap state density. This yielded an impressive efficiency of 36 % under FL lamp with 1000 lx intensity.

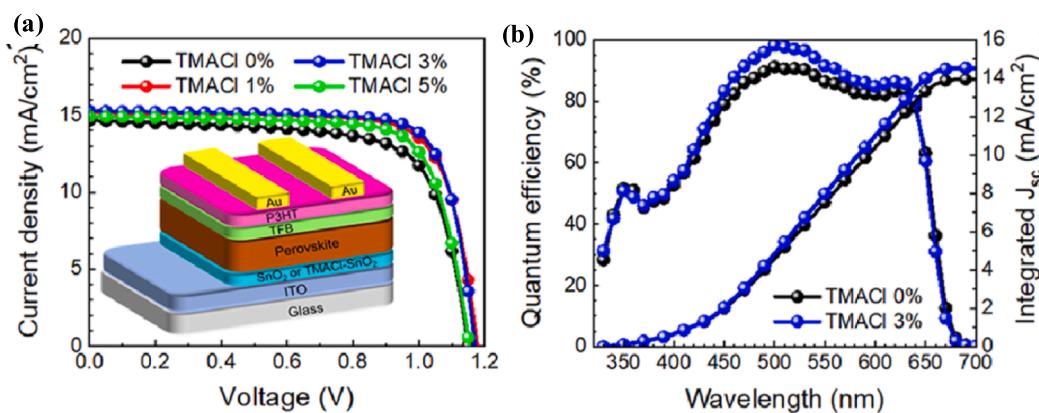
It has been well documented in literature to tune and modify the B site of the perovskite Pb to other cations for the indoor light applications. Yang et al. have used Sn cation in B site of the perovskite, to reduce the ratio of Sn $^{4+}$  in the Sn based perovskite [210]. They introduced an antioxidant called catechin which would suppress the Sn oxidation. A stable p-i-n device was obtained using Sn based perovskite which yielded 12.81 % PCE under 1000 lx illumination. Same group afterwards modified the HTL with nicotinamide to obtain the PCE of 14.4 % with Sn based perovskite [19]. HTL material and facilitate perovskite crystallization in Sn based perovskite device to achieve improved PCE of 17.57 % under 1060 lx illumination [18]. Peng and group replaced lead based perovskite with bismuth oxyiodide and cesium antimony chloride-iodide which has band-gap of 1.9 eV and achieved PCE of 4–5 % under FL and LED illuminations [154]. Cheng and



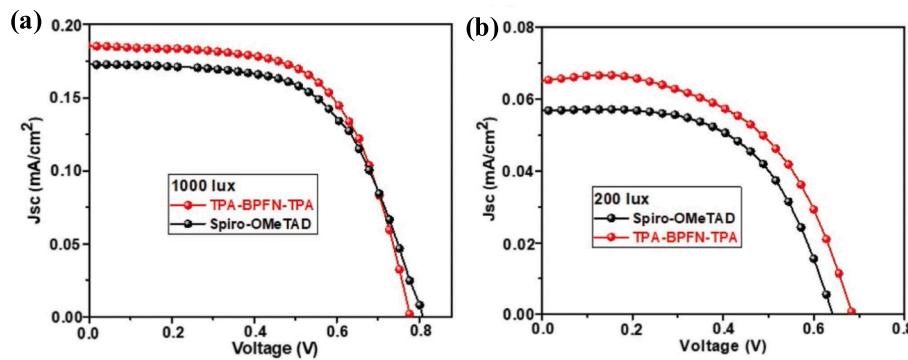
**Fig. 14.** (a) 1000 lx White LED intensity on PALCs based devices and corresponding J-V curves measured using different perovskite layers. (b) Optimized power conversion efficiency histograms of 20 PALC devices. (c) Represents  $E_{\text{loss}}$  vs PCE under 1000 lx illumination. (d) Comparative graph of light intensity vs  $E_{\text{loss}}$  of current work with previous literature. (Lee et al., Copyright 2022 Wiley-VCH).

group introduced air-knife crystallization method to enhance the performance of the device by controlling the morphology of the  $\text{MAPbI}_3$  perovskite layer [25]. High crystalline perovskite layer was obtained by this method with smooth micrometer sized grains and also reduced trap density. Under 1000 lx illumination they obtained PCE of 27 %. To facilitate the crystallization process Dong et al. have introduced  $\text{C}_2\text{O}_4^{2-}$  in the precursor solution, thus they obtained improved morphology of perovskite which yielded PCE of 34.86 % under 1000 lx intensity [43].

To maximize the extraction and collection of charges which are generated under indoor light, controlling the surface trap is essential. Lee and group introduced phenethylammonium iodide (PEAI) salt on top of the perovskite layer to solve the issues related to photo induced phase segregation and non radiative energy loss at the device interface to improve device efficiency (Lee et al., 2021). PEAI layer improved crystallinity and absorption of the perovskite film and showed better hole transport to HTL compared to the non-treated film. The device



**Fig. 15.** (a) Concentration dependant J-V curves of TMACl. (b) IPCE profile of TMACl at different concentrations. (Parida et al., Copyright 2021 ACS).



**Fig. 16.** TPA-BPFN-TPA and Spiro-OMeTAD HTMs based PSC device's J-V curves under (a) 1000 lux and (b) 200 lux illuminations. (Pham et al., Copyright 2020 Wiley-VCH).

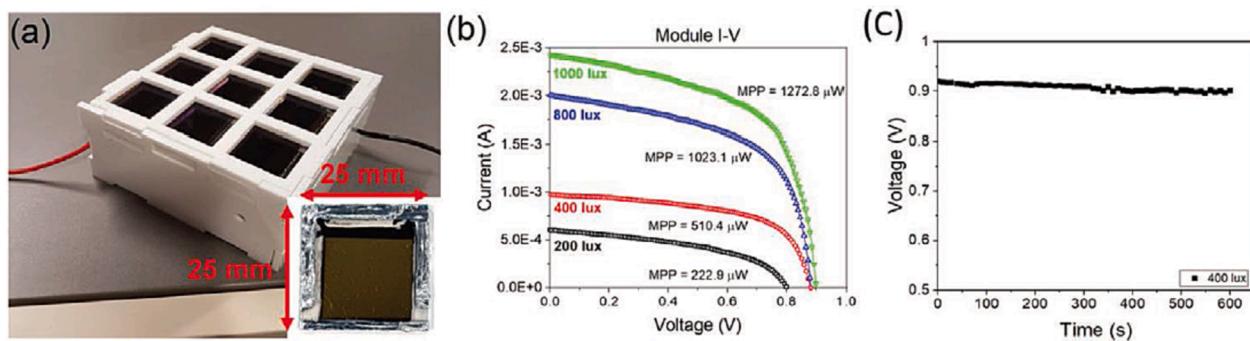
exhibited high  $V_{OC}$  of 0.9 V with an output power of  $18 \mu\text{Wcm}^{-2}$  under 200 lux white LED illumination. To reduce the trap state in thick perovskite film, Liu et al. have incorporated guanidinium and 2-(4-methoxyphenyl)ethylamine hydrobromide [72]. This method achieved a high PCE of 40.1 % under ambient conditions. Later Jea and group achieved much higher PCE of 42.1 % under LED light by comprehensive composition tuning; PEABr induced interfacial treatment and optimizing the active layer thickness (Fig. 14) [109,110]. Further Dong and group used lycopene as a surface modification layer on the perovskite films instead of PEAX derivatives and achieved highly stable and efficient indoor device with PCE of 40.24 % under 1000 lux LED illumination [44]. Along with that, surface of the  $\text{CsPbBr}_2\text{I}_2$  films were functionalized with  $(\text{NH}_4)_2\text{C}_2\text{O}_4\text{H}_2\text{O}$  to enhance the quality of perovskite film and to minimize the trap density for which they obtained PCE of 28.48 % under 1000 lux intensity [118]. In an another study, Xu et al. introduced inorganic bilayer to modify perovskite surface by inserting ultra-thin KF film between charge transport layers and the perovskite which helps in suppressing interfacial traps and minimizes ion migration [197]. This KF treated device showed high thermal and operational stability and achieved PCE of 35.7 % under 1000 lux LED. Au-nanoparticle decorated grapheme oxides were inserted by Lin and group between hole transport layer and perovskite layer to induce interfacial plasmonic effect [116]. Upon insertion it was observed that spectral matching was improved between artificial light emission and the absorption of the device, which led to the PCE of 21.1 % under 1000 lux condition compared to 19 % of simple perovskite.

Researchers have tried to modify the hole transport layer (HTL) and electron transport layer (ETL) to enhance the device performance of the PSC. Parida and group used tetramethylammonium chloride (TMACl) to passivate the oxygen vacancies on the  $\text{SnO}_2$  ETL for *n-i-p* i-PPVs (Fig. 15) [151]. Upon treatment with TMACl,  $\text{SnO}_2$  charge recombination was minimized which enhances the interfacial charge transfer and extraction in the device. With this passivated  $\text{SnO}_2$  ETL device efficiency was found to 28.68 % under 1000 lux illumination which also stabilizes the  $\text{CsPbI}_2\text{Br}$  from moisture and thermal stress. Further Bi and group doped  $\text{SnO}_2$  with  $\text{PbO}$  to enhance the transport property under indoor conditions, for which they observed raise in shunt resistance which helped to increase in  $V_{OC}$  and fill factor of the device hence obtaining the high efficiency of 34.2 % under white LED condition [16]. To enhance the stability and the performance of the device Dagar et al. exploited the binary ETL layer in the device [37]. Over  $\text{SnO}_2$  it formed a uniform bilayer ETL by inserting a thin  $\text{MgO}$  layer. This composition helped in reducing the interfacial recombination and enhanced the device stability. This device exhibited 26.9 % PCE under 400 lux LED illumination. Later reports suggests upon insertion of thin layer of  $\text{ZnO}$  between indium tin oxide and  $\text{SnO}_2$ , favoured band matching with suppressed trap assisted recombination at ETL-perovskite interface. Under 1000 lux white LED light the modified  $\text{ZnO}/\text{SnO}_2$  layer based device showed PCE of 37.2 % owing to efficient charge collection [141]. In addition, PCBM was also used as ETL layer

but efficiency of the device remained at ~ 25 % under 1000 lux light intensity [21,113,108].

Hole transport layer and anodal interface are also of equal important in the performance of the device for which researchers have focused to tune the HTL and anode interface. Pham et al. have developed small molecule in D-A-D fashion in which triphenylamine and biphenyl fumaronitrile as donor and acceptor respectively (Fig. 16) [155]. These materials have used as dopant free HTL for mesoporous i-PPVs. This material suggested enhancement in charge transfer dynamics and also the hydrophobic nature which resulted in a high PCE of 30 % under 1000 lux illumination. When compared to the benchmark spiro-OMeTAD it was noticed that improved device stability without encapsulation. Prasad and group used small molecules in the form acceptor-donor-acceptor (A-D-A), which are in V shape as hole transport materials (HTM) [157]. When dibenzothiophene was introduced as a core moiety and indole units were set up as substituent these materials were noticed to be optimized. The modified HTL showed high thermal stability and hole mobility that delivered 26.3 % PCE under 1800 lux LED light. Jea et al. have used polymeric HTL materials having interactive groups with the perovskite [146,147]. They tailored PEG side chain in a benzo[1,2-b:4,5-b']dithiophene based graft type polymer which showed PCE of 38.2 % under 1000 lux LED. In addition, they tried to infuse triphenylamine unit partially between polymeric HTL and the perovskite layer, this lowered the trap assisted recombination and further enhanced the performance of the indoor device (Lee et al., 2022). The device with triphenylamine substituted HTL displayed PCE of 26.7 % under the 1000 lux LED illumination whereas the control device without triphenylamine showed 17.6 %. Lee and group fabricated devices using three different HTLs PEDOT:PSS, poly triaryl amine and poly(4-butyltriphenylamine) to assess the influence of HTL materials on the photovoltaic performance *p-i-n* devices under indoor light conditions [105]. Out of these devices poly-TPD gave the highest power density of  $111 \mu\text{Wcm}^{-2}$  under 1000 lux illumination. Even under 200 lux conditions device noted  $19 \mu\text{Wcm}^{-2}$  power density. This enhanced performance is due to reduced leakage current when poly-TPD was chosen at HTL. NiO has played a predominant role in the context of inorganic HTL for *p-i-n* i-PPVs [79,175]. This is because of its facile synthesis and fabrication protocol which also reduces device hysteresis and leakage current.

Wu and group fabricated a large area device of area  $4 \text{ cm}^2$  by connecting two single junction cells, for which reported PCE of 17.35 % under 600 lux FL illumination with the power output of  $34.02 \mu\text{Wcm}^{-2}$  [192]. Li and group have up scaled the ionic liquid treated small scale device with an active area of  $4 \text{ cm}^2$  to achieve PCE of 23.16 % under 1000 lux illumination [113]. With the active layer of  $9.75 \text{ cm}^2$  Hin et al., devised a  $5 \times 5 \text{ cm}^2$  i-PPV using screen printing technique [105]. It contained stacked structure of mesoporous layers of  $\text{TiO}_2$ ,  $\text{ZrO}_2$  and a perovskite layer with carbon infiltration. The device obtained a maximum power output of  $70.1 \mu\text{Wcm}^{-2}$  under the 1000 lux condition with fill factor of 70 %. Lee and group designed a cell with  $20 \text{ cm}^2$  by



**Fig. 17.** (a) Image of module and cell with large area. (b) Module PV performance under indoor conditions (c) Output voltage measured with halogen lamp of 400 lx. (Lee et al., Copyright 2021 Wiley-VCH).

**Table 1**  
The device efficiency of few organic photovoltaic technology under low-light conditions.

S. No.	Polymer used	Light intensity	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA)	FF	η(%)	Reference
1.	PCDTBT: PC71BM	300 Lux LED	0.74	31.1	63.4	18.72	[203]
2.	PCDTBT: PC71BM	300 Lux LED	0.72	27.7	0.69	16.60	[104]
3.	PTB7: PC71BM	300Lux LED	0.61	28.6	0.69	14.60	[104].
4.	P3HT: ICBA	500 Lux FL	0.73	50	62	13.76	Singh et al., 2019
5.	1DTP-ID: PNP	200 Lux LED	0.67	24.6	67	19.3	Arai et al., 2016

connecting 4 cells in series and obtained maximum power levels of 223, 510, 1023 and 1273  $\mu\text{W}$  under halogen illuminations of 200, 400, 800 and 1000 lx illuminations respectively (Fig. 17) (Lee et al., 2021). By using roll to roll process Castro-Hermosa et al. examined a flexible device on an ultra thin flexible glass substrate [20]. These flexible devices have an importance in the portable electronics. The flexible glass substrate gave negligible sheet resistance, remarkable flexibility and high transparency. The flexible device has showed PCE of 20.6 % and 22.6 % efficiency under 200 and 400 lx illuminations. Lucarell and group have prepared flexible devices using compact and mesoporous TiO<sub>2</sub> groups for efficiently harvesting light and studied their performance [125]. They obtained efficiencies of 10.8 and 12.1 % under illuminations of 400 lx respectively when they had combined ETL of compact TiO<sub>2</sub> deposited using atomic layer deposition and mesoporous TiO<sub>2</sub>. Dagar and group reported a 12 cm<sup>2</sup> active layer fully laser patterned perovskite module [36]. To obtain high rectification ratio, low series resistance, and high shunt resistance, they introduced a SnO<sub>2</sub> and mesoporous TiO<sub>2</sub> bilayer ETL on polyethylene terephthalate/indium tin oxide substrate. Under 400 lx illumination 8.0 % PCE was delivered. Kim and group fabricated flexible device on polyethylene naphthalate substrate by involving an environmental friendly butyl acetate anti-solvent to obtain crystal of perovskite [93]. Large grained and pin hole free perovskites were obtained by using anti solvent which has minimal trap and improved charge carrier mobility. This flexible i-PPV achieved PCE of 23.33 % under 400 lx illumination with 0.063mWcm<sup>-2</sup> power density.

Antimony based perovskite inspired materials were recently reported by Paola Vivo and group, these materials show interesting optoelectronic properties, good intrinsic stability and low toxicity. Having bandgap of around 2 eV makes them more suitable for indoor photovoltaics. The first triple-cation Sb-based PIM (CsMAFA-Sb) in which the A-site of the A<sub>3</sub>Sb<sub>2</sub>X<sub>9</sub> structure consists of inorganic cesium alloyed with organic methylammonium (MA) and formamidinium (FA) cations is introduced. The external quantum efficiency peak of 77 % and the indoor power conversion efficiency of 6.4 % at 1000 lx are the highest

**Table 2**  
The device efficiency of few DSSC technology under low-light conditions.

S. No.	Dye used	Light intensity	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA)	FF	η(%)	Reference
1.	Y1A1	350 Lux LED	0.476	56.6	0.75	19.5 %	[124]
2.	YD2	6000 Lux FL	0.582	721	0.78	20 %	[162]
3.	SK7	6000 Lux LED	0.584	739	0.77	19.7 %	[162]
4.	MS + XY1B	1000 Lux LED	0.98	0.387	0.81	34.5	Zhang et al 2021
5.	XY1 + D35	1000 Lux FL	797	138	0.80	28.9	Freitag et al., 2018

values ever reported for pnictohalide-based photovoltaics [100].

### 1.13. Challenges

Overall, excitonic solar cells have showed better conversion efficiency overall, when compared to first two generation solar cells under low-light condition as shown in Table 1. Compatible to the indoor conditions, researchers should search for the electrodes and the top contacts. The stability of the device depends on the electrodes, electrical conductivity of the electrodes must be maximized and the toxicity of the materials used in the making of electrodes should be minimized [179,19,154]. In addition, more diversification required in ETL and HTL to improve charge transfer and stability. In few cases HTL free devices may be used in the longer run carbon electrodes which are processed at low temperatures should be researched [63] (Govind et al., 2020). Synthesis of photoactive materials i.e., should be tried to synthesized in the ambient conditions not in the glovebox environment. Optimum encapsulation approaches should be used to protect the final device from moisture. Under indoor conditions relatively humidity is much lesser compared to the outdoor environment, but still even minute moisture should not be neglected. There is a need for the emergence of novel recipes which have only environmentally friendly precursors and solvents. Usage of non-halogenated and green solvents along with lead free photoactive materials should be stressed as these things have not been explored to the full extent and they haven't reached to their full potential. Optimum encapsulation should be searched for to avoid the danger of Pb leakage. Many efforts need to put in achieving a lab to market transition, specifically upscaling challenges, eliminating the defects, surface should be super clean, tolerant materials should be properly chosen for the usage under ambient conditions. Output power density under ambient conditions need to be improved significantly under low, mid and high indoor intensities which can help in minimizing the final products dimensions. Stability studies of iPPVs should be thoroughly studied more to ensure they function even after partial shading, dark storage mechanical fatigue etc [145,160,97,44,105].

**Table 3**

The device efficiency of few PSC technology under low-light conditions.

S. No.	Perovskite used	Light intensity	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA)	FF	η(%)	Reference
1.	Cs0.05MA0.95 PbBrxI3-x	1000 Lux LED	0.99	403	80	36.3	[179]
2.	FAPbI3(0.97 (MAPbBr3)0.03	1000 Lux LED	1.0	152	79.5	40.01	[72]
3.	MA0.91FA0.09PbI0.96Br0.94	(1000*32)Lux LED	1.10	5810	77.8	42.1	Lee et al., 2022
4.	FA0.88MA0.12)0.95PbI3	1000 Lux LED	0.93	148	75.7	35.7	[197]
5.	MAPbI2-XBrx (10 % Br)	1000 Lux LED	0.82	170.8	68.8	34.5	[173]

**Table 4**

The device efficiency of various photovoltaic technologies under low-light conditions.

S. No.	PV type	Light intensity	V <sub>oc</sub> (V)	J <sub>sc</sub> (mA)	FF	η(%)	Reference
1.	a-Si	500 Lux LED	—	—	—	9.60	Cui et al., 2019
2.	a-Si:H	1000 Lux LED	0.61	0.113	0.68	~21	a
3.	c-Si	1000 Lux LED	0.40	0.138	0.35	5.6	a
4.	mc-Si	1000 Lux LED	0.30	0.119	0.35	3.7	a
5.	Ga-As	580 Lux LED	—	—	—	19	[19]
6.	Al <sub>0.2</sub> Ga <sub>0.8</sub> As	1000 Lux LED	—	—	—	21	[39]
7.	InGaP	867 Lux LED	0.98	0.491	0.80	30.3	[40]
8.	OSC	1650 Lux LED	0.84	0.245	0.76	30.8	[127]
9.	DSSC	1000 Lux FL	0.98	0.387	0.81	34.4	[130]
10.	PSC	1000 Lux LED	1.10	5.810	0.77	42.1	[189]

<sup>a</sup>Reich, N. V.; Van Sark, W. G.; J. H. M.; Turkenburg, W. C. (2011). Charge yield potential of indoor-operated solar cells incorporated into Product Integrated Photovoltaic (PIPV). *Renewable Energy* 2011, 36, 642–647.

## Tables 2-4.

### 1.14. Market perspective

It believes that perovskite solar module to be economically viable due to its abundant inexpensive starting materials and processes which will allow being the leader in the future of PV market. When compared to Si PV it is expected that perovskite PV to cost one third of Si PV [137,201]. If the perovskite module exceeds the efficiency and lifetime of 12 % and 15 years levelized cost of electricity (LCOE) of perovskite solar module will be of  $0.06\$/kWh^{-1}$  which is comparable with LCOE of fossil fuels [85]. Currently it is projected that the manufacturing cost for perovskite module if of  $100\$m^{-2}$  [75]. Upon increasing the production, new set of challenges arises like availability of materials, sustainability and recycling. Currently the usage of Ag in the manufacturing ranges for 15–20 metric tons per produced GW. In future if TW scale is produced by 2030 total global Ag production will be surpassed. Hence there is a need to replace Ag with any other material which can be used in long run [68]. It is expected that perovskite solar modules assembled in factory with sizes ranging between  $0.3\text{ MW year}^{-1}$  and  $1\text{ GW year}^{-1}$  to cost between  $3.30$  and  $0.53\text{ \$ W}^{-1}$ . By manufacturing the tandem cells it may help in reducing the manufacturing cost, like Si-PPV tandem cells which gives high PCE of up to 29 % [131]. With this there is a scope in the market to for new entrants to commercialize there goods with these emerging market including IoT, BIPV vehicle integration, telecommunication and others rather than competing with higher cost of current existing PV market.

## 2. Conclusions

We have performed a detailed review in the developments of the various generations of solar cells under ambient conditions. Despite the fact that inorganic solar cell technology is most commercialized technology for the grid connectivity and for outdoor applications, it's found that not much of its applicability is found in applications for ambient conditions due to the spectral mismatch and low bandgap energy. Whereas the materials used in others technologies like OSCs, DSSCs and PSCs are found to be having unique properties like better spectra matching, high band gap energy which can be tuned further, good thermal and mechanical stability which acts as promising candidates in

indoor light conditions. In all recent technologies there are number of reports in which they have fabricated and tested devices for indoor conditions. There is a noteworthy improvement in the both PCE and stability of the devices tested in the early days of the indoor light to the current day research. Although they have shown satisfactory results in small scale levels, there are still few issues to be addressed to perform in large scale and for getting commercialized. In case of DSSC it has already been commercialized but still results are inadequate and further exhaustive studies are necessary their acceptance in the market. Durability is another factor need to be addressed where Si-cells retain almost 80 % of initial PCE even after 10 years of the fabrication of the device. Such long term durability is required from these indoor devices to run these IoT based devices. Usage of the biocompatibility materials should be focussed to replace the hazardous currently used semiconductors. Still there is a scope for optimizing the open circuit voltage, short circuit current density and fill factors in all the technologies. This systematic review provides the current status of the indoor photovoltaics and challenges to solve for commercialization in future.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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