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Fluorinated Fullerene Derivatives for Tin Halide Perovskite Solar Cells With Reduced Carrier Transport Losses

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ABSTRACT

Tin halide perovskite solar cells (Sn-PSCs) are promising alternatives to their lead-based counterparts. However, their performance remains limited by high non-radiative recombination at interfaces, which compromises charge extraction and ultimately leads to poor charge transport and fill factor (FF) losses. Herein, we present the synthesis and application of two novel fluorinated C₇₀-based fulleropyrrolidines as precursor additives in Sn-PSCs. Due to their dual functionality, the fluorinated moieties effectively passivate structural defects, reducing trap states and reducing non-radiative recombination. On its part, the C₇₀ cage provides high electron affinity, which facilitates charge transport across perovskite and improves charge extraction at the perovskite/ETL interface. These effects lead to a significant enhancement in the average FF, from 64 to 72%, directly increasing the PCE of champion devices from 11.7% for reference devices up to 12.7% for devices with C₇₀ additives. Moreover, C₇₀-modified devices also exhibited a prolonged shelf stability, retaining up to 97% of their initial efficiency after more than 350 h of storage. Overall, this work demonstrates that C₇₀ derivatives can be employed as effective additives in Sn-PSCs to mitigate charge transport losses and boost FF, providing a reliable strategy to enhance performance in Pb-free optoelectronics.

1 | Introduction

Lead-based halide perovskite solar cells (Pb-PSCs) have rapidly emerged as promising candidates to dominate the photovoltaic market, with power conversion efficiencies (PCEs) increasing from 3.8% in 2009 to the current record of 27.4% [1–4]. However, the presence of Pb may hamper their commercialization as Pb is classified as a toxic element whose use has been

progressively restricted in many compounds over the last decades [5, 6]. These concerns have motivated the search for safer materials, stimulating the development of tin-based perovskite solar cells (Sn-PSCs). Sn-PSCs have demonstrated remarkable optical and electrical properties similar to or even better than those of their Pb-based counterparts [7–11]. In fact, state-of-the-art Sn-PSCs have already achieved PCEs above 17% [12, 13] and operational stabilities comparable to those of Pb-PSCs, exceeding

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1300 h of operation at the maximum power point (MPP) [14]. However, there are still some important challenges that must be addressed in order to unlock their whole potential [15].

The main drawbacks associated with Sn-PSCs can be summarized as follows: (i) the easy oxidation of Sn^{2+} to Sn^{4+} induces self-p-doping and makes them highly sensitive materials, which compromises device stability and slows down the progress in the field [16–18]; (ii) the fast reaction kinetics between perovskite precursors often lead to low-quality perovskite films [12, 19]; and (iii) the high non-radiative recombination losses in both the bulk and at the interfaces with charge-selective contacts seriously limit the overall device performance [13, 20, 21]. During the first years of development of the field, early studies were mainly focused on addressing the first two issues by using reducing agents [14, 22, 23] and crystallization regulators [24–27]. More recently, the interest has progressively shifted towards interface engineering approaches, emphasizing the design of effective interlayers and alternative transport layers to mitigate interfacial charge losses [13, 28, 29]. Although all these strategies have proven to be highly effective and achieved significant advancements in the field, most studies have mainly focused on maximizing V_{OC} and J_{SC} , while the low fill factor (FF) remains a critical limitation of Sn-PSCs that has received less attention. Indeed, FF is a particularly important parameter for Sn-PSCs as resistive and interfacial losses become more prominent in large-area or multi-junction devices, which are necessary to achieve commercial Pb-free PSCs [30, 31].

In Sn-PSCs, FF losses mainly come from inefficient charge extraction processes and parasitic current leakage that occur through shunt pathways. These loss mechanisms can be described as series and shunt resistance, respectively. Specifically, shunt resistance refers to leakage charge transport pathways that bypass the solar cell diode, mainly through electrical shorting. In contrast, series resistance reflects the overall conductivity of the device, including bulk resistances in the active layer as well as interfacial contact resistances [32, 33]. Importantly, series resistance is highly affected by charge accumulation and recombination losses at interfaces, which usually originate from mismatched energy-level alignments and interfacial defects [34].

In this context, precursor additive engineering has proven to be an effective approach to maximize FF by reducing self-p-doping, passivating structural defects, and improving interfacial charge transport [35–38]. Within the different types of additives, fullerene derivatives have attracted considerable attention due to their strong electron-accepting character and their ability to passivate charged defects in Sn-based perovskites [39, 40]. To date, most studies using fullerenes have focused on C_{60} -based materials, which have been successfully utilized not only as additives but also as interlayers or electron transport layers (ETLs). In contrast, the employment of C_{70} allotropes remains largely unexplored, even despite their higher electron affinity, which could be strategically exploited to improve electron extraction [41–43]. This preference for C_{60} derivatives originates from the difficulty of synthesizing isomerically pure C_{70} analogs and the consequent challenges of forming highly ordered films, which are essential for efficient charge extraction at the interfaces [44–49]. Nevertheless, C_{70} derivatives can still be highly effective when incorporated within the perovskite layer, where strict structural

ordering is not required and their favorable properties can be exploited.

Given their underexplored potential, in this work, we synthesized and introduced two different fluorinated C_{70} derivatives, namely, **JM14** and **JM15**, as additives into the perovskite precursor solution and evaluated their impact. By electronically compensating charged structural defects, **JM14** and **JM15** enhance charge extraction across the perovskite, ultimately improving both the FF and the stability of Sn-PSCs. A systematic optical and electrical characterization was performed to assess their influence on film quality, defect passivation, and device performance, providing insight into their role as functional additives for high-efficiency Pb-free perovskite solar cells.

2 | Results and Discussion

In this work, we designed and synthesized two novel [70]fulleropyrrolidines, **JM14** and **JM15**, functionalized with different fluorinated moieties through a 1,3-dipolar cycloaddition reaction. Specifically, **JM14** incorporates a pentafluorophenyl unit, and **JM15** presents a 3,5-bis(trifluoromethyl)phenyl group. The synthetic route is shown in Scheme S1, and Figure 1a presents their molecular structures, which were confirmed through nuclear magnetic resonance (^1H NMR, ^{13}C NMR, and ^{19}F NMR) and mass spectrometry (MS); see Figures S1–S8. It is important to mention that, as commonly observed for C_{70} derivatives, the synthesis yielded a mixture of regioisomers with different NMR patterns [44]. However, this isomeric mixture is not expected to critically affect their performance as additives, as they are anticipated to locate mainly at grain boundaries where regioisomeric purity is not critical [39, 50, 51].

We incorporated both **JM14** and **JM15** as additives within the Sn-based perovskite precursor solution; see Supporting Information (SI) for further details. For clarity, Sn-based perovskite films or devices containing **JM14** and **JM15** will henceforth be referred to as **Sn-JM14** and **Sn-JM15**, respectively. To evaluate the impact of the fullerene additives on the perovskite film quality, we performed top-view scanning electron microscopy (SEM) imaging and X-ray diffraction (XRD) measurements, as shown in Figures S9 and S10, respectively. The SEM images reveal uniform, pinhole-free morphologies for all samples, indicating that the additives do not induce significant changes in the crystallization process. The XRD patterns exhibit the characteristic peaks of the standard Sn-based perovskite patterns at $2\theta = 13.38^\circ$, 23.80° , 27.61° , 31.06° , and 39.84° , which correspond to the (100), (120), (200), (211), and (300) crystallographic planes, respectively (orthorhombic system, *Amm*2 space group). No noticeable peak shifts or changes in the full width at half-maximum (FWHM) are observed in the samples with **JM14** and **JM15**, suggesting that the fullerenes do not disrupt the perovskite lattice and are likely to be located at the grain boundaries instead, as reported in the literature for other molecular species [52, 53]. Grain boundaries are well-known as defect-rich regions where non-radiative recombination channels are predominant and lead to performance losses in the final PSCs [54, 55]. In this regard, this fullerene distribution within the film favors an effective defect passivation.

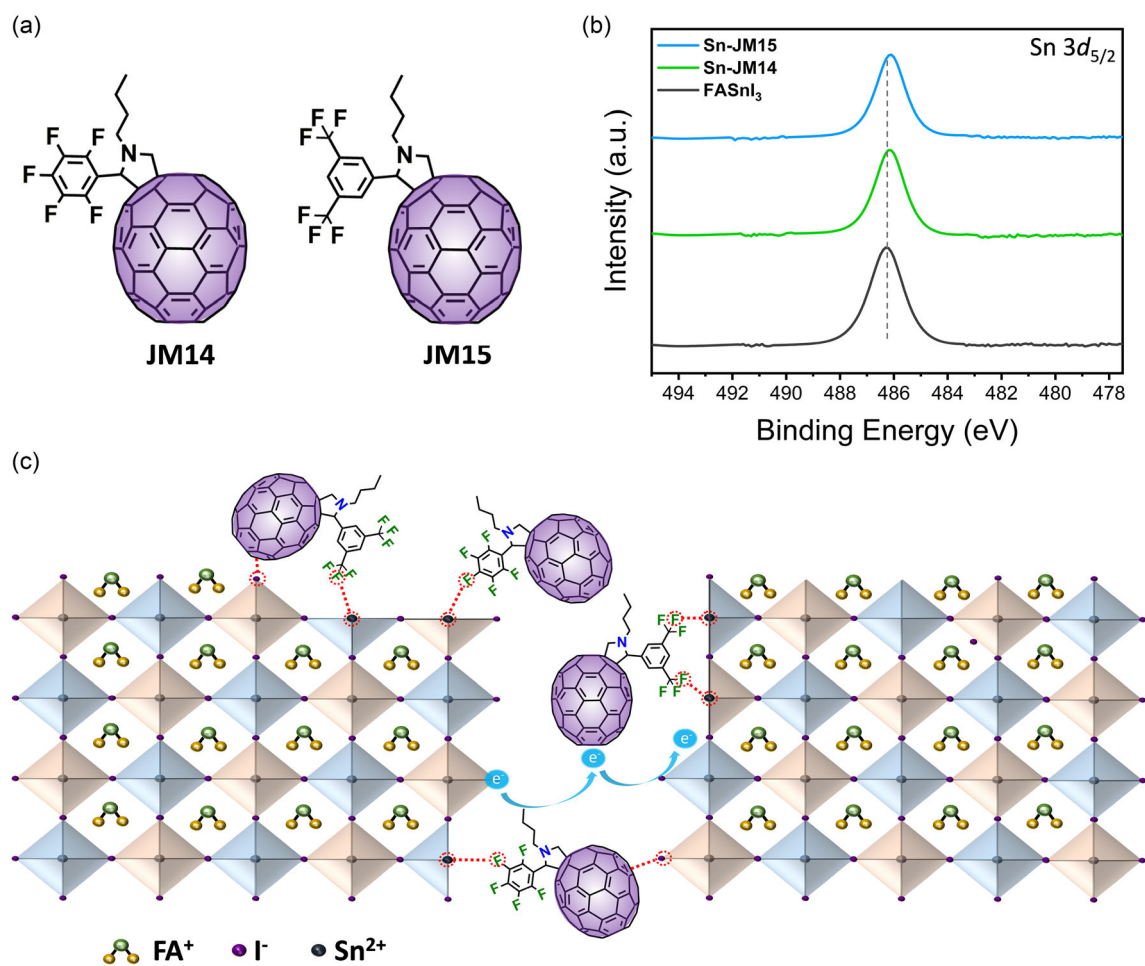


FIGURE 1 | (a) Molecular structures of **JM14** and **JM15**. (b) X-ray photoelectron spectroscopy spectra of the Sn 3d_{5/2} core level for perovskite films with and without **JM14** and **JM15**. (c) Schematic representation of the effect of fullerene derivatives on perovskite films, including the chemical interaction with structural defects and the enhanced charge transport across the film.

To gain some insights into the possible passivation effect, we performed X-ray photoelectron spectroscopy (XPS) measurements. Figure 1b shows the Sn 3d_{5/2} core-level spectra of FASnI₃, **Sn-JM14**, and **Sn-JM15** films, where clear differences in binding energy can be observed among samples. Specifically, the control film presents an Sn 3d_{5/2} binding energy of 486.30 eV, while **Sn-JM14** and **Sn-JM15** exhibit shifts of ~0.10 and ~0.15 eV toward lower binding energies, respectively. Such shifts reflect changes in the local chemical environments, where lower binding energies indicate increased electron density around the Sn nucleus. In our previous work, we demonstrated that electron-rich fluorinated moieties in fulleropyrrolidines can donate electronic density to compensate for the electron-deficient Sn sites [56]. Therefore, the observed downfield shift is likely associated with electronic compensation between the fluorinated moieties and uncoordinated Sn sites, as illustrated in Figure 1c [56]. Furthermore, Figure S11 shows the full high-resolution Sn 3d XPS spectra for all the samples, where Sn 3d_{5/2} and 3d_{3/2} are deconvoluted into the Sn²⁺ and Sn⁴⁺ components, and Table S1 summarizes Sn atomic concentrations and Sn²⁺/Sn⁴⁺ ratios, showing a clear trend, where **Sn-JM15** exhibits the highest Sn²⁺/Sn⁴⁺ ratio, consistent with an efficient defect passivation that retards the formation of Sn⁴⁺ species. In addition to the Sn-based passivation effect, we analyzed the I 4d core level.

As shown in Figure S12, upon incorporation of **JM15**, the I 4d_{5/2} peak exhibits a shift of ~0.1 eV toward higher binding energies compared to those of the pristine film, indicating a decrease in the electronic density around this nucleus. The observed chemical shift is consistent with an additional interaction between **JM15** and I⁻, complementary to the Sn-based passivation discussed above.

To further support the proposed interaction mechanism, we performed additional Fourier transform infrared (FTIR) spectroscopy of the perovskite films containing the champion additive, that is, **JM15**. As shown in Figure S13, the best-resolved C—F stretching band, located at the fingerprint region at ~1130 cm⁻¹ [57], shows a shift toward lower wavenumbers, consistent with a weakening of the C—F bond resulting from an electronic donation from the fluorinated moiety to Sn²⁺ sites. Altogether, these FTIR experiments and the existing XPS results presented in Figures 1b and S12 (Sn 3d_{5/2} and I 4d_{5/2}, respectively) comprehensively demonstrate the atomic-scale interactions between the fullerene additives and the FASnI₃ perovskite.

Since the performance of Sn-PSCs is strongly influenced by film quality, we systematically investigated the impact of **JM14** and **JM15** on the optical and electronic properties of the perovskite

films. Figure 2a shows the ultraviolet–visible absorption (UV–Vis) absorption spectra of FASnI₃, **Sn-JM14**, and **Sn-JM15** films. The UV–Vis absorption spectra of **JM14** and **JM15** in chlorobenzene are plotted in Figure S14. Both **JM14** and **JM15** show the typical absorption spectrum of C₇₀ derivatives in the visible region, coinciding with the FASnI₃ perovskite absorption spectrum. Nevertheless, all the films display the characteristic absorption profile of typical Sn-based perovskites as the absorption from the additives can be neglected due to the small amount added. Samples containing **JM14** and **JM15** show an overall increase in absorption intensity compared to the control sample, with **JM15** showing the most pronounced enhancement. This enhancement can be attributed to improved film quality, which reduces optical losses. Moreover, the optical band gap (BG) of the films is estimated from the absorption onset in the UV–Vis spectra and summarized in Table S2. We also assessed the effect of the fullerenes on the electronic structure of the perovskite films using photoelectron yield spectroscopy (PYS), as shown in Figure S15. The addition of **JM14** and **JM15** results in a valence band maximum (VBM) shift toward deeper energies, indicating a modification of the energy band alignment. In this regard, the VBM values are determined to be -5.25 eV, -5.28 and -5.30 eV for FASnI₃, **Sn-JM14**, and **Sn-JM15** films, respectively. By combining these values with the optical bandgaps, we determined the conduction band maximum (CBM) for each film; see Table S2. As shown in Figure 2b, fullerene-containing films exhibit deeper CBMs than the control film, improving the band alignment with the C₆₀ ETL, which is essential for efficient charge extraction at the perovskite/ETL interface.

Beyond this interfacial effect, fullerene derivatives can also facilitate charge transport across the perovskite layer. We estimated the lowest unoccupied molecular orbital (LUMO) energy levels of the sole **JM14** and **JM15** molecules by cyclic voltammetry (CV), see Figure S16, and obtained values of -3.97 and -3.98 eV, respectively. These LUMO energies are lower than the CBM of the FASnI₃ perovskite, thereby indicating a thermodynamically favorable electron transfer from the perovskite to the C₇₀ cages across the grain boundaries, as proposed schematically in Figure 1c. In fact, Gharibzadeh et al. demonstrated that C₇₀ molecules infiltrated at Pb perovskite grain boundaries can accept photogenerated electrons from the perovskite [58]. Interestingly, they observed that these electrons are not deeply trapped by the C₇₀ cage and can instead be reinjected into the perovskite, which is consistent with the FF improvement reported in their PSCs. Therefore, beyond their passivation ability, the intrinsically high conductivity of C₇₀ fullerene derivatives can facilitate charge transport both at the perovskite/ETL interface and across grain boundaries, reducing non-radiative recombination pathways.

To further investigate the effect of the additives on the optical properties of the Sn-perovskite, we also measured steady-state photoluminescence (PL) and time-resolved PL spectroscopy (TRPL). The PL spectra are shown in Figure 2c, and no significant PL shift is noticed among the samples. However, a clear increase in PL intensity is observed upon the addition of both fullerenes on perovskite samples prepared on glass substrates. This enhancement can be attributed to a reduction in

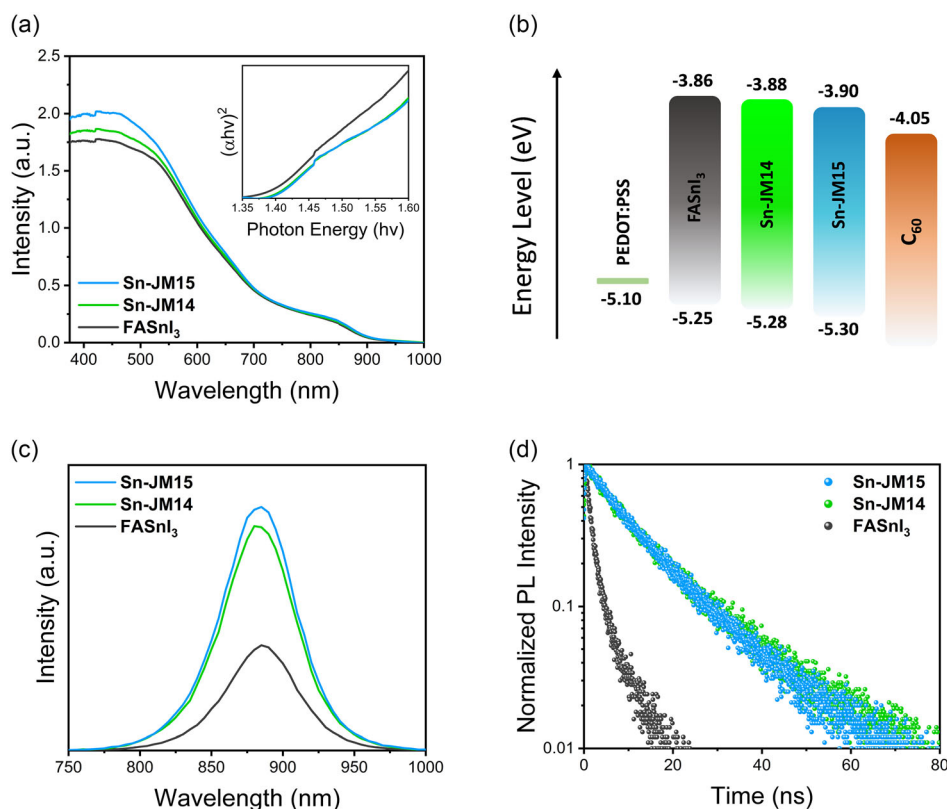


FIGURE 2 | Optical characterization of FASnI₃ films deposited on glass and prepared with or without **JM14** and **JM15**. (a) UV–vis absorption spectra of FASnI₃ films with and without additives; the inset includes the corresponding Tauc plots. (b) Energy level diagram extracted from the optical and spectroscopic measurements. (c) Steady-state PL spectra and (d) time-resolved PL decays of FASnI₃ films with and without additives.

non-radiative recombination channels. More specifically, since fullerene derivatives are most likely located at grain boundaries and on the surface, they are expected to passivate charged defects and suppress trap-assisted recombination. These findings are consistent with the electronic charge compensation observed by XPS, as shown in Figure 1b. Furthermore, TRPL measurements are presented in Figure 2d, and the average lifetime, τ_{ave} , is calculated through biexponential fittings, where τ_1 and τ_2 correspond to the fast and slow decay components, respectively. All fitting parameters are summarized in Table S3. Thus, the FASnI₃ film exhibits a τ_{ave} of 3.56 ns, which is elongated to 14.59 and 13.53 ns for **Sn-JM14** and **Sn-JM15** films, respectively. In Sn-based perovskites, trap states located at grain boundaries and interfaces often act as dominant non-radiative channels, so such an enhancement in the lifetime decay is consistent with the aforementioned suppression of trap-assisted recombination centers [59, 60]. To further quantify the trap-state densities (N_t), we performed space-charge-limited current (SCLC) using hole-only devices with the structure FTO/PEDOT:PSS/FASnI₃/PTAA/Ag under dark conditions; see Figure S17. The trap-filled limit voltages (V_{TFL}) are estimated to be 0.34, 0.30, and 0.26 V for control, **Sn-JM14**, and **Sn-JM15**-containing devices, respectively, which in turn correspond to the calculated N_t of 1.47×10^{16} , 1.28×10^{16} , and 1.11×10^{16} , respectively. This systematic reduction in N_t suggests that **JM14** and **JM15** are effectively passivating electronic traps at the grain boundaries and interfaces, which is in good agreement with the PL and XPS analyses.

With the aim of validating the potential of our approach, we fabricated inverted p-i-n solar cells using the following architecture: FTO/PEDOT:PSS/FASnI₃/PCBM:P3HT:ICBA/C₆₀/BCP/Ag; see SI for further details. Figure 3a shows the schematic representation of typical Sn-PSCs employed in this work, and further details on the preparation methods are described in the SI. Figure 3b shows the statistical distribution of the key photovoltaic parameters, including short-circuit current (J_{SC}), open-circuit voltage

(V_{OC}), FF, and PCE. The optimal concentrations of **JM14** and **JM15** were determined through a systematic optimization process as shown in Figure S18. The J - V curves of the champion devices are shown in Figure 3c, and the control devices achieved a maximum PCE of 11.3%, with a corresponding J_{SC} of $24.01 \text{ mA} \cdot \text{cm}^{-2}$, a V_{OC} of 0.73 V, and an FF of 67%. In contrast, devices treated with **JM14** and **JM15** exhibited improved PCE values of 12.0% and 12.7%, respectively, with J_{SC} values of 24.03 and $24.25 \text{ mA} \cdot \text{cm}^{-2}$, V_{OC} values of 0.73 and 0.72 V, and FFs of 69% and 72%, respectively. Figure S19 shows the incident photon-to-current conversion efficiency (IPCE) spectra for the different compositions. All devices display similar spectral shapes, and the integrated current densities calculated from the IPCE spectra are 23.72, 23.58, and $23.23 \text{ mA} \cdot \text{cm}^{-2}$ for FASnI₃, **Sn-JM14**, and **Sn-JM15** devices, respectively. While the J_{SC} and V_{OC} remain almost unchanged upon the addition of **JM14** and **JM15**, a clear enhancement in FF is observed, as shown in Figure 3b. FF in Sn-PSCs is typically dominated by charge extraction and parasitic current leakages, which can be determined by series, R_s , and shunt resistances, R_{sh} , respectively [61, 62]. In this regard, the statistical distribution of R_s and R_{sh} is shown in Figure S20. Control devices display an average R_s of $5.05 \Omega \cdot \text{cm}^2$ and an R_{sh} of $44.31 \Omega \cdot \text{cm}^2$. In contrast, **Sn-JM14** and **Sn-JM15** devices show an average R_s of 4.45 and $4.02 \Omega \cdot \text{cm}^2$, respectively, and R_{sh} of 74.74 and $94.48 \Omega \cdot \text{cm}^2$, respectively. The observed decrease in R_s can be attributed to enhanced charge transport within the perovskite or at the perovskite/ETL interface. In contrast, the increase in R_{sh} is likely associated with a reduction in leakage current, a well-known recombination mechanism in PSCs [63]. These observations suggest that the implementation of **JM14** and **JM15** additives effectively improves the overall device performance by facilitating charge extraction and suppressing leakage pathways, leading to higher FFs and enhanced PCEs.

To further understand the origin of the FF enhancement in our devices and the differences among **JM14** and **JM15**, we also

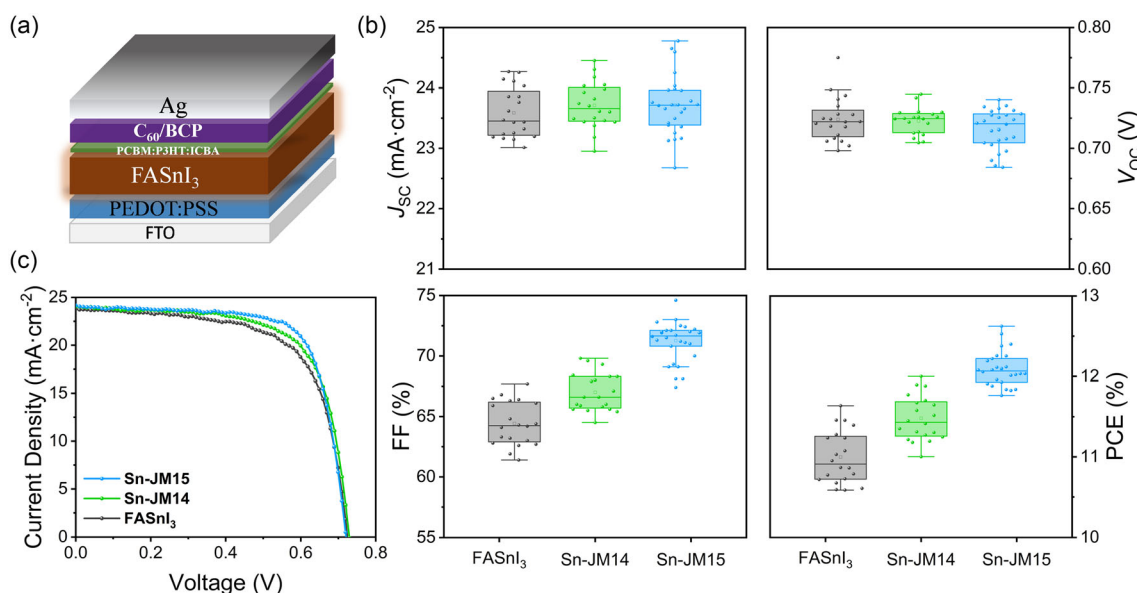


FIGURE 3 | (a) Sn-PSC device architecture. (b) Statistic distribution of the photovoltaic parameters including J_{SC} , FF, V_{OC} and PCE. (c) Champion J - V curves for the different perovskite compositions.

performed intensity-modulated photocurrent spectroscopy (IMPS) and intensity-modulated photovoltage spectroscopy (IMVS), see Figures S21 and 4a, respectively. The IMPS spectra (Figure S21) show no significant difference in the high-frequency response between the samples. Such behavior can be expected as IMPS relates to the charge extraction time and the EQE, which are quite similar for all the cases, as shown in Figure S19. However, a clear differentiation is observed in the IMVS spectra; see Figure 4a. The IMVS peak, which represents the competition between recombination and other slow relaxation processes,

shows a different shift. Specifically, the peak of the **Sn-JM15** sample shifts toward lower frequencies compared to the pristine FASnI_3 device, which is likely related to a longer recombination time. In FASnI_3 systems, this low-frequency response can be associated with mobile ions (typically I^- migration facilitated by V_{Sn} vacancies) [64–66]. The shift observed in the **Sn-JM15** devices indicates that fullerenes are effectively slowing ionic movement, suggesting that C_{70} -based additives are reducing the density of mobile defects or increasing the activation energy for ion migration. By hindering ion migration and reducing

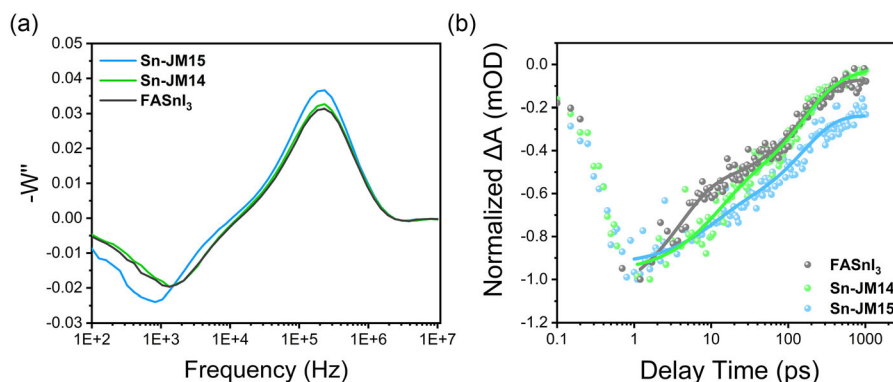


FIGURE 4 | (a) Bode plot of imaginary part of the IMVS transfer function W measured at V_{OC} under 0.1 sun illumination, and (b) normalized transient absorption spectroscopy. Solid lines correspond to the fitting to a biexponential function.

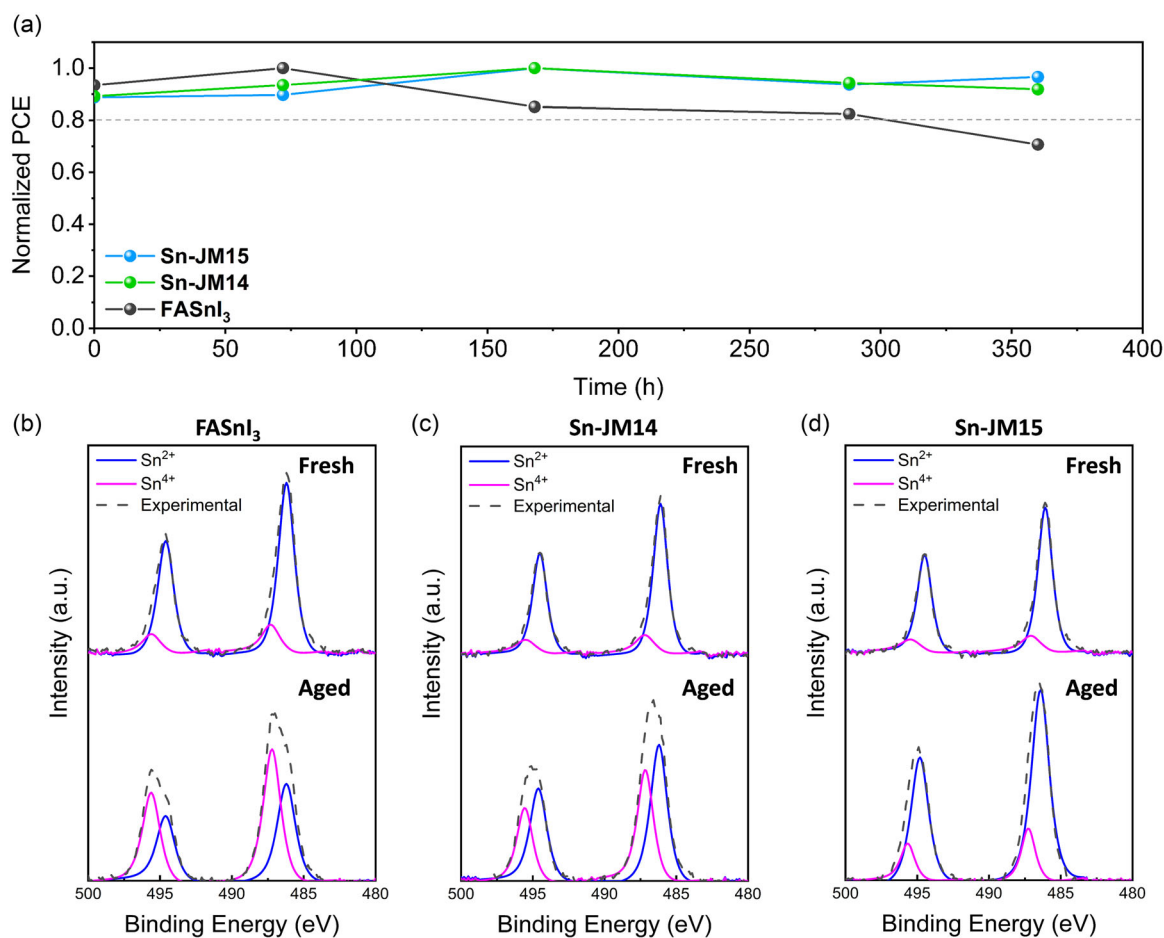


FIGURE 5 | (a) Evolution of the PCE for unencapsulated devices stored in N_2 atmosphere at 25°C under dark conditions. High-resolution XPS spectra of Sn 3d core levels for (b) FASnI_3 , (c) **Sn-JM14**, and (d) **Sn-JM15** measured before and after air exposure.

interfacial charge accumulation, C_{70} derivatives are minimizing electric field screening and non-radiative recombination, ultimately improving FF.

To gain deeper insights into the charge carrier dynamics and the specific role of the fluorinated moieties in the additives, we performed femtosecond transient absorption (TAS) spectroscopy. All fitting parameters are summarized in Table S4. Figure 4b displays the normalized ground-state bleach (GSB) decay kinetics for the control $FASnI_3$, **Sn-JM14**, and **Sn-JM15** films. In the initial short-delay time region, the control film exhibits a rapid signal decay, which is typically ascribed to severe trap-assisted non-radiative recombination at defect-rich grain boundaries. Upon the incorporation of the fullerene additives, both **Sn-JM14** and **Sn-JM15** films show a nearly identical, significantly suppressed fast decay component. This indicates that both fluorinated C_{70} derivatives are equally effective in passivating the shallow trap states responsible for early-stage interfacial recombination. Interestingly, in the long delay time regime, the control and **Sn-JM14** films display parallel decay kinetics. This observation suggests that while **JM14** effectively addresses the initial fast surface recombination, it does not significantly alter the slower recombination pathways. In sharp contrast, the **Sn-JM15** film exhibits a noticeably prolonged carrier lifetime in this long-timescale region compared to **Sn-JM14**. This extended slow decay component implies that the 3,5-bis(trifluoromethyl)phenyl group in **JM15** provides a superior and more comprehensive passivation effect, successfully suppressing even the slower non-radiative recombination centers. These distinct charge carrier dynamics perfectly align with the lowest N_t and the highest FF observed in the **Sn-JM15** devices.

Although Sn-PSCs are considered a promising technology, their limited stability remains a critical obstacle to their development. In this context, we monitored the performance evolution of our Sn-PSCs stored in a N_2 -filled glove box. Figure 5a shows device stability as a function of storage time. Notably, all devices exhibited a slight PCE enhancement during the initial hours of storage. This behavior has been widely reported and is commonly attributed to a gradual defect passivation process, typical in devices employing amine-based perovskite surface post-treatments, such as ethylenediamine (EDA) in this case [26, 67]. After reaching the performance maximum, control devices experienced a progressive degradation, with the PCE decreasing to 70% upon 350 h of storage. In contrast, **Sn-JM14** and **Sn-JM15** devices stabilized after their performance peak, retaining 91% and 97% of their initial performance, respectively. Such stability enhancement can be attributed to the effective defect passivation provided by the fullerene additives. We also evaluated the role of fullerenes in suppressing environmental degradation by exposing bare perovskite films to ambient air. Specifically, the ratio Sn^{2+}/Sn^{4+} of the films was quantified using XPS before and after 30 min of air exposure; see Figure 5b–d. It is well established that O_2 and H_2O molecules can easily degrade Sn-based perovskites by oxidizing Sn^{2+} to Sn^{4+} species, and this degradation pathway is significantly accelerated in films with high defect densities, which act as adsorption and reaction sites for the oxidation agents. Accordingly, the improved oxidation resistance observed for the films with **JM14** and **JM15** aligns with the defect passivation mechanism exposed earlier, where they passivate structural defects impeding the reaction of O_2 and H_2O with the perovskite lattice.

3 | Conclusions

In summary, this work introduces two novel fluorinated C_{70} -based derivatives, **JM14** and **JM15**, as additives to overcome the intrinsic charge transport limitations of Sn-PSCs that affect their FF. A comprehensive optical and electrical analysis reveals that the synergistic combination of the C_{70} cage's high electron affinity and the fluorinated moieties creates a multifunctional additive system. Both derivatives enhance charge transport across the perovskite and reduce resistive losses by reducing R_s and improving R_{sh} while also modifying recombination kinetics through effective passivation of shallow trap states at grain boundaries. This passivation decreases non-radiative recombination and facilitates charge extraction at the perovskite/ETL interface. Notably, the 3,5-bis(trifluoromethyl)phenyl group in **JM15** provides superior passivation. This dual electronic and chemical modification translates into a substantial FF improvement, higher than 12%, passing from an average FF of 64% from reference cells to 72% for **Sn-JM15**. As a result, the PCE of best-performing devices increased from 11.7% for the control devices to 12.0% and 12.7% for **Sn-JM14** and **Sn-JM15**, respectively. Beyond efficiency improvements, the addition of **JM14** and **JM15** also improves device shelf stability and enhances the resistance of Sn-based perovskite to air-induced oxidation. Such a protective effect against environmental degradation further supports the strong correlation between defect passivation and enhanced device durability. Overall, this study provides a simple and effective approach to address FF and stability limitations in Sn-PSCs, offering a viable pathway toward high-performance Pb-free alternatives.

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Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at <https://zenodo.org/uploads/20328230>, reference number 20328230.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.