Supporting information

Biomass-Derived Functional Additive for Highly Efficient and Stable Lead Halide Perovskite Solar Cells with built-in Lead Immobilisation

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Experimental section

1. Materials

All materials were commercially acquired and underwent no further processing. N, Ndimethylformamide (DMF, 99.9%), dimethyl sulfoxide (DMSO, 99%), chlorobenzene (CB, 99.8%), methylammonium iodide (MAI, 99.99%), methylammonium bromide (MABr, 99.99%), formamidine iodide (FAI, 99.99%), lead iodide (PbI₂, 99.99%) lead bromide (PbBr₂, 99.99%), cesium iodide (CsI, 99.999%), bis(trifluoromethane)sulfonimide lithium salt (Li-TFSI, 99.95%), bathocuproine (BCP, 99.9%), tetrabutylammonium hydroxide solution (TBAOH), and 4-tert-butylpyridine (tBP, 99%) were purchased from Sigma-Aldrich. [2-(3,6dimethoxy-9H-carbazol-9-yl) ethyl] phosphonic acid (SAM, MeO-2PACz, >98.0%) were purchased from TCI (Tokyo Chemical Industry). Low molecular weight sodium alginate (5,000-20,000 Da) was purchased from Shanghai Haohong Biomedical Technology Co., Ltd. Tin (IV) oxide (SnO₂, 15% in H₂O colloidal dispersion) was obtained from Alfa Aesar. Spiro-OMeTAD (>99.0 purity) was purchased from Ossila. [6,6]-phenyl-C61-butyric acid methyl ester (PCBM, 99.9%), Indium Tin Oxide (FTO) and I-doped tin oxide (ITO) were purchased from Libra Technology Corporation.

2. Synthesis of target polymer: Tetrabutylammonium Alginate (TBA-Alg)

Low molecular weight (5000-20000 Da) sodium alginate (600 mg) was dissolved in a 60 mL solution of ethanol (99.9%) and HCL (39%) in water (1:1 v/v). The mixture was stirred at room temperature for 3 hours, and then filtered, and purified to produce low molecular weight alginic acid. TBAOH was then added to this acidic solution to maintain pH between 6.0 and 7.0. After being stirred in an ice bath, the product was centrifuged and washed with ethanol.

3. Perovskite solution fabrication

Perovskite composition is $Cs_{0.05}(FA_{0.95}MA_{0.05})_{0.95}Pb(I_{0.95}Br_{0.05})_3$. FAI (232.95 mg), PbI₂ (677.07 mg), MABr (8.13 mg), PbBr₂ (28.07 mg), and CsI (19.98 mg) were dissolved in 1 ml of DMF: DMSO (4:1) and stirred for 12 hours at a constant temperature of 60 °C, the solution was then filtered before use. The target polymer, TBA-Alg, was added to the perovskite precursor solution at a concentration of 1 mg/mL to prepare the treated sample, while the precursor solution without the polymer additive served as the control sample.

4. Full device fabrication

p-i-n type: etched ITO substrates were cleaned using detergent, deionised water, and ethanol, then dried with nitrogen and treated with ultraviolet (UV)-ozone for 15 minutes. The hole transport layer (HTL) was formed by spin-coating a SAM (MeO-2PACz) solution (0.3 mg ml⁻¹ in ethanol) on the treated ITO substrate at 3000 rpm for 30 s, followed by annealing at 100 °C for 10 minutes on a hot plate. Next, 100 μ L of perovskite precursor solution was spin-coated at 1000 rpm for 10 s, and then 5000 rpm for 30 s. During the spin-coating process, 200 μ L of chlorobenzene was added at the 30th second. The sample was annealed at 100 °C for 45 minutes and then the perovskite film was obtained. Subsequently, 100 μ L of PCBM solution was spin-coated on the perovskite film at 3000 rpm for 30 s without annealing. Finally, a 15 nm layer of BCP was deposited by thermal evaporation, followed by a 110 nm silver top electrode, which was also deposited by thermal evaporation.

n-i-p type: etched FTO substrates were cleaned using detergent, detergent, deionised water, and ethanol, hen dried with nitrogen and treated with ultraviolet (UV)-ozone for 15 minutes. The ETL was formed by spin-coating a SnO₂ solution (3% diluted) on the treated FTO substrate at 3,000 rpm for 30 s, then baked on a hot plate in ambient air at 150 °C for 30 minutes. After cooling to room temperature, the perovskite precursor solution was spin-coated onto the SnO₂-coated FTO substrates using a two-step program (1000 rpm for 10 s and 5000 rpm for 30 s), during which an anti-solvent was dropped at the 30th second. The films were then annealed at 100 °C for 40 minutes to promote perovskite crystallization. Subsequently, a HTL was prepared by spin-coating a Spiro-OMeTAD solution (containing 72.3 mg of Spiro-OMeTAD in 1 mL of chlorobenzene, with additives 17.5 μ L of Li-TFSI solution and 28.8 μ L of 4-tert-butylpyridine) at 3,000 rpm for 30 seconds in ambient conditions with controlled humidity. Finally, a 100 nm thick gold electrode was thermally evaporated under high vacuum (~10⁻⁷ Torr) through a shadow mask, defining an active device area of 0.982 cm².

5. Characterization and Measurements

Proton nuclear magnetic resonance (¹H NMR) spectra were recorded on Bruker NMR spectrometers operating at 400 MHz, using samples dissolved in DMSO-d6. Fourier transform infrared (FTIR) spectra were recorded on a PerkinElmer Spectrum 65 spectrometer within a scan range of 4000-500 cm⁻¹. Crystallinity was characterised using X-ray powder diffraction (XRD, D8-ADVANCE from Bruker, Germany) using Cu-K α radiation. Monitoring of the crystallization process was conducted using wide-angle X-ray scattering (GIWAXS, BL14B1 beamline, Pilatus 2M detector of the Shanghai Synchrotron Radiation Facility (SSRF) using an X-ray with a wavelength of 0.6887 Å). X-ray photoelectron spectroscopy (XPS) was performed using monochromatic Al-K α (hv = 1,486.6 eV, p = 150 W) as an X-ray source, UPS using a nonmonochromated He I photon source (hv = 21.22 eV). Ultraviolet-visible (UV-vis) absorption spectroscopy was performed using a PerkinElmer Lambda 950 spectrophotometer. The morphology and elemental composition of the films, were analyzed using scanning electron microscopy (SEM, FEI Inspect F) and energy-dispersive X-ray spectroscopy (EDS). Conductive atomic force microscope (c-AFM) measurements were performed using a Bruker Dimension Icon atomic force microscope (AFM) equipped with a PF-TUNA probe (0.4 N/m spring constant). During the measurements, a -2 V bias was applied to the films. The lightinduced measurements were conducted under bottom illumination using fiber optics connected to a Newport Xenon lamp. Additionally, the topographic image of the films was captured using a ScanAsyst Air probe (0.4 N/m spring constant) in non-contact mode. Transmission electron microscopy (TEM) images were obtained using a JEOL F200 multipurpose electron microscope.

Water contact angle was measured using a Krüss droplet analyzer at room temperature. Trap density of states (t-DOS) measurements were conducted using a precision impedance analyzer (Agilent 4294A). Photoluminescence (PL) was recorded at room temperature on a fluorescence spectrophotometer (FLS980, Edinburgh Instruments), and the steady-state emission was performed under a wavelength of 765 nm light source excitation using a monochromatised Xe lamp. The time-resolved PL decays (TRPL) were recorded with a picosecond pulsed diode laser excitation source (frequency 1,000,000 Hz and a fluence of ~ 1 nJ cm⁻²) at 765 nm. Transient

photovoltage (TPV) and transient photocurrent (TPC) measurements were conducted using equipment from Shanghai Jinzhu Technology Co., Ltd., with a 570 nm laser. Electrochemical impedance spectroscopy (EIS) was conducted using an electrochemical workstation from the Netherlands, (EIS, Electrochemical Workstation, Netherlands). Maximum power output point (MPP) measurements were conducted using a Taiwan Enli Technology KA6000. The *J-V* curves under dark conditions, space-charge-limited current (SCLC), and power conversion efficiency were performed using a sunlight simulator and a digital source meter (KA6000, EnLi Technology). External quantum efficiency (EQE) was conducted using the photoelectric conversion efficiency system ENLITECH QE-R from Guangyan Technology. The SCLC curve was measured for a device with a ITO/SnO₂/perovskite/C₆₀/Ag structure. Trap density (N_t) was calculated using the trap-filled limit voltage (VTFL) equation (1):

$$N_t = \frac{2\varepsilon\varepsilon_0 V_{TEL}}{qL^2} \tag{1}$$

where V_{TFL} is defined as the transition voltage from the ohmic region to the trap-filled limit region, ε is the relative dielectric constant of perovskite, and ε_0 is the vacuum permittivity, *L* is the thickness of the perovskite film, and *q* is the elementary charge.

Inductively coupled plasma mass spectrometry (ICP-MS) measurements for lead ion concentrations were conducted using an Agilent 7900 ICP-MS instrument.

The viscosity-average molecular weight (M $_{\eta}$) was determined using a temperature-controlled Brookfield rheometer (BROOKFIEL, USA) to measure the intrinsic viscosity of the TBA-Alg solution. Measurements were conducted at 20 °C The molecular weight was calculated using the Mark-Houwink equation, with intrinsic viscosity determined by equation (2).

$$[\eta] = \boldsymbol{K}^{M_{\eta}^{\alpha}}(2)$$

Where $[\eta]$ is the intrinsic viscosity obtained from Huggins extrapolation¹, and *K* and α are the Mark–Houwink parameters for sodium alginate in aqueous solution².

The intrinsic viscosity $[\eta]$ is determined using the Huggins equation (3):

$$\frac{\eta_{sp}}{c} = [\eta] + \kappa'[\eta]^2 c (3)$$

Where η_{sp}/c is the reduced viscosity, c is the polymer concentration (g/dL), [η] is the intrinsic viscosity (to be determined), κ' is the Huggins constant.

Density functional theory (DFT) analysis section: all DFT calculations were performed using the CP2K package. Based on XRD data, a FAI-terminated (001) surface of cubic FAPbI₃ was constructed. Geometry optimizations of FAPbI₃ and TBA-Alg were carried out using the PBE functional under the GGA scheme, with DZVP-MOLOPT-SR-GTH basis sets and GTH pseudopotentials. The FAPbI₃ structure was modeled as a $4 \times 4 \times 4$ supercell, and the optimized lattice constants were determined to be a = 6.39270 Å, b = 6.47190 Å, and c = 6.30000 Å. A slab model containing the same supercell and a 25 Å vacuum layer was constructed to study surface properties, and surface atoms were relaxed at the Γ -point. For the TBA-Alg molecule, full structural optimization was performed using PBE, followed by electronic structure calculations using the B3LYP functional with the 6-311G basis set. A plane-wave cutoff of 450 Ry and a relative cutoff of 55 Ry were used. Dispersion corrections were applied using the DFT-D3(BJ) method. Geometry optimization convergence thresholds were: MAX_DR $\leq 3 \times 10^{-3}$ Å, RMS_DR $\leq 1.5 \times 10^{-3}$ Å, MAX_FORCE $\leq 4.5 \times 10^{-4}$ Hartree/Bohr, and RMS_FORCE $\leq 3 \times 10^{-4}$ Hartree/Bohr. VESTA, VMD, and Multiwfn were used for structure visualization and electronic analysis^{3, 4}.

Results and Discussion



Figure S1. Optical images of (a) sodium alginate and (b) TBA-Alg polymer in DMSO/DMF solutions.



Figure S2. Schematic diagram of the synthesis and functional mechanism of tetrabutylammonium alginate (TBA-Alg) that involves acidifying sodium alginate with HCl in an ethanol/water solution, followed by cation exchange with TBAOH.



Figure S3. ¹H NMR spectrum of TBA-Alg in DMSO-d6. The ¹H NMR spectrum of sodium alginate typically shows resonances corresponding to the protons on the backbone, with signals around 3.6-5.1 ppm. After modification with TBA, new peaks appear at 0.95-1.7 ppm, corresponding to the protons of the tetrabutylammonium groups. The presence of these signals confirms the successful introduction of TBA onto the alginate backbone.



Figure S4. FTIR spectra of sodium alginate and target polymer TBA-Alg.



Figure S5. Viscosity of TBA-Alg at different concentrations.

TBA-Alg was weighted and dissolved in deionized water to prepare solutions at concentrations of 1, 2, 4, 6, 8, and 10 g/dL. These solutions were stirred using a magnetic stirrer for 4 hours to ensure complete dissolution, and were then to stand at room temperature for 12 hours to remove bubbles before use.

The rotational viscosity measurement was performed using a Brookfield rotational viscometer (Brookfield DV3T). The samples were equilibrated in a thermostatic water bath at 20 °C for 30 minutes before measurement. A No.2 spindle was selected based on the viscosity range of the samples, and the rotation speed was set to 60 rpm to ensure a consistent shear rate. Each sample was measured for three times, and the average viscosity (in mPa·s) was recorded.

The intrinsic viscosity $[\eta]$ was obtained from the Huggins equation (3), and the measured intrinsic viscosity was 8.1 dL/g (Figure S5), leading to a calculated viscosity-average molecular weight:

$$M_{\eta} = \frac{\left(\frac{[\eta]}{K}\right)^{1/\alpha}}{K} = \frac{\left(\frac{8.1}{1.69 \times 10^{-4}}\right)^{1/1.67}}{1.69 \times 10^{-4}} = 28.7 \ k \ Da$$



Figure S6. FTIR spectra of the TBA-Alg polymer and the TBA-Alg polymer with PbI₂.



Figure S7. (a) Electrostatic potential (ESP) map of the TBA-Alg molecule. (b) Supercell constructed for DFT calculations, in which a fragment of TBA-Alg is adsorbed on the perovskite (001) surface via PbI_2 terminations.



Figure S8. HRTEM image showing the interface between crystalline and amorphous regions, with insets highlighting distinct electron diffraction patterns for each structural phase.



Figure S9. HRTEM image and corresponding energy-dispersive X-ray spectroscopy (EDS) elemental mapping of the amorphous region.



Figure S10. Crystal size statistics from SEM images.



Figure S11. Atomic force microscopy (AFM) images and root-mean-square (RMS) roughness of (a-b) control and (c-d) TBA-Alg-treated perovskite films.



Figure S12. (a) Schematic of the perovskite crystallization process, showing the transition from the precursor state to the intermediate phase (e.g., MAI-PbI₂-DMSO) and finally to the crystallized perovskite film. (b) GIWAXS time-evolution profiles for the control (blue, left) and TBA-Alg-treated (red, right) samples. The shaded region at $q = 5.8 \text{ nm}^{-1}$ highlights the intermediate phase, which appears early and disappears as crystallization progresses.



Figure S13. GIWAXS map of the control and TBA-Alg treated perovskite films.



Figure S14. Photoluminescence (PL) spectra of the control and TBA-Alg treated perovskite films.

Table 51. I fulling parameters of the TREE method of the control and TDR Ang fredered minis.								
Sample	τ_1 (ns)	Amplitude τ_1	$\tau_2(ns)$	Amplitude τ_2				
Control	886.04	1028120	4890	2				
TBA-Alg	1085.63	88079	5699	2.3				

Table S1. Fitting parameters of the TRPL lifetime of the control and TBA-Alg treated films.



Figure S15. (a) UV-vis absorption spectra and (b) band gap curve of perovskite films with and without TBA-Alg treatment.



Figure S16. Normalised TPC plots of PSCs with and without TBA-Alg treatment.



Figure S17. SCLC of electron-only $(ITO/SnO_2/Perovskite/C_{60}/Ag)$ of the control and TBA-Alg treated devices.



Figure S18. Nyquist plots of PSCs with and without TBA-Alg treatment. In the fitting model, R_s represents the series resistance of the device, R_{rec} denotes the recombination resistance of the perovskite, and C_{rec} is the constant phase element.



Figure S19. Dark current curves of PSCs with and without TBA-Alg treatment.



Figure S20. The power conversion efficiencies of perovskite solar cells prepared with different TBA-Alg concentration under standard sunlight conditions, with 20 devices per concentration.

Sample	V _{oc} (V)	J _{SC} (mA cm ⁻²)	Fill Factor (%)	Effici (%	iency 6)
	Average	Average	Average	Average	Champion
Control	1.11 (±0.02)	24.23 (±0.58)	73.47 (±3.68)	19.78 (±1.39)	22.64
0.5 mg/ml	1.13 (±0.02)	24.77 (±0.75)	75.70 (±5.03)	21.36 (±1.35)	24.08
1.0 mg/ml	1.16 (±0.02)	24.81 (±0.47)	80.30 (±2.75)	22.91 (±1.29)	25.01
2.0 mg/ml	1.13 (±0.02)	24.09 (±0.57)	75.09 (±3.85)	21.17 (±1.37)	23.53
3.0 mg/ml	1.12 (±0.02)	23.94 (±0.47)	75.39 (±4.03)	20.25 (±1.34)	22.75
5.0 mg/ml	1.11 (±0.01)	23.42 (±0.82)	71.24 (±1.91)	18.51 (±0.68)	19.71

Table S2. Photovoltaic parameters of devices based on perovskite layers with varying TBA-Alg concentrations.



Figure S21. Statistical distribution of (a) PCE, (b) J_{sc} , (c) V_{oc} , and (d) FF for the control solar cells and solar cells treated with 1 mg/mL TBA-Alg.



Figure S22. Schematic illustration of the operational stability test setup.



Figure S23. XRD patterns of (a) the control and (b) the TBA-Alg treated perovskite films after 30 days of air exposure.



Figure S24. J-V curve and an image of the large-area perovskite solar module.



Figure S25. (a) Schematic illustration of the device architecture. (b) *J-V* curves of TBA-Alg treated devices. (c) *J-V* curves of the control devices. (d) Statistical distribution plots across multiple devices.



Figure S26. Unencapsulated perovskite films treated with TBA-Alg on the left and control samples on the right, immersed in 20 ml of water from 0 to 60 minutes.



Figure S27. Lead ion leakage at different temperatures: (a) 0 °C, (b) 25 °C, (c) 50 °C, and (d) 75 °C) after immersion in 40 mL of water.



Figure S28. Lead ion leakage under different pH conditions: (a) pH 3.2, (b) pH 5.1, (c) pH 7.0, and (d) pH 11.2 after immersion in 40 mL of water.



Figure S29. *J-V* curve of the champion device incorporating TBA-Alg synthesized from sodium alginate with a molecular weight of (a) 30-100 kDa, (b) 100-200 kDa, and (c) 300-500 kDa. (d) Statistical comparison of PCE for perovskite devices with different TBA-Alg polymer additives.

	Perovskite	Device structure	Additives	PCE (%)	stability	Pb ²⁺ interaction	Ref.
1	Cs _{0.1} FA _{0.9} PbI ₃	ITO/PTAA/2P ACz/Perovskite /C ₆₀ /BCP/Cu	HPβCD-BTCA 2-Hydroxypropyl- β-cyclodextrin (HPβCD) 1,2,3,4-Butane tetracarboxylic acid (BTCA)	22.14	Maintained 99% efficiency after 700 hours under continuous one-sun illumination. Retained 96% efficiency after 4000 hours of air aging (RH ~30%). Maintained 80% efficiency retention in thermal stability tests at 85 °C for 300 hours	The cross-linked HPβCD–BTCA network coordinates with Pb ²⁺ and I ⁻ via multidentate chelation, hydrogen bonding, and ester linkages. The supramolecular network prevents Pb ²⁺ migration and leakage while stabilizing the film microstructure	5
2	MAPbI ₃	ITO/PTAA/Per ovskite/PCBM/ BCP/Ag	Usnic acid (UA)	20.38	Retained 78% of initial PCE after 1000 hours at 65% RH and 20-30 °C. In a glovebox (ambient temp, dark), retained >90% efficiency after 2 months	Usnic acid chelates Pb ²⁺ via carboxyl and hydroxyl groups, stabilizing iodide lattice and suppressing I ⁻ migration	6
3	FA _{0.8} MA _{0.15} C s _{0.05} Pb(I _{0.83} Br ₀ .17)3	ITO/SnO ₂ /Pero vskite/Spiro- OMeTAD/Au	PBDF-DFC (biomass-derived furan polymer)	21.39	Retained 90% of initial PCE after 1100 hours of dark storage in N ₂ . Maintained α -phase under 70% RH for 120 h, while control degraded to PbI ₂	Oxygen atoms (from furan rings and ketone groups) in PBDF-DFC coordinate with Pb ²⁺ , guiding PbI ₂ distribution during crystallization	7
4	FAPbI3	FTO/SnO ₂ /pero vskite /Spiro- OMeTAD/Au	Astaxanthin (ASTA)	24.56	Retained >90% PCE after 400 h, under 60% RH. Under oxygen exposure, retained 88% of PCE after 600 h. Under ambient storage (RH = 30%), retained 89% PCE after 1152 h	Astaxanthin provides amphiphilic interaction, carbonyl and hydroxyl groups chelate Pb ²⁺ , forming a stable complex and protecting interfaces from water and oxygen	8
5	$\begin{array}{c} MAPbI_3 \mbox{ and } \\ Cs_{0.05}FA_{0.85}M \\ A_{0.1}PbI_3 \end{array}$	FTO/NiOx/Per ovskite/PCBM/ BCP/Ag	Cellulose triacetate (CTA)	22.40	Maintained 81% of its initial grayscale value for up to 147 min, whereas that of the w/o CTA perovskite film drops to 0% at 147 min on a 300 °C hot plate	Cellulose triacetate coordinates with undercoordinated Pb ²⁺ via carbonyl groups. CTA enhances charge transfer across Pb-I bonds and stabilizes the crystal structure, helping to suppress ion migration and reduce trap density	9

Table S3: Representative additives for enhancing the performance, stability, and lead leakage mitigation of perovskite solar cells.

6	(FAPbI ₃) _{0.97} (MAPbBr ₃) _{0.03}	ITO/SnO ₂ /Pero vskite/Spiro- OMeTAD/Ag	Nicotinamide (Vitamin B ₃)	21.72	Maintained over 95% of their original PCE after over 1000 h storage	Pb ²⁺ coordination through amide and pyridine groups strengthens lattice and minimizes surface traps	10
7	FAPbI ₃	ITO/SnO ₂ / Perovskite/Spir o- OMeTAD/Au	Starch-iodine complex	22.60	Device maintained 91.12% efficiency after 1500 hours of aging under 25 °C 35% RH atmosphere	Starch coordinates with Pb ²⁺ and passivates perovskite grain boundaries via hydrogen bonding (-OH····I ⁻ and - OH····Pb ²⁺)	11
8	MAPbI ₃	ITO/PTAA/Per ovskite/PCBM/ BCP/Ag	Hydroxyethyl cellulose (HEC) and hydroxypropyl cellulose (HPC)	21.25	After 1080 hours under dark, air- stored conditions without encapsulation, the HEC- and HPC- based devices retained 98.5% and 96.3% of initial PCE	Hydroxyl groups on cellulose coordinate with Pb ²⁺ in perovskite, passivating both surface and grain boundary defects. The cellulose backbone promotes grain alignment and suppresses trap states	12
9	MAPbI ₃	FTO/TiO ₂ /Pepe rovskite/Spiro- OMeTAD/Ag	Cellulose acetate (CA)	19.53	Maintained 82.6% of initial PCE after 15 days at 85% relative humidity without encapsulation. retained ~80% of PCE after 100 hours under continuous light and 85 °C	Hydrogen bonding with MA ⁺ and I ⁻ ions improve crystal quality and inhibits lattice distortion, thereby passivating grain boundaries and reducing trap states	13
1 0	$\begin{array}{c} FA_{0.88}Cs_{0.12}Pb\\ I_{2.64}Br_{0.36} \text{ and }\\ (FA_{0.925}Cs_{0.075}\\ PbI_{2.895}Br_{0.105})\end{array}$	ITO/MeO- 2PACz/Perovsk ite/PC ₆₁ BM/BC P/Ag	Coumarin (biomass-derived)	24.14	In 30-40% RH ambient air without encapsulation, device retained over 90% PCE after 185 days. Maintained >97% PCE after 150 h light soaking (100 mW/cm ²). Sustained thermal operation at 120 °C for 30 days with suppressed PbI ₂ formation	Coumarin partially decomposes during annealing, forming intermediates that coordinate with Pb ²⁺ , iodine, and organic cation defects	14
1 1	FA _{0.87} Cs _{0.13} Pb I _{2.7} Br _{0.3}	FTO/MeO- 2PACz/Perovsk ite/PC ₆₁ BM/BC P/Ag	Amino acid derivatives (L- arginine and L- glutamic acid)	23.00	Retained >98% of initial PCE after 1000 h in N_2 storage. Under 85 °C heating in N_2 , glutamic acid-treated device showed superior thermal resistance. Under 85% RH environment, devices with both additives resisted humidity-induced degradation significantly better than	L-glutamic acid with -NH ₂ and C=O function group combined with PbI ₂ in ordinary perovskite films to form cross-linking between perovskite crystals and fill vacancies in perovskite films	15

					control		
1 2	MAPbI3	Glass/FTO/TiO 2/Perovskite /Spiro- OMeTAD/Au	Biomolecules including artemisinin (ART), camphor, menthone, heptanal (hep), dihexyl ketone, and laurone, featuring carbonyl and alkyl chain structures	23.04	Retained ~70% of initial PCE after 3 hours under 85 °C and 85% RH without encapsulation (vs rapid failure of control) <1% drop over 11 hours under 1.2 sun and 40-65% RH	Hydroxyl, amino, phosphate, and carbonyl, acting either as an electron donor or acceptor when they come in contact with the partially bonded Pb at the lattice edge, as a result stabilizing the terminal active sites at the lattice boundary	16
1 3	ITO/SAM/per ovskite/PCB M/BCP/Ag	$\begin{array}{c} Cs_{0.05}(FA_{0.95}M\\ A_{0.05})_{0.95}Pb(I_{0.95}\\ Br_{0.05})_{3} \end{array}$	Tetrabutylammoni um alginate (TBA- Alg)	25.01	Retained 95% of their initial performance after 2,000 hours of storage under a nitrogen atmosphere. Under continuous one-sun illumination at approximately 60% relative humidity for 1050 hours, the devices maintained 85% of their initial efficiency	TBA-Alg chelates lead ions through Lewis base-acid interactions involving C=O groups, extending the crystallization time and minimizing defects. The TBA-Alg forms a connected network at the grain boundaries and perovskite surfaces, creating hydrophobic barriers that protect the perovskite films from moisture-induced erosion, a critical factor for long-term stability	This work

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