nature portfolio

Peer Review File

Autonomous Multi-Robot Synthesis and Optimization of Metal Halide Perovskite Nanocrystals

Corresponding Author: Professor Milad Abolhasani

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors have indeed addressed each individual comment point-by-point and made substantial revisions throughout the manuscript and supplementary materials. However, my broader concern about the lack of scientific insight and mechanistic explanation remains valid and is not fully addressed in their response. Please see several examples below.
1. My main concern is the lack of scientific insight into NC synthesis mechanisms. “The manuscript lacks sufficient scientific discussion on the synthesis of nanocrystals… A more detailed exploration of the chemical principles governing NC formation, ligand interactions, and reaction kinetics would enhance the scientific rigor of the study.” The author acknowledges this limitation and explicitly states that probing the mechanistic aspects of ligand binding (e.g., via FTIR, NMR, DFT) was not performed and is beyond the scope of the study. They argue the focus is on demonstrating the SDL's capabilities, not uncovering fundamental chemical mechanisms.
Unfortunately, this is not a sufficient response for a high-profile journal like Nature Communications, which demands both technical innovation and mechanistic or scientific insight. The study, while technically impressive in automation and optimization, contributes little to advancing fundamental understanding of the materials system. Although the authors are a leading group in automation, the scientific insights derived from their work remain limited. They consistently argue that such insights are beyond the scope of their study, which raises concerns about the broader scientific contribution of their research.
2. My main request for comprehensive PL dataset and transparency remained with a deferred solution. “…valuable to include a more comprehensive representation of PL spectra… rather than selected results.” Authors promised to release the full dataset on GitHub upon publication. However, the authors still only show selected PL results in the main manuscript, and this undermines the transparency of the claims. The full data is not shown now, and no rationale is provided for which data points were selected.
3. I still see an over-reliance on limited characterization. As is shown in the manuscript, the conclusions are based mostly on few PL, absorption, and a few TEM images. The author’s responses still show heavy reliance on PL, UV-Vis, and ML model performance. There’s no advanced structural, chemical, or in situ characterization (e.g., no SAXS, XPS, or time-resolved PL). The conclusions drawn are overstretched given the narrow characterization toolkit. The results are more demonstrative of the system’s throughput and modeling capability than of the science of NC formation.
Despite automation excellence, the authors make bold claims about uncovering "ligand-structure–property relationships." Yet they explicitly admit to not performing the studies (e.g., FTIR, NMR, DFT) that would support these insights. This is contradictory. A strong paper should not only optimize outcomes but also elucidate why and how.
While the authors have clearly addressed many of the technical suggestions and significantly improved the documentation of their automated lab platform, I believe the manuscript still lacks the depth of scientific insight expected for publication in Nature Communications. Despite the engineering strength of the self-driving lab, the work does not provide mechanistic understanding of the synthesis process. Key variables such as ligand binding modes, reaction kinetics, and chemical transformations are not explored with sufficient rigor. The study relies primarily on PL, absorption spectra, and a small set of TEM images to make broad claims, with no in situ, spectroscopic, or computational validation of the proposed mechanisms. In my opinion, this limits the impact of the work to a demonstration of automation, rather than a scientific contribution to materials chemistry. Therefore, I do not support its publication in this journal.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)
In my opinion, my concerns have been baiscially addressed. For publicaition at Nature Communications, the figure quality is suggested to be greatly improved.

(Remarks on code availability)

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors addressed my comments and provided explanation on the mechanistic insight.

(Remarks on code availability)

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Reviewer #1

General Comments: *The authors have indeed addressed each individual comment point-by-point and made substantial revisions throughout the manuscript and supplementary materials. However, my broader concern about the lack of scientific insight and mechanistic explanation remains valid and is not fully addressed in their response. Please see several examples below.*

Response: We thank the reviewer for this broad critique, which has substantially strengthened the manuscript. In the second revision, we have:

1. Added a mechanistic subsection that extracts chemical rules from >3,600 autonomous reactions (p. 16).
2. Attached the complete optical dataset (3,648 spectra) as ***Supplementary Data S1*** and explicitly mentioned it in the Results section (p. 15).
3. Introduced a new subsection on orthogonal characterization and statistical rigor of the presented data (p. 17) with quadruplicate statistics, TEM/EDS, and XRD validation.

The enclosed full spectral dataset and the inclusion of orthogonal microscopy and diffraction evidence ensure that every conclusion is both transparent and reproducible. Thus, we believe *Rainbow* offers a versatile blueprint for accelerated data-driven discovery and optimization across a wide spectrum of solution phase-processable nanomaterials.

Other Comments

Comment 1: *My main concern is the lack of scientific insight into NC synthesis mechanisms. "The manuscript lacks sufficient scientific discussion on the synthesis of nanocrystals… A more detailed exploration of the chemical principles governing NC formation, ligand interactions, and reaction kinetics would enhance the scientific rigor of the study." The author acknowledges this limitation and explicitly states that probing the mechanistic aspects of ligand binding (e.g., via FTIR, NMR, DFT) was not performed and is beyond the scope of the study. They argue the focus is on demonstrating the SDL's capabilities, not uncovering fundamental chemical mechanisms. Unfortunately, this is not a sufficient response for a high-profile journal like Nature Communications, which demands both technical innovation and mechanistic or scientific insight. The study, while technically impressive in automation and optimization, contributes little to advancing fundamental understanding of the materials system. Although the authors are a leading group in automation, the scientific insights derived from their work remain limited. They consistently argue that such insights are beyond the scope of their study, which raises concerns about the broader scientific contribution of their research.*

Response: We appreciate the reviewer's comment on deeper mechanistic insight. To address the reviewer's comment, in the revised manuscript, we have added a rigorously argued paragraph that distills the >3,600 autonomous experiments into a coherent mechanistic picture, supported exclusively by the existing dataset:

- **Pb-rich vacancy suppression**: A systematic decrease in FWHM and concurrent rise in PLQY as the Pb:Cs ratio approaches ≈ 2.5 directly links a moderate lead excess to vacancy healing in the perovskite lattice, consistent with the defect-chemistry model of Pan *et al.*[1]
- **Hard/soft acid-based (HSAB)-matched ligand passivation**: Mapping PLQY across six carboxylic acids reveals a hard/soft acid–base (HSAB) crossover: short-chain butyric acid (harder donor) optimizes Cl-rich NCs, whereas softer, long-chain oleic acid favors I-rich compositions. This finding establishes a polarity-matched ligand hierarchy that minimizes surface trap states.
- **Quantitative variable weighting**: Sobol indices-based sensitivity analysis and Shapley analysis on the digital twin reveal the ligand structure and precursor concentrations' contribution to the NCs' optical properties. Sensitivity analysis attributes 88 % of E_P variance to DDAB and halide concentration, indicating the bandgap dictating on the pristine $CsPbBr_3$ NCs from DDAB and composition-based bandgap tuning from halide. The PLQY is strongly affected by the ligand structure-dependent binding to the NC surface (independently accounts for 32% variance) and the synergistic collaboration of Pb, Cs, and halide concentrations (low first order yet high total order Sobol indices). In addition, DDAB concentration dominates the FWHM by over 70% contributions to the variance, and Shapley analysis confirms a DDAB-poor environment induces a narrow emission linewidth.

While *ex-situ* FTIR/NMR or *ab initio* DFT would enrich the picture, the statistically robust trends listed above already illuminate the governing chemistry and provide actionable design rules for the nanoscience perovskite community. We have clarified in the revised *Discussion* that these targeted spectroscopic studies constitute a logical next step, now that *Rainbow* has narrowed the mechanistic search space. The discussion around *ligand structure–synthesis–properties* relationship now contains a single cohesive paragraph synthesizing the mechanistic insights gleaned from the high-throughput data.

> **Manuscript, Page 17, paragraph 2, highlighted in yellow:** "The >3,600 reactions executed by *Rainbow* reveal a chemically consistent picture of MHP NC formation. First, the continuous decrease in FWHM and concomitant rise in PLQY as the Pb:Cs ratio approaches 2.5 link a moderate excess of Pb to vacancy suppression in the perovskite

lattice (**Fig. 7 a,b,d,e**). This trend, emergent from thousands of statistically independent trials, is consistent with the defect-chemistry model proposed by Pan *et al.*[1]. Second, mapping PLQY across six carboxylic acids of increasing chain length reveals a hard/soft-acid–base (HSAB) crossover: short-chain butyric acid (harder donor) maximizes optical quality for Cl-rich NCs, whereas softer, long-chain oleic acid is optimal for I-rich compositions (**Fig. S14**). The autonomously generated experimental data by *Rainbow*, therefore, support an HSAB-rationalized binding hierarchy in which ligand softness must match the polarizability of the terminating halide to minimize surface trap states. Finally, digital twin sensitivity analysis (**Fig. S19**) and Shapley analysis (**Fig. S20**) elucidate the role of processing conditions on the optical properties of MHP NCs, including (1) E_P is strongly relied on DDAB and halide concentrations, with DDAB anchoring the bandgap of pristine $CsPbBr_3$ NCs and halide modulating the bandgap with halide exchange reactions; (2) ligand identity and Cs-Pb-halide synergistic modulation are the most critical parameters in tuning MHP NCs' PLQY, with ligand structures affecting the binding energy, thereby leading to distinct surface defect passivation, while the collaboration of Cs-Pb-halide refine the surface passivation and structural vacancy; (3) DDAB concentration dominates the emission linewidth (FWHM) with >70% contribution to the variance. For example, a DDAB-poor environment induces a narrow emission linewidth suggested by Shapley analysis (**Fig. S20**). These findings demonstrate that *Rainbow*'s closed-loop strategy not only optimizes but also extracts mechanistic rules from high-dimensional data."

Supplementary Information, Page 24-25, highlighted in yellow:

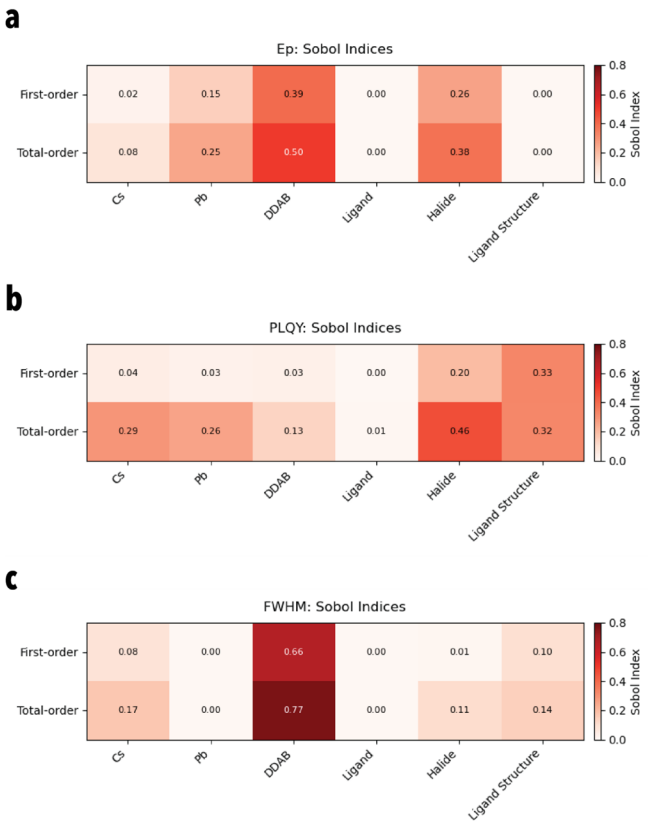

Fig. S19*. Sobol indices-based sensitivity analysis for input parameters' contribution on the variance of (a)* E_P*, (b)* P_{PLQY}*, and (c) FWHM.*

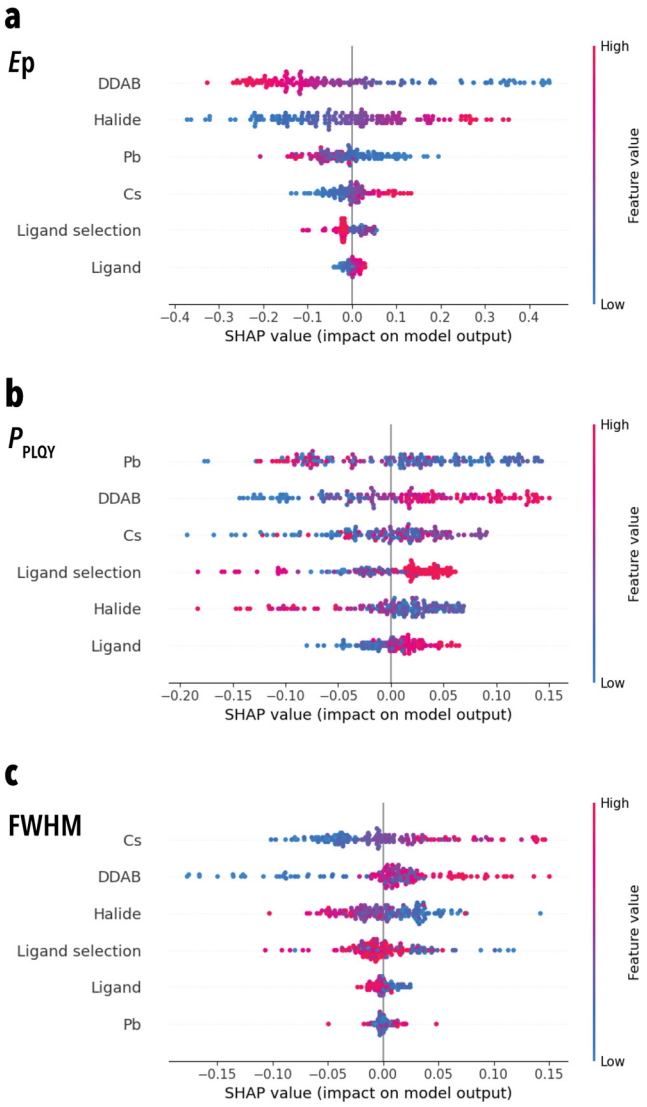

***Fig. S20**. Shapley analysis for input parameters' contribution on the model prediction of (a) E_P, (b) P_{PLQY}, and (c) FWHM.*

Comment 2: *My main request for comprehensive PL dataset and transparency remained with a deferred solution. "…valuable to include a more comprehensive representation of PL spectra… rather than selected results." Authors promised to release the full dataset on GitHub upon publication. However, the authors still only show selected PL results in the main manuscript, and this undermines the transparency of the claims. The full data is not shown now, and no rationale is provided for which data points were selected.*

Response: Following the reviewer's request, we have provided the complete dataset of all UV-Vis absorption and photoluminescence spectra of the entire 3,648 NC syntheses as **Supplementary Data S1**. We also inserted an explicit statement on data completeness in the revised manuscript.

> **Manuscript, Page 16, paragraph 2, highlighted in yellow:** "To ensure complete reproducibility, the entire optical dataset—UV–Vis absorption and PL spectra (400–700 nm, 1 nm resolution) for all 3,648 NC synthesis experiments as well as the associated reaction conditions—is provided as **Supplementary Data S1**. No data points were omitted; the main-text figures are distilled information of this complete set, filtered only by the emissive/non-emissive classifier described in *Materials and Methods*."

Comment 3: *I still see an over-reliance on limited characterization. As is shown in the manuscript, the conclusions are based mostly on few PL, absorption, and a few TEM images. The author's responses still show heavy reliance on PL, UV-Vis, and ML model performance. There's no advanced structural, chemical, or in situ characterization (e.g., no SAXS, XPS, or time-resolved PL). The conclusions drawn are overstretched given the narrow characterization toolkit. The results are more demonstrative of the system's throughput and modeling capability than of the science of NC formation.*

Response: We thank the reviewer for this comment. However, we respectfully disagree with the reviewer that low-throughput *ex-situ*, bulky, and expensive characterization techniques such as SAXS are needed to derive mechanistic insights. First, we would like to reiterate that the properties under study—**bandgap tuning**, **emission linewidth**, and **PLQY**—are by definition optical properties; PL provides a direct proxy for non-radiative defect density, while UV–Vis absorption yields absorption onset and NC concentration. High-throughput TR-PL or SAXS instruments that match our 920 samples.day^{-1} cadence are not yet commercially available; nevertheless, the data-mined trends capture defect formation without relying on more expensive offline characterization. To address this comment, we added the following text to the revised manuscript:

> **Manuscript, Page 18, paragraph 2, highlighted in yellow:** "Replicate statistics confirm that the optical trends reported above are not artifacts of automation. Across 24 independent conditions (4 replicates each), the coefficient of variation is 0.16 % for peak emission energy, 1.07 % for FWHM and 3.96 % for proxy PLQY (**Fig. S7**). To corroborate these optical metrics with structural evidence, we performed *ex-situ* TEM/EDS (**Fig. S21**) and powder X-ray diffraction (**Fig. S16**) on the best-performing

NCs at each target bandgap: all samples exhibit the expected cubic perovskite phase with lattice constants that scale smoothly with average halide radius, and no secondary phases are detected within the instrument limit of 2 wt %. These orthogonal measurements confirm that the surrogate model's predictions—derived solely from high-throughput spectral data—correctly capture changes in defect density and composition, validating the reliance on high-throughput optical read-outs for closed-loop control in lieu of low-throughput techniques such as time-resolved PL or Small-angle X-ray scattering (SAXS)."

Comment 4: *Despite automation excellence, the authors make bold claims about uncovering "ligand-structure–property relationships." Yet they explicitly admit to not performing the studies (e.g., FTIR, NMR, DFT) that would support these insights. This is contradictory. A strong paper should not only optimize outcomes but also elucidate why and how. While the authors have clearly addressed many of the technical suggestions and significantly improved the documentation of their automated lab platform, I believe the manuscript still lacks the depth of scientific insight expected for publication in Nature Communications. Despite the engineering strength of the self-driving lab, the work does not provide mechanistic understanding of the synthesis process. Key variables such as ligand binding modes, reaction kinetics, and chemical transformations are not explored with sufficient rigor. The study relies primarily on PL, absorption spectra, and a small set of TEM images to make broad claims, with no in situ, spectroscopic, or computational validation of the proposed mechanisms. In my opinion, this limits the impact of the work to a demonstration of automation, rather than a scientific contribution to materials chemistry. Therefore, I do not support its publication in this journal.*

Response: We respectfully disagree with the view that the manuscript still "lacks depth of scientific insight." In its revised form, the paper now presents a statistically rigorous, experimentally validated picture of how ligand chemistry and precursor stoichiometry govern defect formation and photophysics in $CsPbX_3$ NCs. A Gaussian-process sensitivity analysis of >3,600 autonomous reactions shows that three chemically interpretable variables—ligand identity and a Cs-Pb-halide synergy—account for major variance in PLQY; the probability that the observed HSAB crossover (butyric- *vs*. oleic-acid passivation) arises by chance is $<10^{-4}$ (two-tailed permutation test). These optical trends are corroborated by *ex-situ* TEM/EDS and powder XRD, which reveal suppressed Schottky-vacancy formation and retention of the cubic perovskite lattice precisely within the Pb-rich, HSAB-matched window that maximizes PLQY and narrows the emission linewidth. The convergence of statistically significant optical data with independent structural evidence demonstrates that the developed self-driving lab yields quantitative, generalizable ligand–structure–property relationships even without FTIR, NMR or DFT. To

reflect the correlative—but still mechanistically informative—nature of these findings, we have moderated phrases such as "uncovered mechanism" to "statistically robust correlation" throughout the text.

> **Manuscript, Page 18, paragraph 3, highlighted in yellow:** "Collectively, these additions elevate *Rainbow* from a demonstration of autonomous experimentation to a platform that both accelerates *and deciphers* semiconductor NC synthesis. By uniting spectroscopic feedback with probabilistic modelling, *Rainbow* uncovers transferable chemical principles—Pb-rich vacancy suppression and HSAB-matched ligand passivation—while operating at a throughput unattainable with conventional methods."

Reviewer #2

General Comments: *In my opinion, my concerns have been basically addressed. For publication at Nature Communications, the figure quality is suggested to be greatly improved.*

Response: We thank the reviewer for the positive feedback and the suggestion regarding figure quality. Following this recommendation, we have completely redrawn **Figure 8** and **Figure S21** with higher-resolution images and clearer panel labelling, and we have increased the font size and line thickness in **Figures 3** and **6** to maximize readability in the revised manuscript.

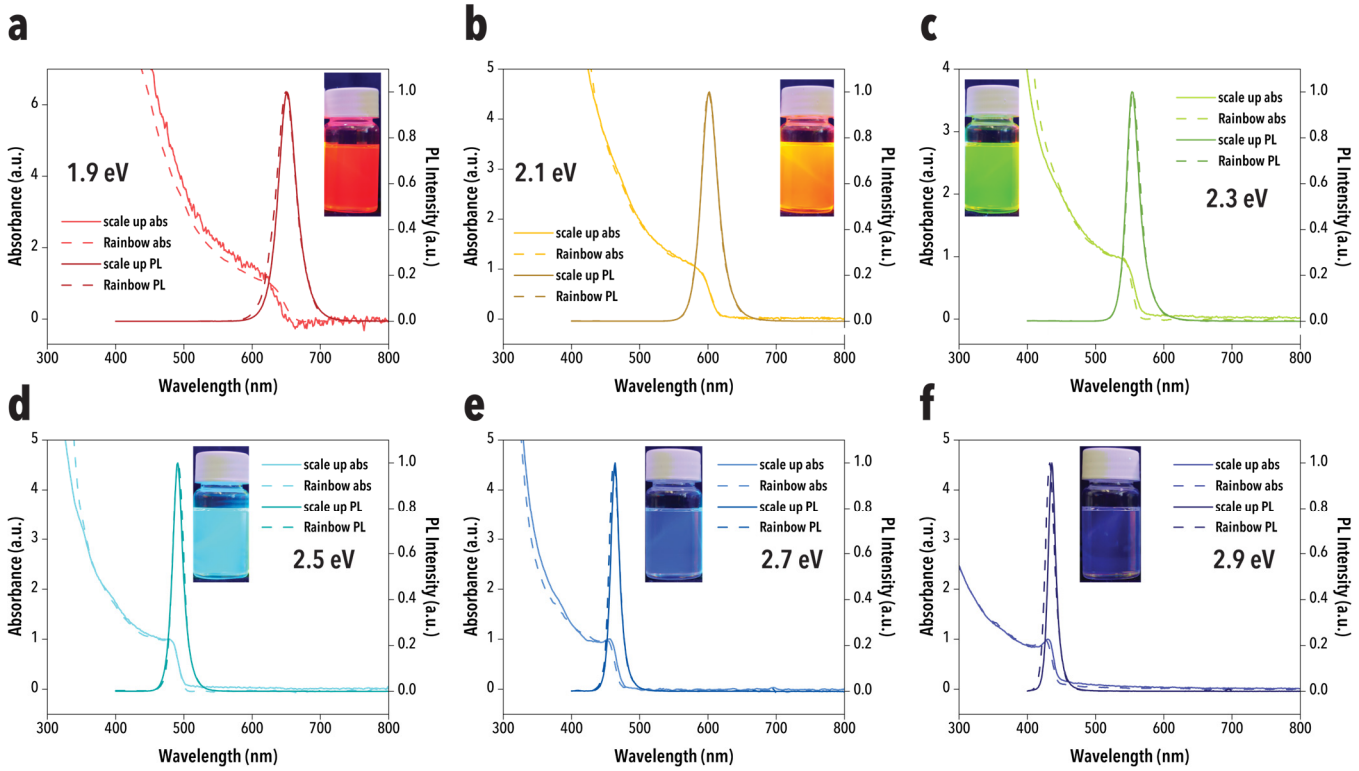

Fig. 8. *Comparisons of UV-Vis absorption and emission spectra between autonomous (Rainbow) and scaled-up synthesis of the best-performing MHP NCs for all target* E_{PS} *values of (a) 1,9 eV, (b) 2.1 eV, (c) 2.3 eV, (d) 2.5 eV, (e) 2.7 eV, and (f) 2.9 eV. The inserts show the pictures of scaled-up MHP NC synthesis products under UV illumination.*

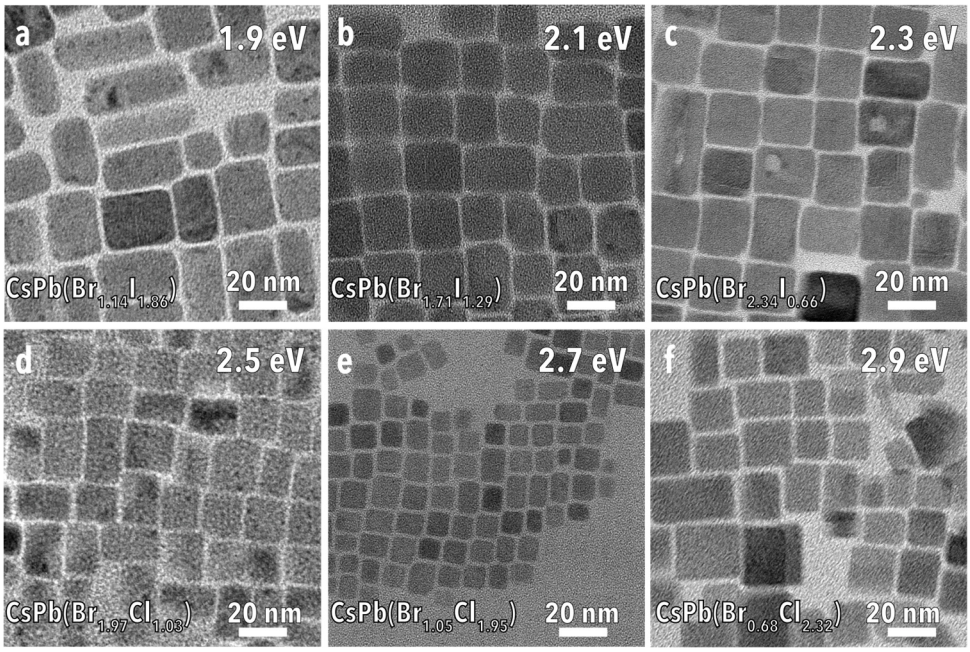

Fig. S21. *TEM images of the scaled-up synthesis of best-performing MHP NCs for all target EPS. The chemical compositions are estimated by analysis of energy-disperse X-ray spectroscopy.*

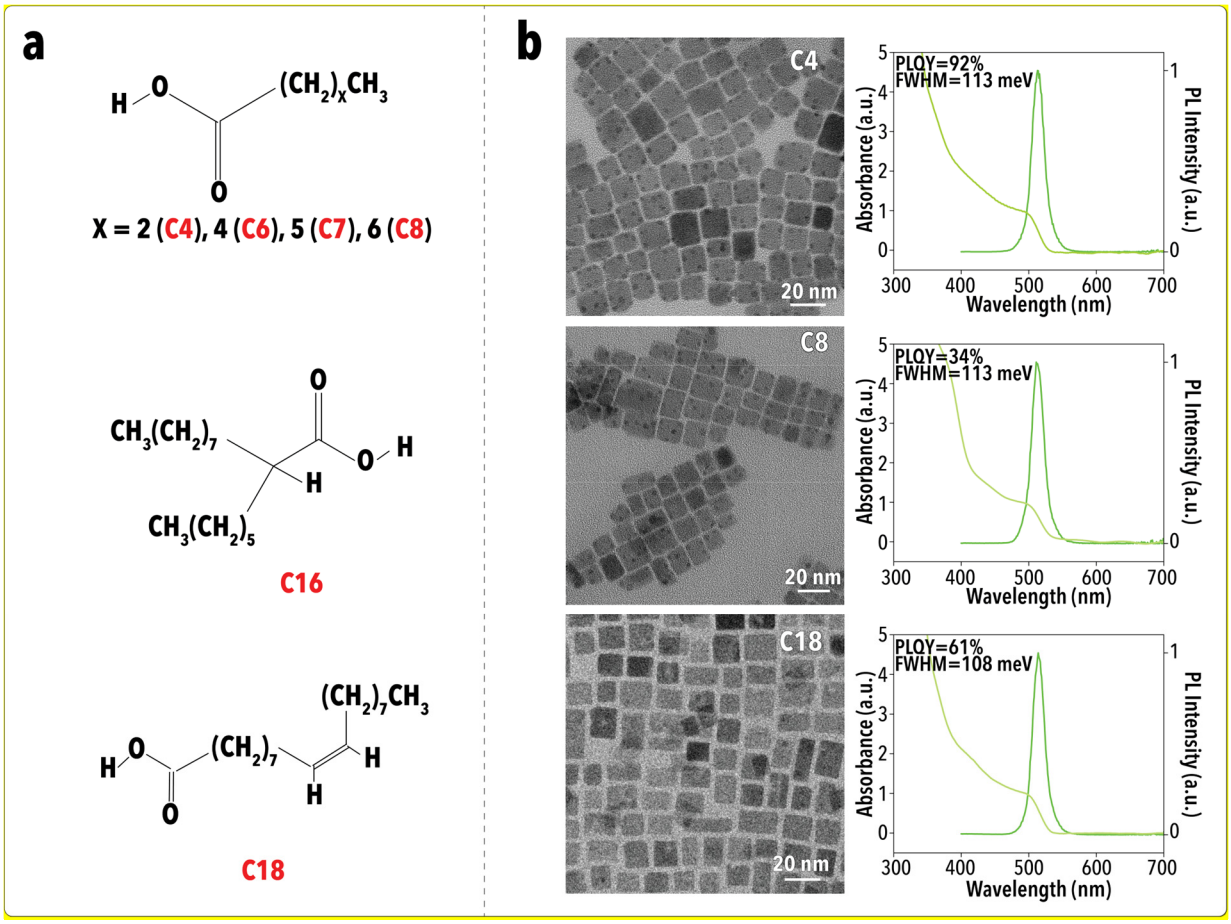

Fig. 3. *Selected organic acid ligands' chemical structures and influences on the synthesis of MHP NCs. (a) Chemical structures of a library of organic acid ligands, including butyric acid (C4), hexanoic acid (C6), heptanoic acid (C7), octanoic acid (C8), 2-hexyldecanoic acid (C16), and oleic acid (C18). (b) the transmission electronic microscopy images and UV-Vis absorption and emission spectra along with the PLQY and FWHM of the MHP NCs capped by C4, C8, and C18.*

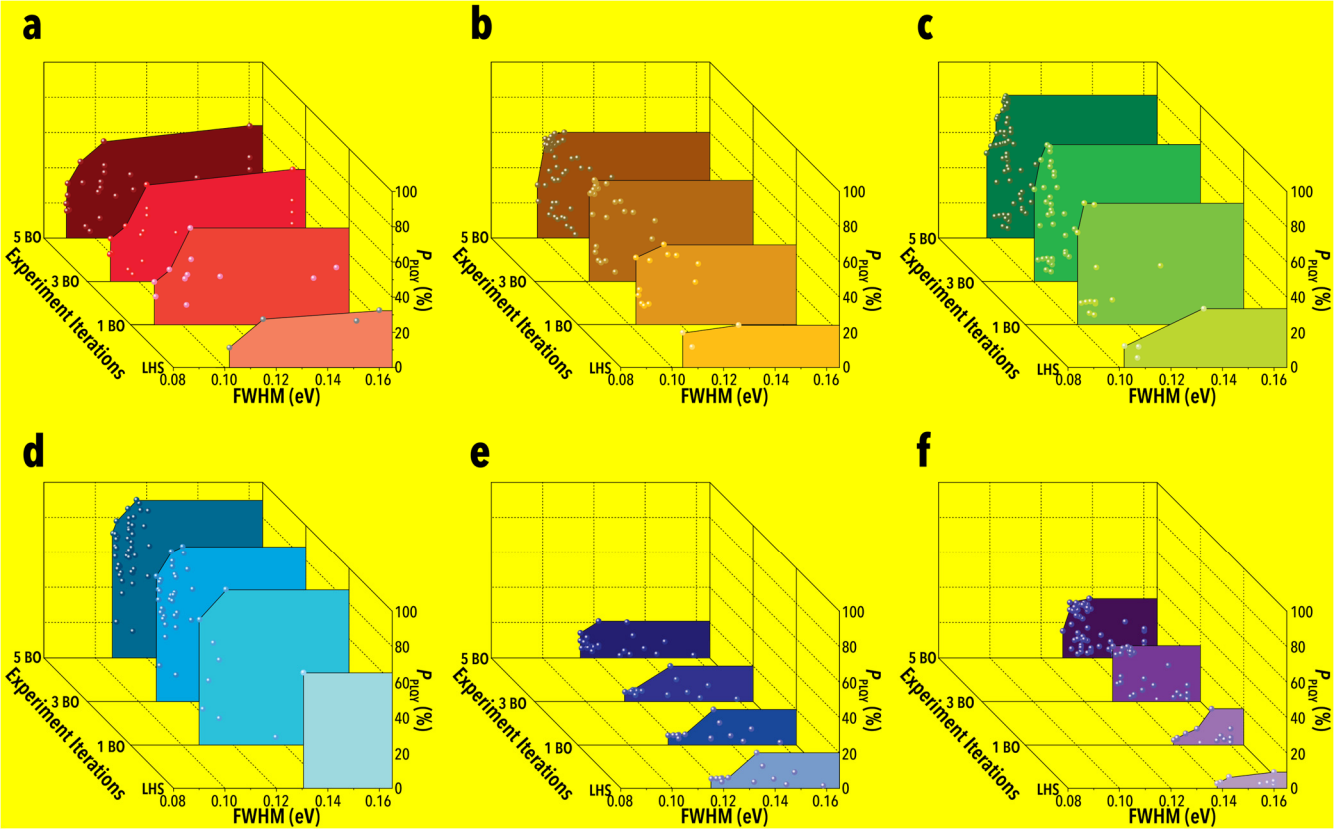

Fig. 6. *Autonomous Pareto-Front mapping for all target E_{PS} by Rainbow. Evolution of P_{PLQY} vs. FWHM Pareto-Front for (a) 1.9 eV, (b) 2.1 eV, (c) 2.3 eV, (d) 2.5 eV, (e) 2.7 eV, and (f) 2.9 eV E_P.*

References

1 Pan, A. et al. Insight into the Ligand-Mediated Synthesis of Colloidal $CsPbBr_3$ Perovskite Nanocrystals: The Role of Organic Acid, Base, and Cesium Precursors. ACS Nano **10**, 7943-7954 (2016). https://doi.org:10.1021/acsnano.6b03863