News & views

Organic photocatalysis

https://doi.org/10.1038/s44160-024-00498-5

Scaling up discovery

Seonghwan Kim & Charles M. Schroeder

By systematically exploring a large chemical space using automated experimentation, a high-performing organic photocatalyst for hydrogen evolution is discovered.

The goal of photocatalysis is to harness energy from light to drive challenging or kinetically unfavourable chemical reactions[1]. Nature provides inspiration for the development of photocatalysts through the process of photosynthesis which efficiently captures energy from sunlight to catalyse useful chemical transformations, such as the synthesis of organic molecules or the reduction of carbon dioxide. The naturally occurring processes in photosynthesis have long motivated the development of synthetic organic photocatalysts for chemical transformations that rely on sunlight as a sustainable energy source[2]. However, even though the use of photocatalysts for solar fuel production is promising, several challenges hinder the practical implementation of organic photocatalysts beyond academic laboratories.

The traditional approach to develop organic semiconductors has relied on iterative and often tedious experimentation that typically relies on known molecules. In contrast, the de novo design of new organic semiconductors and organic photocatalytic materials is complex and requires a comprehensive understanding of molecular electronic properties, solid-phase morphology, and processing conditions, all of which influence charge separation and transport[3]. From this view, there is a need to accelerate the discovery of organic photocatalysts with enhanced light absorption and charge separation properties by leveraging advances in the automated screening of materials. Now, writing in *Nature Synthesis*, Cooper and co-workers report the use of an automated high-throughput screening workflow for the discovery of photocatalytic materials for hydrogen evolution[4].

To date, automated high-throughput screening has been used to conduct numerous experiments in parallel, substantially expediting the discovery and characterization of new materials[5]. In addition, automated robotic synthesis has been used to expand the scope of chemical libraries using batch reactions[6,7] and flow-based synthesis[8] of organic compounds. More recently, automated synthesis was used in a closed-loop process to optimize the efficiency of reaction conditions[9] and to guide the property-driven optimization of organic dyes[10]. Beyond automated synthesis, practical implementation of automated screening is relatively challenging because the characterization methods required are application-specific for different classes of materials.

Cooper and co-workers report the use of automated screening for the discovery of organic nanojunction photocatalysts, composed of a donor molecule and an acceptor molecule, capable of yielding a greatly enhanced sacrificial hydrogen evolution rate. A library of 26 acceptor molecules is synthesized using a two-step, metal-free Hantzsch pyridine condensation reaction (Fig. 1a). In total, 156 molecular nanojunctions are prepared by combining these 26 acceptor molecules with 6 electron-rich donor molecules via ultrasonic nanoprecipitation, followed by high-throughput photolysis (Fig. 1c). Finally, the hydrogen evolution rates of the nanojunctions are measured by automated gas chromatography. Using this approach, three high-performing donor–acceptor nanojunctions are identified with ((3-(4-(bis(4-methoxyphenyl)amino)phenyl)-2-cyanoacrylic acid) MTPA-CA as the donor molecule (Fig. 1b). Notably, the automated screening process required only three days to characterize 186 donor–acceptor nanojunctions.

It is well established that results from automated screening on a small scale do not always translate to bulk materials, in particular if morphology has a strong influence on the properties of the material. To investigate the translation of functional activity from a small scale to the bulk scale in the materials discovery process, Cooper and co-workers use flow synthesis to scale up the preparation of the donor–acceptor nanojunctions that show high hydrogen evolution rates in small-scale batch reactions. This flow-based flash nanoprecipitation method is a continuous process capable of making large quantities of photocatalyst in ~1 litre solutions (200-fold larger amounts than prepared in batch reactions in the first round). It is revealed that the donor–acceptor nanojunctions consisting of MTPA-CA and 2,6-bis(4-cyanophenyl)-4-(4'-fluoro-[1,1'-biphenyl]-4-yl)pyridine-3,5-dicarbonitrile) CNP147 (Fig. 1b) prepared using this flow-based method show a high performance in terms of hydrogen evolution rate (330.3 mmol h^{-1} g^{-1}) and external quantum efficiency (80.3% at 350 nm) after compositions were optimized to yield 4:6 w/w MTPA-CA:CNP147 with 9 wt% Pt.

The high photocatalytic performance of the MTPA-CA and CNP147 nanojunction is attributed to the 1D nanofibre structure, observed by electron microscopy to have a width of approximately 30 nm and a length of several micrometres. This morphology is thought to reduce the probability of charge recombination events between electrons and holes compared to a spherical nanostructure morphology with a large interfacial area. Furthermore, cryo-electron microscopy and X-ray diffraction experiments show that within the nanofibre, the CNP147 component is highly crystalline and, as a result, may enhance phase segregation between the donor and acceptor regions, thereby reducing the likelihood of charge recombination. Overall, the nanofibre morphology generated in both the small-scale batch and large-scale flow-based syntheses of the high-performing materials demonstrates the transfer of knowledge of materials functionality for organic semiconductors across these different scales.

Following the synthesis and characterization of the photocatalysts, Cooper and co-workers perform molecular modelling via quantum chemistry calculations to understand their activity. Interestingly, results from molecular modelling imply that heterojunction photocatalysts show a high hydrogen evolution rate when the donor and acceptor molecules have a moderate binding energy. This finding suggests that despite the complexity of charge transport in organic semiconductors, achieving a moderate binding energy between donor and acceptor molecules may be a useful design rule for light-active organic materials beyond photocatalytic hydrogen evolution, such as in the field of organic photovoltaics.

This research demonstrates the power in using combinatorial synthesis and automated screening for materials discovery. Beyond

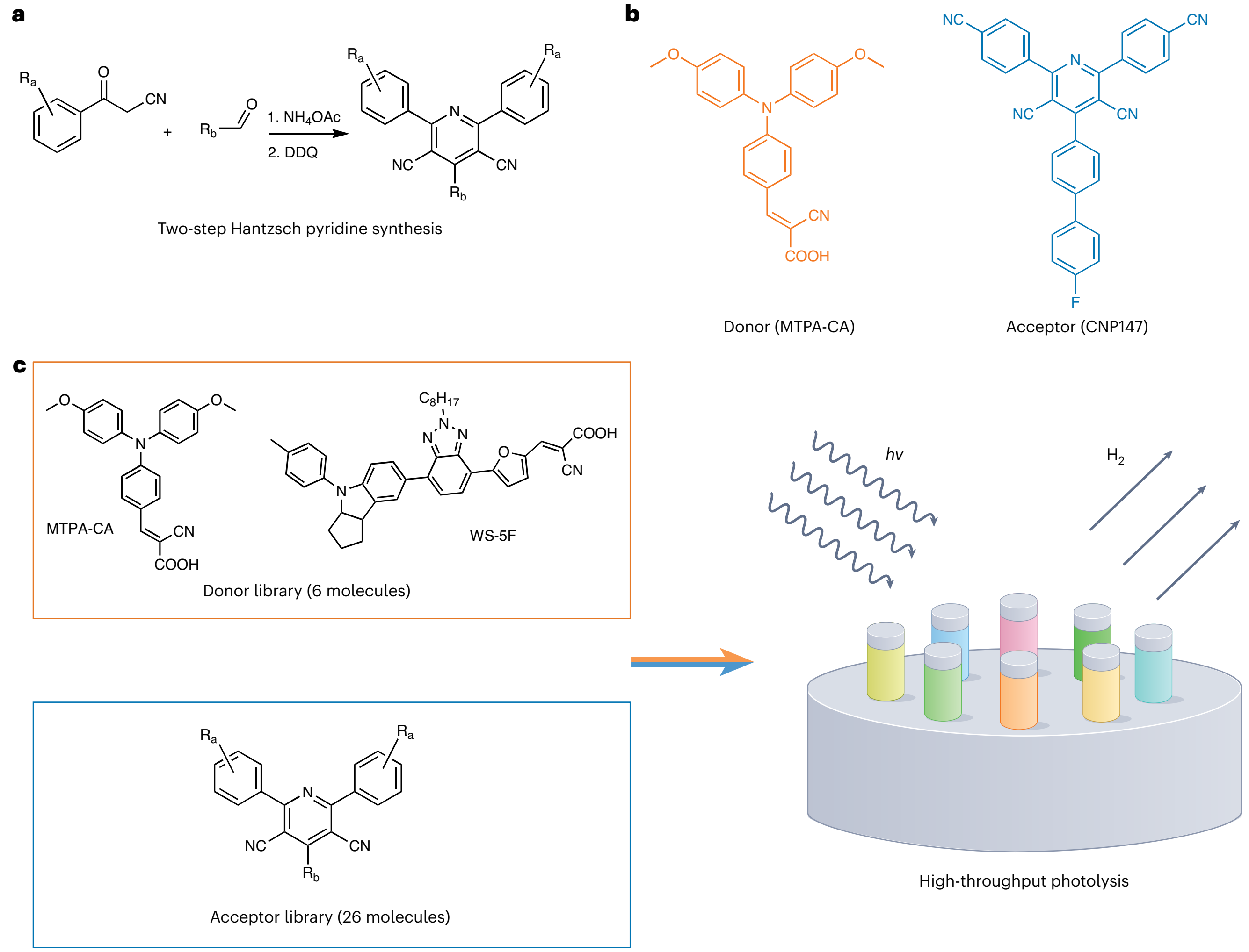

Fig. 1 | High-throughput experimentation for automated screening of donor and acceptor photocatalytic nanojunctions. a, Two-step Hantzsch pyridine synthesis reaction used to generate 26 acceptor molecules. R_a and R_b denote side groups to be attached for acceptor molecules. **b**, The donor and acceptor molecules of the highest performing organic photocatalyst. **c**, Schematic of automated screening procedure to determine photocatalytic hydrogen evolution rate. DDQ, 2,3-dichloro-5,6-dicyano-p-benzoquinone.

photocatalyst development, our understanding of how photo-induced charge separation of organic semiconductors is governed by their multiple factors such as morphology and intermolecular interactions is enhanced. Cooper and co-workers discover that a 1D crystalline nanofibre morphology and a moderate binding energy between a donor and an acceptor molecule are factors that potentially contribute to high-performing photocatalytic water splitting. Moreover, on scale-up of the chemical reactions using flow-based methods, the photocatalytic activity of the best-performing donor–acceptor nanojunctions is maintained. This transfer of knowledge from batch scale to flow scale synthesis implies that automated high-throughput screening may aid in the discovery of organic semiconductors more generally.

By combining automated synthesis and characterization together with machine learning, materials discovery can be further enhanced by integrating active learning methods based on Bayesian optimization[11,12]. Taken together, strategies that combine automated synthesis, screening methods, and machine-learning-based methods offer a glimpse of an exciting future that will transform our approach to the systematic discovery of functional materials.

Seonghwan Kim [1] **& Charles M. Schroeder** [1,2,3,4] ✉
[1]Department of Materials Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA. [2]Department of Chemical and Biomolecular Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA. [3]Department of Chemistry, University of Illinois at Urbana-Champaign, Urbana, IL, USA. [4]Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, IL, USA.
✉e-mail: cms@illinois.edu

References

1. Yang, X. & Wang, D. *ACS Appl. Energy Mater.* **1**, 6657–6693 (2018).
2. Zhang, G., Lan, Z.-A. & Wang, X. *Angew. Chem. Int. Ed.* **55**, 15712–15727 (2016).
3. Bronstein, H., Nielsen, C. B., Schroeder, B. C. & McCulloch, I. *Nat. Rev. Chem.* **4**, 66–77 (2020).
4. Zhang, W. et al. *Nat. Synth.* https://doi.org/10.1038/s44160-024-00494-9 (2024).
5. Potyrailo, R. et al. *ACS Comb. Sci.* **13**, 579–633 (2011).
6. Steiner, S. et al. *Science* **363**, eaav2211 (2019).
7. Christensen, M. et al. *Commun. Chem.* **4**, 112 (2021).
8. Coley, C. W. et al. *Science* **365**, eaax1566 (2019).
9. Angello, N. H. et al. *Science* **378**, 399–405 (2022).
10. Koscher, B. A. et al. *Science* **382**, eadi1407 (2023).
11. Langner, S. et al. *Adv. Mater.* **32**, 1907801 (2020).
12. Angello, N. et al. Preprint at https://doi.org/10.26434/chemrxiv-2023-jqbqt (2023).

Competing interests

The authors declare no competing interests.