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PERSPECTIVE

Challenges in photocatalysis using covalent organic frameworks

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Abstract

Photocatalysis is an attractive, energy-efficient technology for organic transformations, polymer synthesis, and degradation of environmental pollutants. There is a need for new photocatalysts stable in different media and that can be tailored for specific applications. Covalent organic frameworks (COF) are crystalline, nanoporous materials with π-conjugated backbone monomers, representing versatile platforms as heterogeneous, metal-free photocatalysts. The backbone structure can be tailored to achieve desired photocatalytic properties, side-chains can mediate adsorption, and the nanoporous structure provides large surface area for molecular adsorption. While these properties make COFs attractive as photocatalysts, several fundamental questions remain regarding mechanisms for different photocatalytic transformations, reactant transport into porous COF structures, and both structural and chemical stability in various environments. In this perspective, we provide a brief overview of COF photocatalysts and identify challenges that should be addressed in future research seeking to employ COFs as photocatalysts. We close with an outlook and perspective on future research directions in the area of COF photocatalysts.

1. Introduction

Photocatalysis is a method for driving chemical transformations using light as the primary source of energy. Adsorption of light by a photocatalyst produces photoexcited electrons and holes that can subsequently react with a substrate. Because light supplies the energy to produce photoexcited electrons and holes, photocatalyzed reactions can be conducted under milder conditions than in conventional thermal reactions, potentially producing massive cost savings. There is significant interest from the pharmaceutical and chemical industry in harnessing photocatalysis to produce target chemicals and products more efficiently. There is also the potential to use these types of catalysts for applications such as the degradation of environmental pollutants, reduction of CO_2, water-splitting, light-responsive actuators for robotics, and various other photochemical transformations [1–6].

Given the many potential application areas, there is a need for affordable, scalable, and effective photocatalysts. Many photocatalysts are based on inorganic materials such as TiO_2, CdSe, WO_3, ZnS, and ZnO [7], but these absorb primarily in the UV range and have limited, if any, visible light absorption. Significant advances have been achieved using organometallic photocatalysts with Ir or Ru metal centers [2, 3], but both Ir and Ru are scarce metals. Organic photocatalysts have broader light absorption compared with inorganic or hybrid systems [1], but molecular organic photocatalysts are not easily recovered or recycled after use.

Covalent organic frameworks (COFs) can potentially address the need for photocatalysts that absorb visible light, do not rely on precious metals, and are easily recycled. COFs are exciting nanomaterials with a unique combination of characteristics. They were first reported in 2005 [8], and subsequent work has demonstrated a variety of interesting and useful properties. Reticular chemistry provides molecular-level control over characteristics such as pore size, backbone chemistry, and side-chain functionality [9]. COFs are generally synthesized using dynamic chemistries, and under proper synthesis conditions result in crystalline, nanoporous materials [10–14]. COFs are useful for a variety of applications including separations [15, 16], catalysis [17, 18], energy storage [19, 20], ion transport [21, 22], and electronics [23, 24]. They are also all-organic and synthesized using relatively simple building blocks and reaction steps. Furthermore, a subset of COFs has extended π-conjugation, resulting in optically active materials and photoexcited states that can be harnessed for chemical reactions. They can also be designed with a combination of electron donor and acceptor units, which produce long-lived photoexcited states and charge separated states. Finally, COFs are completely insoluble in both organic and aqueous solvents, and therefore they can be easily recovered through centrifugation or filtration and subsequently re-activated and re-used.

The goal of this perspective is to highlight some of the attractive features of COFs for photocatalysis while also identifying critical areas for further work. We do not provide a comprehensive discussion of photocatalysis or COFs, and for more details we point the reader to several reviews which broadly cover photo-redox catalysis [2, 3, 7], organic photo-redox catalysis [1], polymeric photo-redox systems [4, 25], COF photocatalysts [26–34], and applications of photo-redox systems [35]. We envision an increase in the number of researchers interested in COFs for photocatalytic applications in the coming years and work focused on both applied and fundamental challenges.

2. Background and overview

Photocatalysis generally refers to the use of light and photocatalysts to drive a chemical transformation which is energetically unfavorable in the ground state. The process involves light absorption by the photocatalyst to produce an electronically excited state followed by an electron transfer reaction with a substrate and/or sacrificial agent. The reaction of the excited state with a substrate can involve either electron transfer from the photoexcited catalyst to the substrate (oxidative quenching) or electron transfer to the photoexcited catalyst (reductive quenching). In both cases, the reaction with the catalyst excited state is referred to as photoinduced electron transfer (PET) [1], and this is the primary mechanism by which COF photocatalysts drive chemical transformations. Beyond the charge transfer process, physical interactions between the COF and reagents are also important to the photocatalytic process. This can help bring substrates close to the COF to enable charge transfer and may also preferentially orient the substrate to drive a specific transformation.

COFs present unique challenges and opportunities towards the development of organic photocatalysts, and below we discuss several that we believe are most important. Specifically, we discuss the challenge of designing COFs with desired optical and electronic properties, controlling COF surface chemistry for molecular adsorption, processing COF photocatalysts, understanding the transport of substrates or reaction products through COF pores, enhancing COF stability, and scaling up the preparation of COFs (figure 1). Each of these topics present important challenges that need to be addressed for the development of COF photocatalysts for diverse applications.

3. COF design

COFs are made through reticular chemistry [9], which enables molecular-level control over pore size, pore functionality, the chemistry of the monomers, and the chemistry of the linkage (bond between monomers) (figure 2). The pore size can be tuned by varying the size and functionality of monomeric building blocks and will impact the total accessible surface area for adsorption. The pore functionality can be controlled using monomers functionalized with side groups, and these will influence the interactions between the COF and molecules in solution or adsorbed onto the surface. The COF bandgap will be determined by several factors, including the units that make up the COF backbone, the conformation or planarity of the COF, and also by interlayer interaction, in the case of 2D COFs. The bandgap can be tuned by increasing the conjugation length of the backbone [36], incorporating electron donating or withdrawing substituents [37, 38], incorporating electron donor-acceptor dyads in the COF backbone [39], and through exfoliation of 2D COFs to produce nanosheets [40].

Altogether, these strategies provide ample opportunities for COF design but also represent a significant challenge for optimization of COF structure for a particular application. In the sections that follow, we discuss the design challenges in the context of photocatalytic applications.

4. Challenges and opportunities

The rational design of COFs for photocatalytic applications is challenging because several properties must be optimized simultaneously. Some of the most important properties are:

(1) *Optical and electronic properties* that control how the COF interacts with light and subsequently transfers light-derived energy to catalyze a target reaction.

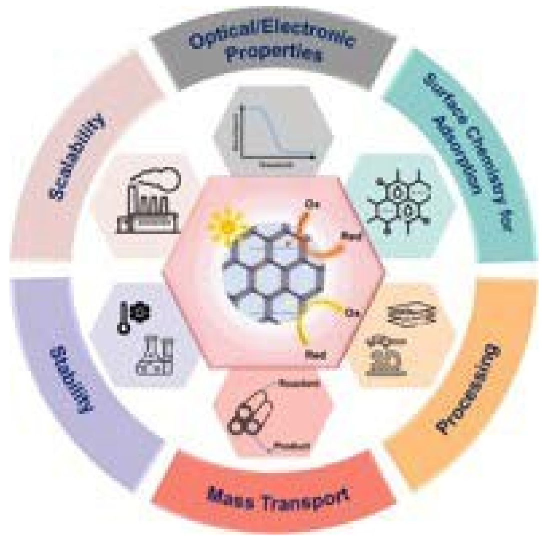

Figure 1. Overview of challenges in the development of COF photocatalysts.

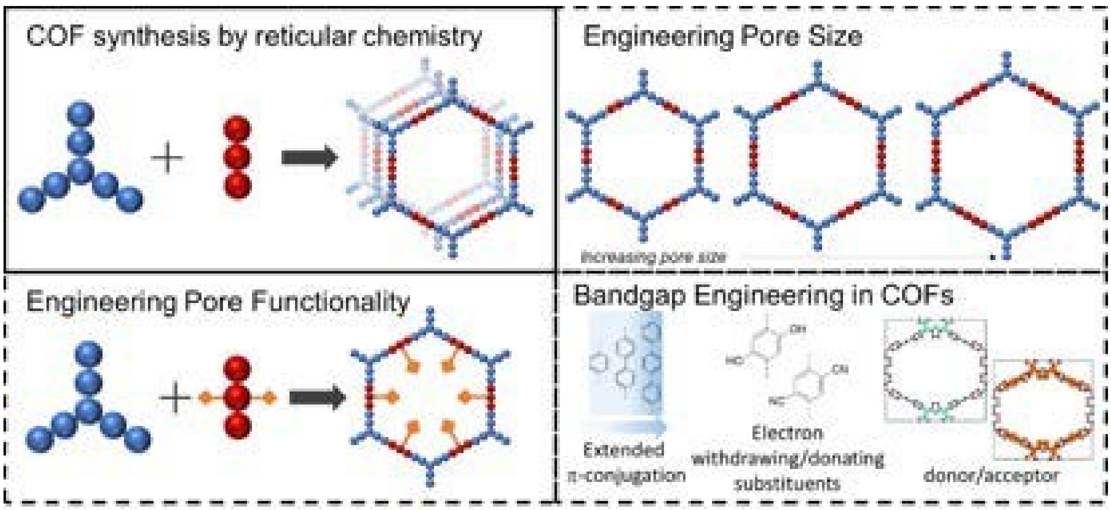

Figure 2. Overview of COF design and engineering. COFs are made using reticular chemistry, which enables engineering pore size, pore functionality, and COF electronic and optical properties through selection of the monomeric building blocks and linkage chemistry.

(2) *Surface chemistry* that controls molecular sorption of reactants at catalytically active sites.
(3) *Transport properties* that control how effectively substrates can be delivered to target sites, often in the presence of competing reactants.
(4) *Structural stability* in differing reaction environments, which dictates catalyst lifetime.
(5) *Processability* of tailored COF designs geared toward specific application scenarios, such as achieving catalyst immobilization without inhibiting light penetration.
(6) *Scalability* for technological application, which governs the ultimate adaptation of the COF photocatalyst.

We address each of these properties and associated design constraints in the following sections. Ultimately, the essential challenge is identifying COF photocatalysts with suitable properties in all of these design categories.

4.1. Designing COFs with desired optical and electronic properties

COFs with conjugated backbones have useful photophysical properties that potentially enable their use as photocatalysts. A full discussion of the photophysical processes that produce excited electrons and holes in COFs is beyond the scope of this perspective and is discussed in more detail elsewhere [1, 41]. Briefly,

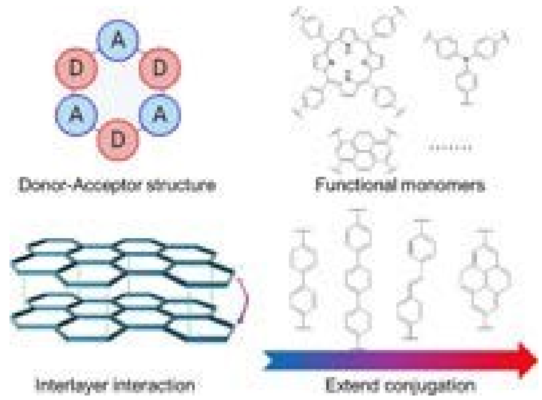

Figure 3. Schematic for COF bandgap engineering strategies.

absorption of light produces electronically excited states. In organic materials, these are bound electron-hole pairs with energies that depend not only on the material chemistry but also on structural conformation and environment. In general, predicting these effects is challenging, and a combination of experiment and modeling is needed to elucidate photophysical characteristics.

A variety of strategies have been implemented to engineer the bandgap and energy levels of COFs, including incorporating alternating electron-rich and electron-deficient (donor-acceptor) monomers, monomers with specific functionalities, tailoring the layer-layer interactions, and engineering the conjugation length (figure 3) As an example, Meier *et al* prepared and studied a series of seven different triazine COFs varying in the length of a phenylene spacer [42]. Experimentally, they observed a decreased optical bandgap with increasing phenylene spacer length due to greater delocalization of electron density. Complementary electronic structure calculations found a reduction in the ionization potential with increasing linker length. The reduced ionization potential indicated that the energy level of the highest occupied molecular orbital increased with linker length. This increase in turn reduced the energetic favorability for a photo-generated hole to oxidize water, thus lowering the thermodynamic driving force for the water splitting reaction. As a result, they observed an optimal linker length intermediate between the longest and shortest linker tested [42]. In another example, Sachs *et al* used experiments and simulations to show that the presence of water along a conjugated polymer backbone produced a more polar environment, which resulted in improved efficiencies for charge separation and longer lifetimes for photoexcited electrons [43]. Similar effects will influence the electronic properties of COFs.

As a result, the design of optical and electrical properties of COFs often relies on empirical approaches. For example, constructing donor-acceptor structures by using electron-deficient and electron-rich monomers to construct the COF backbone can produce broad light absorption and enhanced charge separation. Donor-acceptor pairs can be identified using electronic structure calculations to assess orbital energy level alignments [44]. Another popular approach to the design of COF photocatalysts is the incorporation of functional monomers such as porphyrins that exhibit broad light absorption [45]. Libraries of common monomeric building blocks for photoactive COFs are provided in recent reviews [29, 33].

Linkage chemistry is also important for band gap engineering. In recent work. He *et al* compared a series of COFs with similar monomeric building blocks but varying in the linkage chemistry [46]. They tested hydrazone, imine, azine and carbon-carbon double bond (C=C) linkages and observed an impact on the resulting absorption band, emission color, quantum yield, fluorescence lifetime, HOMO/LUMO levels, distribution of frontier electron density, concentration and mobility of charge carriers, and magnetic permeability, thereby affecting the final photocatalytic performance. Their work also demonstrated that hydrazone linkages do not provide conjugation across the linkage, imine and azine provide partial conjugation, and C=C provides the greatest amount of conjugation between monomers. On the other hand, the synthesis of COFs with C=C linkages is challenging due to the poor reversibility of this bond.

For 2D COFs, interlayer interactions also affect their electronic properties. Lukose *et al* investigated a set of reported and hypothetical 2D hexagonal COFs examining their electronic properties by density functional theory (DFT) and DFT tight-binding (DFTB) methods [47]. They investigated the role of stacking, and while they found that the electronic densities of states (DOS) was not significantly different from that of a monolayer, layering did impact the band gap. These examples demonstrate the complexities involved in designing COFs for a specific photochemical process. While these approaches can be effective, they only

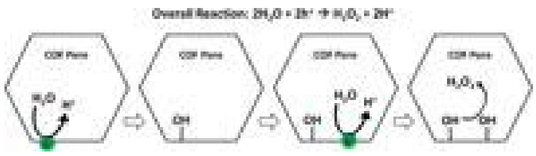

Figure 4. Illustration of COF surface chemistry mediating the direct oxidation of water to form hydrogen peroxide, as proposed in Chen *et al* [50].

provide general guidelines for the preparation of COFs and cannot account for the effects of solvent, crystallinity, or defects.

More efficient and effective approaches for exploring the vast parameter space of COFs are needed. One possible approach is to use high throughput methods for COF synthesis and characterization [48]. Another approach may be to rely on coarse grained computational methods that enable more efficient and accurate exploration of COFs. The large unit cell of COFs often renders electronic structure calculation methods impractical, especially when accounting for several stacking layers and the presence of solvent. In such cases, atomistic interatomic potentials are necessary to study the dynamic structural evolution of the COF under different conditions (e.g. varying solvents and temperatures), as demonstrated by Duong *et al* [49]. Structural information sampled with molecular dynamics using classical interatomic potentials can then motivate appropriately simplified models amenable for more expensive electronic structure calculations. It is currently not possible for experiments or simulations alone to fully elucidate the physical and optoelectronic properties of COFs, and therefore combined approaches to COF analysis will continue to be necessary.

4.2. Controlling COF surface chemistry for molecular adsorption

COF surface chemistry can also play a direct role mediating interactions with different reactants (i.e. substrates, sacrificial agents, and solvent molecules). This chemistry features direct formation of chemical bonds between functional units of the COF structure and the reactants. The impact of COF surface chemistry is relatively understudied compared with electronic and photophysical properties, but prior work has demonstrated how it can have an important impact on photocatalytic activity. Chen *et al* studied the photocatalytic reduction of H_2O to produce H_2O_2 in porous triazine frameworks containing acetylene or di-acetylene linkers functionalities in the backbone. They found that frameworks containing these functional groups could bind to and stabilize the formation of adsorbed OH, an intermediate in the production of H_2O_2. They also observed enhanced production of H_2O_2 and attributed this to the formation of chemical bonds on the linker itself [50]. Thus, in this example the COF structure acts similarly to a traditional heterogeneous catalysis with extended surfaces by directly forming chemical bonds with the substrate to stabilize reaction intermediates (figure 4).

There are several examples where side-chain chemistries are modified to enhance adsorption of a target molecule or tune hydrophilicity. For example, Ji *et al* designed COFs that contained side-chains terminated with primary amine groups. They found that these primary amines significantly enhanced the adsorption capacity for molecules containing an acid functionality, such as perfluorooctanoic acid [51]. Another recent study demonstrated that simply changing the length of alkyl substituents in a hydrazone COF aerogel could widely tune the hydro- and oleophilicity, resulting in a material that could absorb significant amounts of water (up to 20 g/g COF) to one that completely repelled water [52]. Hydrophobic side-chains can also discourage interactions with water and reduce the relative rate of competing redox reactions like water splitting in favor of the target reaction [53]. Additionally, side-chains can also influence interactions with a substrate to provide chiral selectivity [54, 55].

However, predicting these properties *a priori* remains a challenge due to the large size of the required unit cell for computations and the complex interplay of materials chemistry, crystallization, conformation, and solvent environment. Experiments and simulations also must account for various conformations of the adsorbent COF and different locations of the adsorbate to find the lowest energy binding sites while also accounting for interactions with solvent molecules. The impact of dynamic structural changes at the molecular level on electrochemical properties is also challenging to capture with static electronic structure calculations. Additionally, modifications and adjustments to side chains often impact the electronic structure, so side chains introduced to enhance adsorption may have deleterious effects on light absorption and active site reactivity. As an example, Li *et al* introduced pillararenes into a hydrazone-linked COF (see figure 5). This functionality affected charge separation efficiency due to its electron-rich cavity and also enhanced the degree of conjugation of the framework, consequently influencing the photoelectric properties [56].

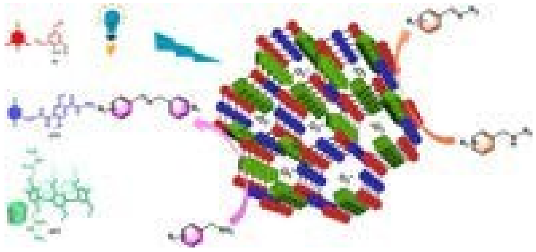

Figure 5. Illustration of the idealized formation of hydrazone- linked macrocycle-enriched COFs. Reprinted with permission from [56]. Copyright (2022) American Chemical Society.

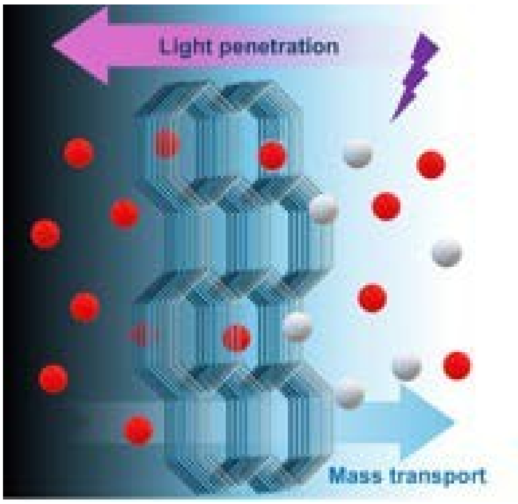

Figure 6. Illustration of light penetration and mass transport during COFs photocatlytical process.

We currently lack design rules for tailoring the surface chemistry of COFs to particular photocatalytic applications. Design rules for enhancing adsorption or reducing interaction with a specific solvent or co-contaminant could help increase photocatalytic activity and may come with other benefits, such as improving stability due to reduced side-reactions. Future work using experiments and simulations to establish such design rules is a critical need in the field.

4.3. Understanding the transport of substrates or reaction products through COF pores

A unique characteristic of COFs is their regular, nanoporous architecture. This potentially provides a large surface area for molecular adsorption and interaction. However, surprisingly, it remains unclear how relevant this nanoporous architecture is for photocatalysis. As in other nanoporous heterogeneous catalysts, the restricted pore size presents transport and diffusion limitations [57]. Additionally, light penetration is reduced inside a pore away from the outer surface, and the COF morphology can also impact the directionality of charge transport (figure 6). As an example of the latter, Niu *et al* prepared crystalline and amorphous triazine framework photocatalysts and found that the amorphous triazine framework outperformed the crystalline COF. They attributed this to three-dimensional charge transport in the amorphous material compared with two-dimensional transport in the crystalline COF [58]. Conversely, Wang *et al* developed a COF based on a benzo-bis(benzothiophene sulfone) moiety and found that their COF showed a much higher activity for photocatalyst hydrogen evolution than its amorphous or semicrystalline counterparts. They attributed the high quantum efficiency of this COF to the crystallinity, strong visible light adsorption, and wettability [59].

While there has been an emphasis on studying and developing transport properties of COFs [60, 61], more work is needed to understand the importance of intrapore transport in photocatalytic COF processes. Independent measurements of molecular transport, such as through pulsed field-gradient NMR measurements [62], should be combined with independent measurements of photocatalytic reaction rates. These can also be coupled with variations in the COF pore size and architecture to gain insight into the relationship between COF structure, pore size, and photocatalytic reaction rates. It is also possible to systematically vary COF crystallinity [63], enabling a deeper understanding of how crystal structure impacts both transport and catalysis. Studies into transport properties can both advance our understanding of morphology in the catalytic process and help identify optimal morphological features for enhancing photocatalytic reaction rates.

4.4. Processing COF photocatalysts

Processing can present unique challenges to the application and use of COF photocatalysts. COFs are typically produced in the form of insoluble powders and are completely insoluble in aqueous or organic solvents. Unlike organic photocatalysts, COFs are heterogeneous catalysts. Therefore, strategies to immobilize the COFs are needed to scale up photochemical transformations. For example, photocatalysts can be immobilized on a surface or the walls of a reactor [64]. Another approach is to use an immersion well reactor, where the source of light is placed inside the reaction vessel [65]. Flow-based photochemical reactors offer a simple approach to scale-up and can also reduce reaction times under the appropriate design considerations [35, 66]. Implementing each of these approaches with COFs requires addressing processing challenges to immobilize the COF photocatalyst in the reactor while also ensuring sufficient light penetration.

There have been important advances in COF processing [67–69] that have not yet been leveraged in COF photocatalysis processes. For example, a variety of methods for making COF foams and gels are now available, affording microporous COF scaffolds for use as photocatalytic materials [70–72]. Several approaches are available for fabricating COF thin films [67], including monolayer COF films with aligned pores [73], enabling approaches to immobilized COF photocatalysts on surfaces and reactor walls. Recent work has also enabled solution-based processing approaches [71], which can facilitate the preparation of coatings, control over film thickness, and potentially produce packed bed microreactors. It remains unclear, however, whether these various processing methods can be used for photoactive COFs and how the processing approach will impact light penetration, morphology, and performance.

4.5. Stability

COFs are formed through dynamic chemistries, which enable crystallization but can also result in chemical and structural degradation. Understanding stability limitations of COFs and degradation mechanisms will be important to any application of COF photocatalysts. For example, Zhu *et al* studied the activation stability of COFs and demonstrated how pore size, pore substituent, and solvent surface tension impacted COF porosity and crystallinity [74, 75]. They also demonstrated that the activation stability could be tuned by selecting building blocks with varying sizes of pore substituents [63]. Several studies have investigated COF stability under basic or acidic aqueous conditions, and in general the stability depends on the linkage chemistry, pore size, and substituent. Boron-based linkages are highly reversible and COFs based on this linkage have high crystallinity and surface area. However, their chemical stability is limited due to their susceptibility to nucleophilic attack by water [76]. Imine-linked COFs have moderate to high chemical stability [77] depending on microenvironment around chemical bonds. Nevertheless, there are cases where imine linkage can be degraded (or digested [78, 79]) under extremely acidic or alkaline conditions, which can lead to the collapse of the COF framework. For example, Qian *et al* investigated the transformation of COF-to-COF using a linker exchange strategy. To determine the extent of linker exchange over time, they subjected COFs to complete hydrolysis in a hot sodium hydroxide solution and monitored the process using ^{1}H NMR spectroscopy. Similar digestion experiments can also be conducted under high concentrations of acidic conditions. Zhu *et al* used concentrated deuterated hydrochloric acid to dissolve COF and determine the monomer ratio in three-dimensional COF [79]. In contrast, triazine and sp^2 carbon-linkage are more robust linking chemistries, providing not only remarkable stability but also enhanced conjugation [80–82]. Nonetheless, obtaining high-quality crystalline materials using these two linking methods is more challenging.

In addition to the reduction in crystallinity of 2D COFs due to chemical stability, other factors in reaction processes can alter the properties of COF material. First, the characteristics of 2D materials determine that changes in interlayer stacking patterns can lead to reduced or lost crystallinity and alterations in photoelectric properties [74, 83]. This is due to the electron transitions, energy transfer, and material exchange occurring during the reaction, which can affect the conformation of COFs, and the reversibility of these changes remains largely unknown. Secondly, different wavelengths of light sources are introduced during the reaction process, yet the photostability of COFs, whether light exposure causes irreversible damage or alteration of the structure, remains relatively underexplored [84]. Research on stability is advantageous for developing long-lasting COF photocatalysts that balance performance and stability, allowing for their repeated and sustainable use.

4.6. Scalability

Although COFs are all-organic materials, this does not mean that they are necessarily low cost, affordable, or scalable. Recent analysis of organic semiconductors for photovoltaics has demonstrated that many high performance materials are also impractical due to synthetic complexity, requiring as many as 14 separate reaction and purification steps [85]. However, a similar analysis of COF scalability has not been reported. While COF building blocks are generally much simpler than those of organic semiconductors, reaction times can be long, and purification of the final product generally involves several solvent washing steps along with activation using supercritical CO_2 or a low-boiling point solvent. There is both an opportunity to analyze the scalability of common COF photocatalysts and also to develop and demonstrate more scalable and low-cost approaches to the synthesis of COF photocatalysts. For example, Zhang *et al* reported COFs prepared from 2,4,6-collidine as a building block and demonstrated the synthesis of charged, vinylene-linked COFs at product yields exceeding 500 g [86]. Further efforts to scale-up the synthesis of COFs and bring down reagent and preparation costs will be necessary to translate COF synthesis to real-world applications.

5. Summary and outlook

COFs provide tremendous opportunities for low-cost, energy efficient transformations through photocatalysis and enable optimization and tailored design through molecular-level tuning of pore size and functionality. Specifically, a variety of photochemical transformations are accessible only using molecular catalysts [3], which can be difficult or impossible to re-use or recycle. COFs can potentially replace these molecular catalysts, providing a reduction in cost with little or no reduction in performance. As detailed in this perspective, work is needed to address both fundamental and practical challenges related to COF photocatalysis.

At a fundamental level, we need more efficient approaches for designing COFs with desired electronic properties tailored to specific photocatalytic applications. We see significant potential in the development of high throughput synthesis and characterization methods coupled with computational predictions and machine learning algorithms to identify promising COF chemistries. These may be essential to take full advantage of COFs and also address challenging targets for photocatalysis, such as the photochemically-catalyzed ring opening metathesis polymerization using pyrylium salts as oxidizers [87].

Tailoring the surface chemistry of COFs for photocatalytic applications remains an understudied area of research. Most studies have emphasized tailoring energy levels and bandgaps, but the physical interactions between COFs and substrates or reagents can play an equally important role in photocatalysis. A simple approach to improve the performance of COF photocatalysts would be to systematically tailor the hydrophobicity/hydrophilicity to identify an optimal surface chemistry for a specific application. A more elegant but challenging approach would be to introduce specific surface functional groups that interact with reagents in a desired way to improve product yields.

Very little is known about the role of transport through nanoscale pores and its importance to photochemical transformations. In some cases, depending on the size of substrates, photochemical transformations may occur on the surface of COF particles and transport through the pores may not be important. Experiments or simulations that can probe the role of transport into/through COF nanopores will help aid in the design of more effective COF photocatalysts.

There has been tremendous progress in the scalable synthesis and processing of COFs [88], but processing strategies relevant to photocatalytic applications are needed. Specifically, flow photochemistry systems [89] provide a number of advantages in terms of cost and efficiency, but are difficult to implement with COFs as the catalyst due to their poor processability. Approaches to produce such continuous flow photoreactors using COFs could provide a boost in terms of conversion efficiency and productivity rates. Advances in COF processing now enable the preparation of gels, thin films, composites, and coatings, but these have yet to be explored widely for photocatalytic applications.

Addressing long-term stability will be an important issue for the implementation of COFs in real-world applications. Work investigating the stability of COFs in the presence of different solvents and solution conditions has demonstrated that highly stable COFs can be produced by engineering the linkage chemistry and introducing appropriate substituents. In some cases, the most stable linkages, such as the C=C double bond, also provide favorable electronic properties. A number of strategies are therefore available for improving COF stability while maintaining favorable electronic properties. The role of extended exposure to radiation should also be emphasized. Finally, the scalable production of COFs will also be critical to translation to real-world applications. Most work with COFs is performed at the laboratory scale, so it remains unclear how feasible it will be to scale up the production at reasonable while maintaining product quality. This may require developing new processing and synthesis strategies or identifying low-cost monomers as building blocks [86].

In summary, a number of fundamental and practical challenges remain in the development and exploration of COF photocatalysts. These challenges provide excellent opportunities for both scientists and engineers to work together to advance the development of COF photocatalysts. We look forward to further developments in the field and envision rapid progress in the development and discovery of COF photocatalysts.

Data availability statement

No new data were created or analysed in this study.

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