RSC
Applied Interfaces

ROYAL SOCIETY
OF CHEMISTRY

REVIEW

View Article Online
View Journal | View Issue

Cite this: *RSC Appl. Interfaces*, 2025, **2**, 1527

Current states and future challenges of multifunctional flame-retardant polyurethane coatings

Xingyao Li, Kangcheng Xu, Jiangtao Wu, Ye-Tang Pan, * Xiangmei Li,
Jiyu He* and Rongjie Yang

Received 28th July 2025,
Accepted 28th August 2025

DOI: 10.1039/d5lf00215j

rsc.li/RSCApplInter

Polyurethane (PU) coatings are widely utilized in fields such as construction, electronics, transportation, and aerospace due to their excellent mechanical properties, resistance to chemical corrosion, and tunable molecular structure. However, their inherent flammability significantly restricts their application in environments with high fire safety requirements. Moreover, single-functionality is no longer sufficient to meet the demands of complex application environments. In recent years, researchers have developed multifunctional flame-retardant PU coatings that combine flame retardancy with additional functionalities, such as corrosion resistance, self-healing, and hydrophobicity, through the application of nanocomposites, surface modification techniques, and synergistic flame-retardant systems. This paper systematically reviews the flame-retardant mechanisms and functional design strategies of advanced polyurethane coatings, with the aim of providing valuable references for the design and development of next-generation high-performance flame-retardant materials.

1 Introduction

Polyurethane (PU) coatings, owing to their unique micro-phase separation structure composed of soft and hard segments, exhibit excellent performance tunability, enabling their application across a wide range of industrial fields.[1–10] However, PU's inherent flammability remains a major obstacle to its widespread application.[11–14]

Researchers have made significant progress in enhancing the flame-retardant properties of polyurethane coatings. For example, Sun *et al.* developed an intrinsically flame-retardant polyurethane coating and applied it to polyimide fabric. The synergistic interaction among phosphorus, nitrogen, and sulfur elements notably enhanced the flame-retardant performance of the coating.[15] Liu *et al.* developed an environmentally friendly flame-retardant polyurethane coating by incorporating ammonium polyphosphate (APP), montmorillonite (MMT), and (3-aminopropyl)triethoxysilane (APTES).[16] Luo *et al.* developed a polyurethane coating exhibiting P/B/N synergistic flame retardancy, which achieved a limiting oxygen index (LOI) of 29.8% and a UL-94 V-0 rating.[17] The aforementioned studies serve as typical examples of synergistic enhancements in polyurethane coatings achieved through combined gas-phase and condensed-phase flame-retardant mechanisms. To address the diverse demands of industrial applications, polyurethane (PU) coatings are increasingly being engineered to integrate multiple functionalities beyond flame retardancy.[18–20] The development of multifunctional flame-retardant materials typically focuses on enhancing flame-retardant performance as the core objective. Through the introduction of various functional fillers or structural design strategies, additional properties, such as electromagnetic shielding, self-healing, and hydrophobicity, which can be imparted to the materials, enabling their use in complex and demanding environments. For example, incorporating conductive fillers such as carbon nanotubes (CNTs), MXene, and graphene into flame-retardant matrices—including polymers, aerogels, and composite materials—can establish highly efficient electromagnetic wave absorption and shielding networks[21–24] (Fig. 1). However, the incorporation of multiple functionalities often compromises the mechanical properties of polyurethane.

Although the research on polyurethane (PU) coatings has made significant progress in terms of multifunctionality and high performance, it still faces many challenges in practical engineering applications. These problems mainly arise from the conflicts between the inherent properties of the material, process limitations, and the adaptability to complex environments. This paper systematically reviews the latest research progress of multifunctional flame-retardant PU coatings, analyzes their application bottlenecks, and discusses the future development trends.

National Engineering Research Center of Flame Retardant Materials, School of Materials Science & Engineering, Beijing Institute of Technology, Beijing 100081, P. R. China. E-mail: pyt@bit.edu.cn, hejiyu@bit.edu.cn

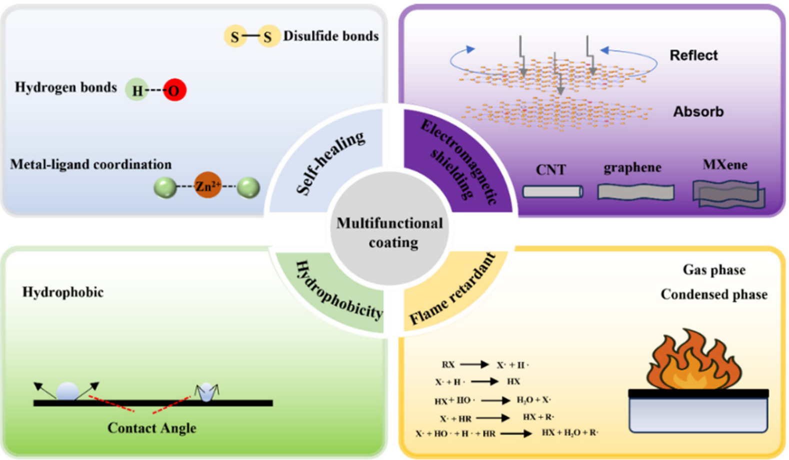

Fig. 1 Schematic diagram of multi-functional polyurethane coating.

Compared with existing similar reviews, this article not only provides a detailed summary of the mechanisms of traditional flame-retardant polyurethane (PU) coatings but also systematically analyzes multifunctional design strategies—such as self-healing, hydrophobicity, and electromagnetic shielding—covering multiple dimensions from basic research to practical applications. The performance degradation of PU coatings in complex environments (*e.g.*, high temperature, high humidity, and corrosive conditions) is summarized, and improvement strategies, including surface micro–nano structure design, are proposed to better align with engineering needs. Current research bottlenecks are clearly identified, including conflicts between multifunctional properties (*e.g.*, balancing mechanical strength and self-repair efficiency), environmental toxicity issues (*e.g.*, isocyanate volatilization), and challenges in large-scale production, thereby providing a clear direction for future research. In line with sustainable development, the discussion also explores the potential of bio-based PU and degradable materials, reflecting the current trend toward environmental protection.

2 Flame-retardant polyurethane coating

The preparation of flame-retardant polyurethane (PU) coatings is generally categorized into two main approaches: additive-type systems and intrinsic-type systems. Additive-type flame retardants, which are physically blended into the PU matrix, typically offer superior flame-retardant performance. However, their incorporation can negatively affect the mechanical properties, compatibility, and long-term stability of the coating.[25–27] In contrast, intrinsic-type flame retardants are chemically bonded to the polymer backbone, providing improved durability and dispersion.[28–30] However, due to their limited flame-retardant effectiveness, intrinsically flame-retardant systems have not yet fully replaced additive-based flame-retardant approaches. The performance of polyurethanes synthesized from different isocyanates was systematically summarized and compared (Table 1). Through orthogonal experimental design, formulations meeting specific performance requirements were efficiently screened. This approach enables the rational design of polyurethane materials tailored to diverse application scenarios.

2.1 Additive flame-retardant polyurethane coating

The physical incorporation of flame retardants into the matrix material offers advantages such as simple preparation, low cost, and flexible compositional tuning, and currently represents the predominant method for fabricating flame-retardant materials. Additive flame retardants primarily include metal hydroxides, brominated compounds, phosphorus-based, nitrogen-based, and silicon-based flame retardants, among others.[31–34] Additive flame retardants primarily include metal hydroxides, brominated, phosphorus-based, nitrogen-based, and silicon-based flame retardants.[35–38] Among these, brominated flame retardants have been gradually phased out due to their environmental and health concerns. We systematically compared additive-type and intrinsic-type flame retardants (Table 2).

During combustion, metal hydroxides absorb heat and release water vapor, while simultaneously decomposing to form metal oxides that deposit on the material surface. These oxides promote char layer formation by acting as a thermal barrier and enhancing surface insulation. When exposed to heat, phosphorus-based flame retardants decompose to generate strong dehydrating agents such as phosphoric acid and polyphosphoric acid. These agents promote dehydration and carbonization of the polymer surface, leading to the formation of a dense char layer that serves as an effective thermal and oxygen barrier. To address the trade-off between flame retardancy and mechanical performance, researchers have incorporated nanomaterials into polyurethane coatings, thereby mitigating the adverse effects of flame-retardant

Table 1 Comparison of the advantages and disadvantages of polyurethane coatings of different isocyanate types

Isocyanate type	Representative monomer	Advantage	Limitation
Aromatic isocyanate	Toluene diisocyanate (TDI)	Low cost, mature industrial production process	Easily yellowing (degradation of benzene rings after UV irradiation)
	Di-phenylmethane diisocyanate (MDI)	High reactivity, fast curing speed High mechanical strength (suitable for hard coatings)	Poor weather resistance. Outdoor use requires the addition of stabilizers. High toxicity (with strong volatile irritant properties)
Aliphatic isocyanates	Hexamethylene diisocyanate (HDI)	Resistant to yellowing, suitable for outdoor use (automobile, building varnish)	High cost (complex synthesis process)
	Isophorone diisocyanate (IPDI)	Excellent chemical resistance (good hydrolysis stability)	The reactivity is relatively low and requires a catalyst or high temperature for curing
		Low toxicity (low volatility)	Excessive flexibility (some high-hardness scenarios require modification)
Aliphatic trimer	HDI trimer	High crosslinking density, wear resistant, solvent resistant	Expensive in price
	IPDI trimer	Excellent weather resistance (high-end automotive paint)	Brittleness may increase (requiring a toughening agent to balance it)
		Low viscosity, easy to process	The conditions for solidification are very strict (requiring precise temperature and humidity control)
Modified isocyanate	Silicone-modified IPDI	Special functions (such as hydrophobicity and anti-fouling properties)	Raw materials are scarce and the cost is extremely high
	Fluorine-modified HDI	Resistant to extreme environments (high and low temperatures, corrosion)	The process is complex (requiring customized synthesis)
		Surface energy can be adjusted (wetting property control)	Compatibility challenge (mixing with other components)

Table 2 Comparison between intrinsic flame retardants and additive flame retardants

Comparison dimension	Intrinsic flame retardants	Additive flame retardant
Definition	Flame-retardant groups can be covalently incorporated into the main or side chains of the polymer	The physical mixture is dispersed within the polymer matrix without forming covalent bonds with the polymer chains
Flame retardant mechanism	Mainly through chemical decomposition to form a carbon layer or release blocking gases (such as phosphorus, nitrogen, silicon, *etc.*)	It achieves flame retardancy through physical actions (such as absorbing heat, diluting oxygen, forming a protective layer, *etc.*)
Advantage	It exhibits good durability, is resistant to migration or precipitation, has minimal impact on mechanical properties, and is environmentally friendly, with no release of small molecules	It is simple to prepare, cost-effective, exhibits high flame retardancy with a flexibly adjustable formulation, and is compatible with existing processing techniques
Disadvantage	It is complex to synthesize and costly, may exhibit relatively low flame-retardant efficiency, possesses a single function, and is difficult to multi-functionalize	It is prone to migration or leaching, which compromises long-term performance; may diminish mechanical properties; and certain halogen-containing flame retardants are environmentally unfriendly
Typical example	Polyurethane structures incorporating phosphorus, nitrogen, and silicon elements (*e.g.*, phosphorus-based polyurethanes and silicon-modified polyurethanes)	Aluminum hydroxide (ATH), ammonium polyphosphate (APP), and bromine-based flame retardants (the latter being gradually phased out)
Applicable scene	High-end applications (such as electronic packaging, aerospace), require long-term stability and environmental friendliness	In the general industrial sectors (such as building materials and textiles), there is a need for rapid implementation of flame retardancy while maintaining cost sensitivity
Future direction of development	Improve flame retardancy efficiency; develop multi-functional intrinsic flame retardant systems	Develop halogen-free and environmentally friendly flame retardants, nano-composite technology improves compatibility

fillers on mechanical properties.[39] Liu *et al.* developed an environmentally friendly polyurethane coating *via* a one-step synthesis process using ammonium polyphosphate, montmorillonite, and triethoxysilane as raw materials. Compared with the unmodified sample, the coating exhibited a 50.8% increase in the limiting oxygen index (LOI), while the peak heat release rate (PHRR) and total smoke production (TSP) were reduced by 80.28% and 66.7%, respectively.[16] Duan *et al.* prepared a core–shell flame retardant by coating a multilayer polyelectrolyte composed of chitosan and silica onto polyphosphoric acid *via* electrostatic interaction[40] (Fig. 2). This preparation process avoids the use

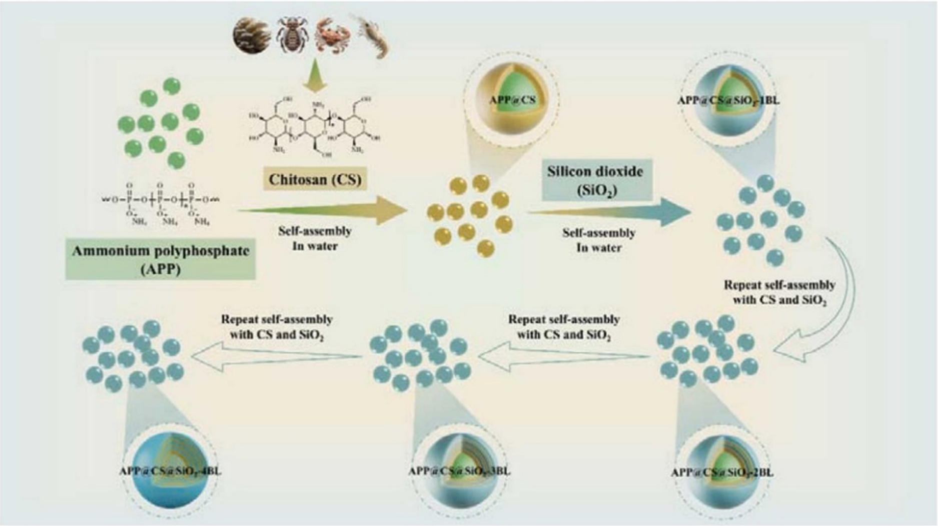

Fig. 2 Synthetic diagram of the shell–core flame retardants. Reproduced from ref. 32 with permission from [Elsevier], copyright.

of organic solvents, making it a relatively environmentally friendly approach. It offers valuable insights for advancing solvent-free strategies in flame-retardant materials research.

2.2 Intrinsic flame-retardant polyurethane coating

Intrinsically flame-retardant polyurethane (PU) coatings achieve flame retardancy through molecular structure design, such as the incorporation of flame-retardant functional groups or heat-resistant segments into the polymer backbone.[41] In contrast to traditional additive-type flame-retardant PU coatings, which rely on the physical blending of flame-retardant agents (*e.g.*, halogenated or phosphorus-based compounds), intrinsic systems offer several notable advantages: superior mechanical properties, enhanced durability, and the elimination of flame-retardant migration over time. Puyadena designed an intrinsic flame-retardant polyurethane coating.[42] Phosphoric acid compounds were grafted onto the molecular chains of polyurethane to prepare an intrinsically flame-retardant polyurethane coating. The results demonstrated that the introduction of phosphorus had minimal impact on the polymerization process, while significantly promoting the crosslinking of the polyurethane network. This study provides a theoretical foundation for the design and fabrication of polyurethane coatings with enhanced mechanical performance.

Currently, intrinsically flame-retardant coatings still face several key challenges in practical applications, primarily related to limited functionality and insufficient durability under complex environmental conditions. Many intrinsically flame-retardant coatings exhibit only basic flame-retardant functionality, lacking additional complementary properties such as corrosion resistance, mechanical robustness, or self-healing capability. For example, while certain polymer-based flame-retardant coatings effectively suppress combustion at elevated temperatures, they often suffer from a significant reduction in mechanical performance. This degradation can lead to cracking and delamination of the coating, ultimately compromising its long-term protective performance and reliability in demanding environments.

Under harsh environmental conditions, such as high temperature, high humidity, acid–base corrosion, or ultraviolet (UV) radiation, the chemical stability of certain flame-retardant coatings may be inadequate. This can result in the decomposition or migration of flame-retardant components, ultimately leading to a gradual loss of protective performance. For example, phosphorus-containing flame retardants are susceptible to hydrolysis in humid environments, which significantly diminishes their flame-retardant efficiency. Similarly, some nanocomposite coatings may undergo photoaging under prolonged UV exposure, thereby compromising their long-term durability and functionality.

Balancing flame-retardant properties with other functional requirements, such as electrical conductivity, hydrophobicity, and wear resistance, remains a significant challenge in the development of multifunctional coatings. For example, in electronic devices, it is essential to simultaneously ensure effective flame retardancy while maintaining optimal heat dissipation and electromagnetic shielding performance. These competing demands place stringent requirements on material selection, structural design, and the integration of multifunctional components, necessitating advanced formulation strategies and precise control over material interfaces.

3 Multifunctional polyurethane coatings

Polyurethane (PU), as a widely used polymer material, its single performance optimization has been difficult to meet the demands of complex environments. In recent years, multi-functional integrated modification has become a research hotspot.[38,43–45] Through molecular design or composite strategies, PU materials are endowed with synergistic functions such as flame retardancy, anti-corrosion, hydrophobic and self-repairing. By introducing dynamic covalent bonds (such as disulfide bonds, imine bonds, Diels–Alder reactions) or supramolecular interactions (such as hydrogen bonds, metal coordination bonds), the material can achieve autonomous repair after being damaged.[46–48] This self-healing ability not only extends the service life of materials but also maintains the integrity of the structure under extreme conditions such as fire. To achieve properties such as water resistance, corrosion resistance, and self-cleaning, micro–nano rough structures can be constructed on the surface or inside flame-retardant materials, or low surface energy substances (such as fluorosilane and polydimethylsiloxane) can be introduced.[49–51]

3.1 Self-healing coating

The integrity of the coating plays a critical role in determining the overall structural performance and safety. The development of self-healing coatings offers an effective strategy to prevent catastrophic failures resulting from minor damages or microcracks.[52–54] The core functionality of self-healing coatings lies in their capacity to partially or fully restore their original structure and performance following physical damage, such as scratches or cracks, *via* internal repair mechanisms. This restoration can occur through dynamic chemical bonds or physical interactions within the material, enabling reversible bond breakage and reformation under specific conditions. Alternatively, repair can be achieved by releasing active components, such as monomers or catalysts, from pre-embedded agents like microcapsules or microvascular networks upon damage. Self-healing coatings have garnered widespread attention across various fields, particularly in aerospace and engineering applications, due to their ability to autonomously repair damage, thereby reducing maintenance costs and preventing failures caused by coating degradation. In radiation shielding applications, damage to protective coatings can result in the loss of shielding integrity, posing irreversible risks to human health. Therefore, the development of self-repairing radiation-shielding coatings is an urgent priority for future research.

Cui *et al.* introduced polydopamine-coated expanded graphite as a functional filler into polyurethane and combined it with multiple hydrogen bonds and disulfide bonds to fabricate a flame-retardant, self-healing polyurethane coating[55] (Fig. 3).

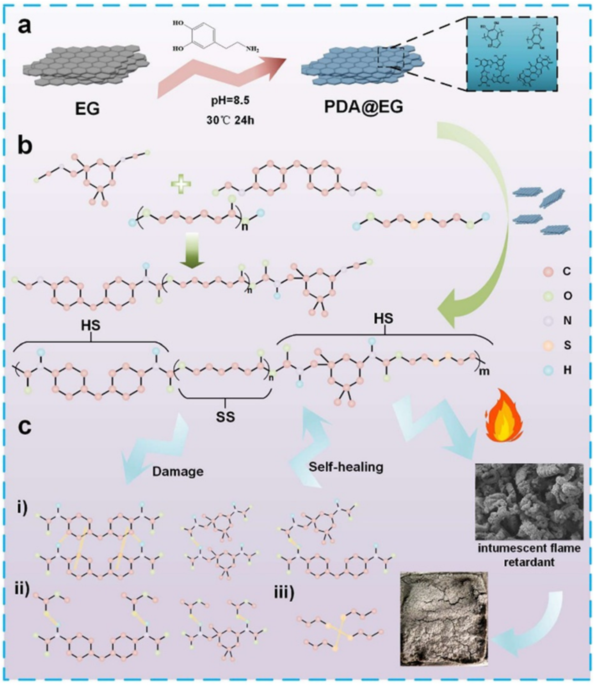

Fig. 3 Preparation method of (a) PDA@EG and (b) PU-3, and (c) the functional mechanism: i) π-bond system, ii) strong hydrogen bonds, iii) weaker hydrogen bonds. Reproduced from ref. 55 with permission from [Elsevier], copyright.

Sokjorhor *et al.* synthesized a disulfide bond-containing monomer based on mercaptobenzothiazole and incorporated it into the polyurethane molecular chain, imparting self-healing capabilities to the material. The coating's anti-corrosion performance was achieved through the release of corrosion inhibitors in response to corrosive stimuli. This study provides valuable insights into the design of self-healing polyurethane systems with intelligent, stimulus-responsive anti-corrosion functionality[56] (Fig. 4). Although substantial progress has been achieved in the development of self-healing coatings, challenges remain—most notably the trade-off between mechanical robustness and self-healing efficiency, as well as the inability of many current systems to meet performance standards under harsh conditions. Consequently, the future direction of coating research lies in the design of multifunctional, high-performance self-healing coatings that simultaneously deliver mechanical strength, environmental resistance, and functional adaptability.

Polyurethane self-healing coatings have achieved active repair of micro-damage through dynamic chemical bonds, such as Diels–Alder reactions and disulfide bond exchange, thereby significantly enhancing their durability. However, their inherently high surface energy often leads to issues such as interface adhesion contamination and water droplet penetration in humid or corrosive environments. In recent years, to broaden their functional applications, research has increasingly focused on imparting hydrophobic properties to self-healing coatings through the design of surface micro–nano structures and modification with low-surface-energy substances.

3.2 Hydrophobic coating

Hydrophobic coatings are widely utilized in a range of applications, including marine anti-fouling, aerospace, and the waterproofing of electronic devices. Currently, the

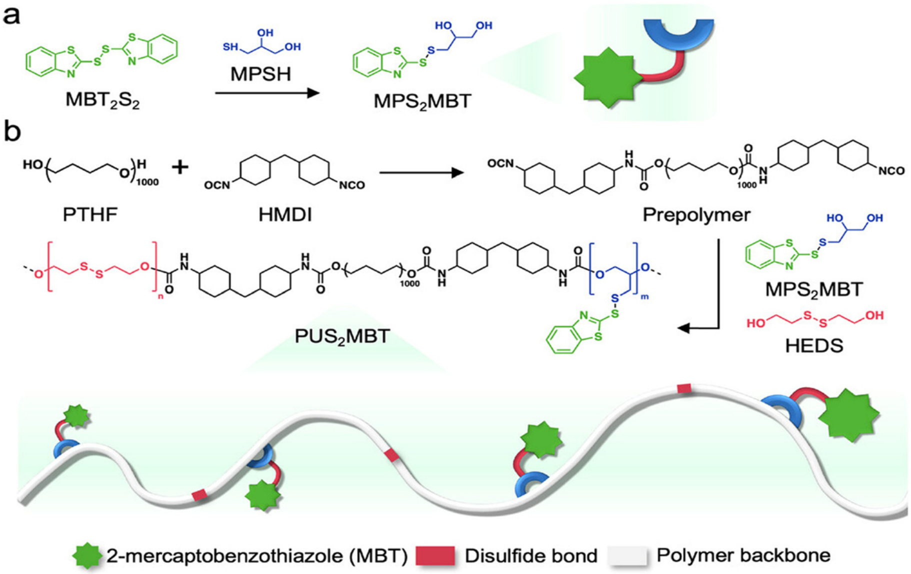

Fig. 4 Synthetic routes for the preparation of a) the functional monomer MPS2MBT and b) polyurethane containing disulfide bonds and conjugated corrosion inhibitor (PUS2MBT). Reproduced from ref. 48 with permission from [Elsevier], copyright.

primary methods for preparing hydrophobic coatings include chemical modification, physical blending, and surface structure engineering, among others. Hydrophobic coatings achieve functions such as waterproofing, self-cleaning, and corrosion resistance through specific chemical compositions and microstructural designs, resulting in a high water contact angle (>90°) on the material surface and low adhesion.[57–61] Vijayan *et al.* developed a hydrophobic and corrosion-resistant coating by chemically modifying cashew phenol with di-hydroxypropyl ether. The resulting coating is colorless, transparent, and exhibits broad application potential across various fields.[62] Schara *et al.* synthesized degradable polyurethanes with low surface polarity, low glass transition temperature, and excellent mechanical properties by utilizing non-polar polyols containing acetal groups. These polyurethanes demonstrated high-yield, closed-loop recyclability under mild acidic conditions. This study provides a promising strategy for the design and fabrication of recyclable multifunctional polyurethane materials[63] (Fig. 5). Hydrophobic coatings have achieved significant advancements in marine anti-fouling and the development of hydrophobic materials for construction applications. However, the operational environments for these coatings are often complex, requiring not only sustained hydrophobicity but also high durability and corrosion resistance. As a result, the future development of this field is expected to focus on high-performance, intelligent-responsive hydrophobic coatings capable of adapting to dynamic environmental conditions while maintaining long-term functionality.

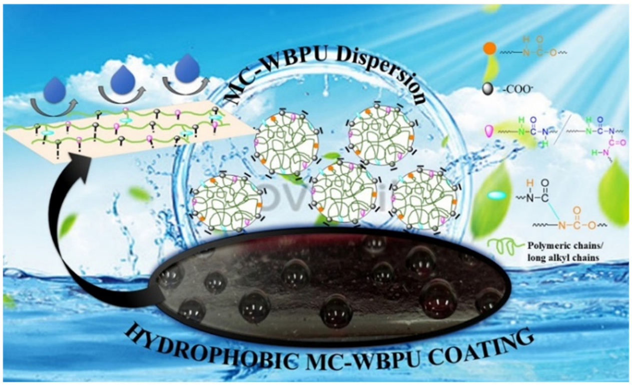

Fig. 5 Schematic diagram of hydrophobic coating. Reproduced from ref. 55 with permission from [Elsevier], copyright.

Although polyurethane-based hydrophobic coatings significantly enhance anti-wetting properties and self-cleaning ability through low-surface-energy chemical modification or micro–nano structure design, meeting the multi-dimensional environmental tolerance required in modern electronics, aerospace, and other fields remains challenging—particularly in addressing the growing issue of electromagnetic pollution. Consequently, researchers have explored electromagnetic shielding polyurethanes.

3.3 Electromagnetic shielding coating

With the rapid advancement of electronic technologies, electromagnetic pollution has become an increasingly critical concern. Electromagnetic shielding coatings are functional materials specifically engineered to attenuate or reflect electromagnetic waves, thereby mitigating electromagnetic interference.[64–67] For example, when applied to the outer casings of mobile phones or laptops, these coatings help reduce signal leakage. In military applications, they are used on the exterior surfaces of fighter jets to minimize radar detectability, enhancing stealth performance. Additionally, these coatings have potential applications in wearable medical devices, where they can protect sensitive electronics from electromagnetic interference. Zhang *et al.* simultaneously incorporated carbon nanotubes and Fe_3O_4 magnetic particles into a polyurethane matrix, resulting in a multifunctional coating with excellent electromagnetic shielding performance and an extremely hydrophobic surface. Remarkably, the shielding effectiveness remained stable even after 6 hours of immersion in acidic or alkaline environments, indicating strong chemical durability. This study offers a promising strategy for the design of acid- and alkali-resistant multifunctional polyurethane coatings[68] (Fig. 6).

Understanding the mechanisms of electromagnetic shielding is fundamental to the rational design of high-performance shielding materials. Electromagnetic shielding functions by attenuating or blocking the propagation of electromagnetic waves through mechanisms such as reflection, absorption, and multiple internal reflections, when electromagnetic (EM) waves strike the surface of a shielding material, the impedance mismatch between the material and free space causes part of the incident waves to be reflected at the surface, while the remainder is converted into heat through dielectric loss (ε'') or magnetic loss (μ'').[69–71] The shielding effectiveness of metals, conductive polymers, and composites varies with frequency due to differences in conductivity, magnetic permeability, and microstructure. For instance, high-conductivity materials (*e.g.*, copper, aluminum) primarily suppress high-frequency electromagnetic interference (EMI) *via* reflection loss, whereas magnetic materials (*e.g.*, ferrites) absorb low-frequency waves through magnetic loss mechanisms.

Additionally, parameters such as material thickness, multilayer structural design, and interface impedance matching play critical roles in determining overall shielding effectiveness (SE). A thorough understanding of electromagnetic wave attenuation, combined with optimization of parameters such as dielectric constant and magnetic permeability, is essential for developing lightweight, broadband, high-strength shielding materials. These materials are urgently needed for applications in 5G communication, aerospace, electronic healthcare systems, and other advanced technological domains.

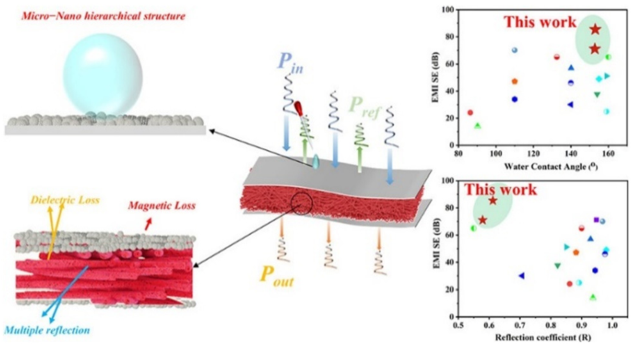

Fig. 6 Schematic diagram of the shielding mechanism. Reproduced from ref. 60 with permission from [ACS], copyright.

4 Future challenges

Although multifunctional polyurethane (PU) has demonstrated significant potential in flexible electronics, biomedical applications, and smart coatings, its continued development faces several key challenges that must be addressed.[72–74] The first major challenge is achieving performance balance. Multifunctional polyurethane (PU) materials are required to simultaneously exhibit diverse properties—such as mechanical strength, self-healing ability, electrical conductivity, and biocompatibility—yet these properties often conflict with one another.[75] For example, increasing the degree of cross-linking can significantly improve mechanical strength, but may compromise the material's self-repairability or biodegradability.[76–78] Moving forward, synergistic optimization of multifunctional performance may be achieved through advanced molecular design strategies, including the incorporation of dynamic covalent bonds and nanocomposite systems.

A second critical challenge lies in environmental sustainability. Traditional polyurethane synthesis is heavily dependent on petroleum-based raw materials (*e.g.*, isocyanates), and often involves toxic reagents such as phosgene, raising serious environmental and health concerns.[79] During the spraying or curing of polyurethane coatings, free isocyanates (*e.g.*, TDI, HDI) and solvents (*e.g.*, xylene) can volatilize, causing acute respiratory irritation and, in some cases, occupational asthma. With long-term use, plasticizers may migrate from the coating and be absorbed through the skin, potentially disrupting the endocrine system. Exposure to ultraviolet radiation or mechanical wear can degrade the coating, releasing micron-sized plastic particles and residual isocyanates. Prolonged inhalation of these substances may result in chronic pneumonia or pulmonary fibrosis. Bio-based polyurethane (BPU) is an environmentally friendly polyurethane material produced by replacing traditional petroleum-derived raw materials with renewable resources such as vegetable oils, lignin, and carbohydrate derivatives. Common substitutes include epoxy vegetable oils (*e.g.*, epoxy soybean oil, castor oil), betalain, lignin, and sugar derivatives. Zarmehr *et al.* analyzed the current gaps in bio-based polyurethane research and evaluated its environmental and performance impacts.[80] Although significant progress has been made in the development of bio-based polyurethanes, including those derived from plant oils, as well as green synthesis approaches such as non-isocyanate polyurethanes (NIPUs), challenges remain, these alternatives are often hindered by high production costs and complex synthesis processes, limiting their scalability. Therefore, the development of low-cost, renewable, and environmentally benign raw material systems is an urgent priority for advancing sustainable polyurethane technologies.

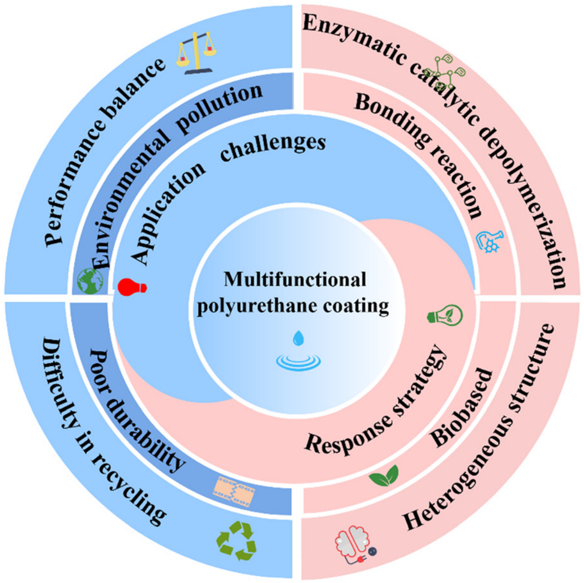

Fig. 7 Multifunctional polyurethane coating design and application challenges.

Polyurethane coatings are typically employed in complex and demanding environments, including high-temperature, high-humidity, and acidic or alkaline conditions. Under prolonged service conditions, these coatings are susceptible to performance degradation. For example, self-healing coatings may exhibit insufficient durability in marine corrosive environments, while conductive polyurethane coatings used in electronic components may experience functional failure due to repeated mechanical deformation that disrupts the integrity of the conductive network. These limitations underscore the need for enhanced stability and long-term performance in multifunctional polyurethane systems (Fig. 7).

The recycling and degradation of polyurethane (PU) remain major challenges in the field. Conventional polyurethane (PU) is inherently difficult to degrade, and the incorporation of functional additives such as carbon nanotubes and metal particles further complicates recycling because of their persistence and incompatibility with degradation pathways. Although advances have been made in the development of degradable polyurethane systems, including the introduction of cleavable ester and acetal bonds, several issues persist, such as controlling degradation rates, achieving high-purity recycling, and retaining or regenerating functional properties. To address these limitations, the design and implementation of closed-loop recycling systems is emerging as a promising future direction for sustainable PU materials.

The preparation of multifunctional polyurethane (PU) materials often relies on precise chemical modification techniques, such as click chemistry reactions and *in situ* polymerization, which tend to involve complex synthetic procedures and low production yields. The core challenge to industrialization lies in scaling up these laboratory-level innovations to enable large-scale production, while simultaneously minimizing energy consumption and reducing raw material costs. Overcoming this obstacle is essential for the practical and sustainable deployment of high-performance multifunctional PU materials in real-world applications.

Conclusions

Multifunctional flame-retardant polyurethane (PU) coatings represent a significant leap forward in materials science, addressing both the pressing need for fire safety and the growing demand for integrated performance in diverse application environments. By leveraging nanocomposites, synergistic flame-retardant systems, and surface modification techniques, recent advances have enabled PU coatings to exhibit not only enhanced flame resistance but also additional functionalities such as self-healing, hydrophobicity, and corrosion resistance. These developments mark a shift from single-purpose materials to complex, adaptable systems.

The transition of these advanced coatings from laboratory-scale innovation to large-scale, real-world deployment hinges on overcoming key challenges. Interdisciplinary strategies, which encompass AI-assisted material design, novel dynamic covalent chemistries, and sustainable manufacturing, will be central to this process. Equally important is the development of standardized testing and safety evaluation protocols tailored to specific applications like wearable electronics, aerospace structures, and biomedical devices. With continued research and cross-sector collaboration, flame-retardant PU coatings are poised to become cornerstone materials in next-generation smart and safe environments.

Author contributions

Xingyao Li: investigation, methodology, writing – review & editing, formal analysis. Kangcheng Xu: investigation. Jiangtao Wu: investigation. Ye-Tang Pan: supervision, investigation, funding acquisition, writing – review & editing. Xiangmei Li: investigation, resources. Jiyu He: conceptualization, data curation, supervision, funding acquisition, writing – review & editing. Rongjie Yang: investigation, resources.

Conflicts of interest

The authors declare no conflict of interest.

Data availability

No data was used for the research described in the article.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 52473070). The National Natural Science Foundation of China (No. 22375023, 22005029), the Natural Science Foundation of Chongqing (CSTB2024NSCQ-

MSX0452), and the Hebei Natural Science Foundation (E2024105006). Shandong Province Natural Science Foundation (ZR2024ME040).

References

1 K. Zhou, Q. Zhang, J. Gong, H. Shen, H. Luo, S. Chen, X. Zhang, N. Zhang, X. Pei, T. Wang, Y. Yang, Q. Wang and Y. Zhang, *ACS Appl. Mater. Interfaces*, 2024, **16**, 64031–64041.

2 W. Zhou, S. Ren, F. Zhang, X. Gao, K. Song, H. Fang and Y. Ding, *Polymer*, 2022, **256**, 125200.

3 Y. Luo, Z. Geng, W. Zhang, J. He and R. Yang, *Polymers*, 2023, **15**, 3711.

4 J. Lu, C. Liao, L. Cheng, P. Jia, Z. Yin, L. Song, B. Wang and Y. Hu, *J. Cleaner Prod.*, 2022, **333**, 130172.

5 S. Y. Kang, Z. Ji, L. F. Tseng, S. A. Turner, D. A. Villanueva, R. Johnson, A. Albano and R. Langer, *Adv. Mater.*, 2018, **30**, 1706237.

6 C. Huyan, D. Liu, C. Pan, D. Wang, Z. Guo, X. Zhang, S. Dai, B. Bin Xu and F. Chen, *Chem. Eng. J.*, 2023, **471**, 144478.

7 E. S. Lobanovskaya, M. V. Mokeev and V. V. Zuev, *Polym. Adv. Technol.*, 2023, **35**, e6249.

8 G. Liang, Y. Qi, R. Gong, Y. Hu, F. Yao, Y. Liu, B. Liu, Y. Zhao, Y. Dai, X. Dong, F. Wang and Y. Li, *Prog. Org. Coat.*, 2023, **178**, 107480.

9 J. Wen, Z. Sun, F. Zhu and H. Fan, *Prog. Org. Coat.*, 2023, **174**, 107254.

10 Y. Xing, X. Li, J. Xu and F. Zhang, *Prog. Org. Coat.*, 2024, **190**, 108372.

11 G. Li, B. Duan, G. Leng, X. Xiu, S. Wang, S. Li, W. Zhao, J. Liu and J. Qu, *J. Appl. Polym. Sci.*, 2024, **142**, e56508.

12 S. Zhao, Q. Zhang, Z. Su, Y. Liu, S. Wang, W. Meng, J. Xie and J. Xu, *Int. J. Biol. Macromol.*, 2025, **311**, 143593.

13 Y. Yao, J. Man, X. Wang, X. Gu, Z. Zheng, H. Li, J. Sun, D. Meng, S. Zhang and Q. Dong, *Polym. Degrad. Stab.*, 2025, **236**, 111302.

14 H. Li, Y. Xu, Z. Zhang, F. Han, Y.-T. Pan and R. Yang, *J. Polym. Mater.*, 2025, **42**, 33–55.

15 Y. Sun, H. Xin, Y. Wu, C. Zhang, C. Chen and X. Zhou, *Prog. Org. Coat.*, 2024, **186**, 108092.

16 C. Liu, K. Chen, B. Wu, W. Sun, L. Ji and Y. Wu, *ACS Omega*, 2024, **9**, 48350–48360.

17 Y. Luo, R. Jiang, Y. Xu, H. Wang, Z. Qiu, J. Huang and Y. Zheng, *J. Appl. Polym. Sci.*, 2024, **142**, e56481.

18 M. Alberto, M. Iliut, M. K. Pitchan, J. Behnsen and A. Vijayaraghavan, *Composites, Part B*, 2021, **213**, 108727.

19 Y. Sun, X. Tian, Z. Chen, S. Dai, N. Xiao, N. Qian, G. Lin, K. Chen and D. Qi, *Fibers Polym.*, 2024, **25**, 1751–1764.

20 B. Becher-Nienhaus, G. Liu, J. V. Buddingh and H. Zheng, *ACS Appl. Polym. Mater.*, 2023, **5**, 3119–3128.

21 H. Chai, J. Luo, J. Li, Y. Zhong, L. Zhang, X. Feng, H. Xu and Z. Mao, *Int. J. Biol. Macromol.*, 2024, **271**, 132435.

22 G. Liu, S. Yang, H. Lin, Y. Li, J. Lei and Z.-M. Li, *Composites, Part A*, 2023, **175**, 107769.

23 C. Wang, Y. Guo, J. Chen and Y. Zhu, *Compos. Commun.*, 2023, **37**, 101444.

24 S. Bai, X. Guo, X. Zhang, X. Zhao and H. Yang, *Composites, Part A*, 2021, **149**, 106545.

25 L.-P. Zhang, Z.-G. Zhao, Y.-Y. Huang, X. Cao, X.-Y. Tian, Y.-P. Ni and Y.-Z. Wang, *Prog. Org. Coat.*, 2024, **194**, 108613.

26 B. Huang, H. Zhang, J. Qu, G. Li, H. Zhao, L. Liu, C. Jiao and X. Chen, *Polym. Degrad. Stab.*, 2025, **240**, 111444.

27 C. Su, Y. Ren, P. Zhu, Y. Zhou, D. Wang and X. Dong, *Polym. Degrad. Stab.*, 2025, **240**, 111445.

28 M. Cui, J. Li, X. Chen, W. Hong, Y. Chen, J. Xiang, J. Yan and H. Fan, *Prog. Org. Coat.*, 2021, **158**, 106359.

29 C.-S. Wang, J. Zhang, H. Wang, M. He, L. Ding and W.-W. Zhao, *Ind. Crops Prod.*, 2021, **163**, 113328.

30 K. Yu, Y. Wang, M. Xu, X. Xue and J. Zhao, *Colloids Surf., A*, 2023, **675**, 132079.

31 J. Cao, Y.-T. Pan, H. Vahabi, J.-i. Song, P. Song, D.-Y. Wang and R. Yang, *Mater. Today Chem.*, 2024, **37**, 102015.

32 K. Song, X. Bi, C. Yu, Y.-T. Pan, H. Vahabi, V. Realinho, J. He and R. Yang, *ACS Appl. Mater. Interfaces*, 2024, **16**, 7617–7630.

33 K. Song, X. Bi, D. Wang, Y.-T. Pan, M. Xie, J. He, D.-Y. Wang and R. Yang, *Chem. Eng. J.*, 2024, **495**, 153850.

34 Q. Li, X. Song, Y.-T. Pan, J. Sun, A. Bifulco and R. Yang, *J. Colloid Interface Sci.*, 2024, **674**, 445–458.

35 Q. Li, Y. Lei, X. Bi, Y. Liu, Y.-T. Pan, W. Wang, W. Zhang, C. Shi and G. H. Yeoh, *Chem. Eng. J.*, 2025, **506**, 160242.

36 G. Huang, Y.-T. Pan, L. Liu, P. Song and R. Yang, *Adv. Nanocompos.*, 2025, **2**, 1–14.

37 X. Sun, T. Lin, Y. Hou, B. Hou, Y. Pan and R. Yang, *Nano Mater. Sci.*, 2025, **12**, 1–15.

38 H. Wang, Y. Wang, T. Li, C. Yu, P. Lin, J. Liu, Y. Lan and Y. T. Pan, *Adv. Funct. Mater.*, 2025, **35**, 2500800.

39 X. Qiu, Y. Wang, C. Wu, L. Ding, J. Lin, W. Gao, Y. Chi, M. Ma and W. Huang, *Polym. Adv. Technol.*, 2025, **36**, e70227.

40 J. Duan, Y. Hou, X. Qian, C. Shi, M. Wan, H. Zhu and H. Wang, *Constr. Build. Mater.*, 2025, **474**, 141120.

41 J. Cui, S. Liu, Q. Li, J. Chen, X. Tang, S. Li, S. Zhong and W. Feng, *Fire Mater.*, 2021, **46**, 443–449.

42 M. Puyadena, I. Etxeberria, L. Martin, A. Mugica, A. Agirre, M. Cobos, A. Gonzalez, A. Barrio and L. Irusta, *Prog. Org. Coat.*, 2022, **170**, 107005.

43 S. Ji, H. Gui, G. Guan, M. Zhou, Q. Guo and M. Y. J. Tan, *Prog. Org. Coat.*, 2021, **156**, 106254.

44 A. S. Rafi, A. A. Sheikh, M. H. Chaion, T. Chakrovarty, M. T. Islam and C. K. Kundu, *Heliyon*, 2024, **10**, e37120.

45 X. Li, M. Xie, J. Gao, K. Song, X. Li, J. Geng, J. He and R. Yang, *Mater. Horiz.*, 2025, 00493d.

46 J. Hu, C. Ji, G. Wei, Q. Tang, F. Chang, B. Zhu, L. Ren and D. Peng, *J. Appl. Polym. Sci.*, 2025, e57408.

47 T. Yimyai, D. Crespy and M. Rohwerder, *Adv. Mater.*, 2023, **35**, 2300101.

48 H. Zhang and Z. Guo, *Nano Today*, 2023, **51**, 101933.

49 J. Peng, S. Yuan, H. Geng, X. Zhang, M. Zhang, F. Xu, D. Lin, Y. Gao and H. Wang, *Chem. Eng. J.*, 2022, **428**, 131162.

50 K. Fu, C. Lu, Y. Liu, H. Zhang, B. Zhang, H. Zhang, F. Zhou, Q. Zhang and B. Zhu, *Chem. Eng. J.*, 2021, **404**, 127110.

51 K. Mantala and D. Crespy, *Macromolecules*, 2025, **58**, 3450–3459.

52 P. Wu, Y. Qi, Y. Wang, X. Wang, Y. Zhang and X. Li, *Surf. Interfaces*, 2024, **51**, 104800.

53 T. Wang, W. Wang, H. Feng, T. Sun, C. Ma, L. Cao, X. Qin, Y. Lei, J. Piao, C. Feng, Q. Cheng and S. Chen, *Chem. Eng. J.*, 2022, **446**, 137077.

54 Z. Sabet-Bokati, K. Sabet-Bokati, Z. Russell, K. Morshed-Behbahani and S. Ouanani, *Prog. Org. Coat.*, 2024, **188**, 108193.

55 Y.-Y. Cui, M.-Y. Zhang, X. Li, L.-J. Guo, Y.-K. Cai, H.-J. Li and Y.-C. Wu, *Polym. Degrad. Stab.*, 2025, **240**, 111499.

56 J. Sokjorhor, C. Phantan, K. Ratanathawornkit and D. Crespy, *Adv. Funct. Mater.*, 2025, **35**, 2508274.

57 X. Li, G. Chen, J. Zhang, Y. Luo, X. Bai, Y.-T. Pan, H. Gao and N. Wang, *Prog. Org. Coat.*, 2025, **206**, 109303.

58 Q. Wen, T. Li, X. Yang, L. Duan and B. Pan, *Mater. Chem. Phys.*, 2025, **341**, 130905.

59 A. van Dam, S. P. Pujari, M. M. J. Smulders and H. Zuilhof, *ACS Appl. Nano Mater.*, 2024, **7**, 19737–19744.

60 A. U. Rahman, S. M. Kabeb and F. H. Zulfkifli, *Prog. Org. Coat.*, 2025, **203**, 109187.

61 J. Bang, H. Choi, K.-S. Ahn, H. Yeo, J.-K. Oh and H. Won Kwak, *Appl. Surf. Sci.*, 2024, **654**, 159419.

62 S. P. Vijayan, B. John and S. K. Sahoo, *Prog. Org. Coat.*, 2022, **162**, 106586.

63 P. Schara, T. Türel, C. Pantazidis, A. M. Cristadoro, R. P. Sijbesma and Ž. Tomović, *ACS Appl. Polym. Mater.*, 2025, **7**, 6055–6066.

64 J. Hu, J. Jiang, Q. Li, J. Cao, X. Sun, S. Huo, Z. Qin and Y.-T. Pan, *Composites, Part A*, 2025, **198**, 109068.

65 A. P. Godoy, L. G. Amurim, A. Mendes, E. S. Gonçalves, A. Ferreira, C. S. de Andrade, R. Kotsilkova, E. Ivanov, M. Lavorgna, L. A. M. Saito, H. Ribeiro and R. J. E. Andrade, *Prog. Org. Coat.*, 2021, **158**, 106341.

66 L. Hu and Z. Kang, *Appl. Surf. Sci.*, 2021, **568**, 150845.

67 A. Bobsin, R. Menezes Kerber, I. J. Fernandes, S. B. Ferreira, W. Hasenkamp, C. R. Peter, P. H. Michels-Brito, A. Akanno, L. Michels, S. Raaen, J. O. Fossum and C. A. M. Moraes, *Prog. Org. Coat.*, 2024, **195**, 108658.

68 Y. Zhang, H. Wu and S. Guo, *ACS Appl. Mater. Interfaces*, 2022, **14**, 40351–40360.

69 L. Zou, C. Lan, S. Zhang, X. Zheng, Z. Xu, C. Li, L. Yang, F. Ruan and S. C. Tan, *Nano-Micro Lett.*, 2021, **13**, 190.

70 Z. Deng, P. Jiang, Z. Wang, L. Xu, Z. Z. Yu and H. B. Zhang, *Small*, 2023, **19**, 2304278.

71 K. Rajavel, X. Yu, P. Zhu, Y. Hu, R. Sun and C. Wong, *ACS Appl. Mater. Interfaces*, 2020, **12**, 49737–49747.

72 H. Wei, H. Liu, M. Li, Z. Fu, L. Liu, H. Zhang, C. Fan, J. Xu and J. Wang, *J. Coat. Technol. Res.*, 2024, **21**, 1333–1342.

73 I. Bramhecha and J. Sheikh, *J. Ind. Eng. Chem.*, 2024, **132**, 247–258.

74 S. Li, X. Lin and S. Gong, *Cellulose*, 2022, **29**, 7397–7411.

75 C. Li, H. Guo, N. Zhang, Y. Jin, K. Han, J. Yuan, Z. Pan and M. Pan, *Nanomaterials*, 2022, **12**, 4216.

76 A. Sharma, I. P. Kaur, F. Gao and G. Verma, *J. Coat. Technol. Res.*, 2024, **21**, 1291–1309.

77 H. Xu, W. Tian, S. Wang, C. Zhao, B. Zhi, S. Wang, L. Tian, H. Jin and L. Ren, *Chem. Eng. J.*, 2024, **499**, 156326.

78 J. R. Ghonia, N. G. Savani, V. Prajapati and B. Z. Dholakiya, *J. Polym. Res.*, 2024, **31**, 95.

79 J. Shi, X. Wu, L. Sheng, M. Chen, L. Shi, Y. Zhang, J. Yang, S. Mao, Q. Liu and Z. Zhou, *Compos. Sci. Technol.*, 2025, **266**, 11178.

80 S. P. Zarmehr, M. Kazemi, N. G. A. Madasu, A. J. Lamanna and E. H. Fini, *Resour. Conserv. Recycl.*, 2025, **212**, 107906.