Materials Horizons

ROYAL SOCIETY OF CHEMISTRY

OPINION

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Mater. Horiz.*, 2025, **12**, 4934

Debonding-on-demand adhesives for recycling and reusing of electronic devices

Daewhan Kim, Youngjoo Park and Min Sang Kwon *

Received 14th March 2025,
Accepted 21st May 2025

DOI: 10.1039/d5mh00468c

rsc.li/materials-horizons

Electronic waste (e-waste) is one of the fastest-growing waste streams, largely due to surging demand for devices like smartphones, tablets, and laptops. While e-waste contains valuable resources, its disposal also involves hazardous components that threaten human health and the environment. A critical barrier to effective recycling is the adhesives used in device assembly, which complicate disassembly and reduce material recovery. Recent research has explored diverse residue-free and efficient debonding methods. Notably, irreversible photo-debondable adhesives show particular promise by enabling precise, controlled, and on-demand release without damaging sensitive components. Moving forward, developing adhesives that incorporate both debonding capabilities and degradability will be essential for achieving efficient, sustainable recycling and minimizing the environmental impact of e-waste.

Introduction: significance of e-waste recycling and reusing

The rapid advancement of technology, coupled with the widespread adoption of electronic devices such as smartphones, tablets, and laptops, has led to the generation of millions of tons of electronic waste (e-waste) annually.[1] Consequently, e-waste is now recognized as one of the fastest-growing waste streams worldwide. Notably, electronic waste contains various hazardous components, including halogenated compounds, heavy metals, radioactive elements, and miscellaneous substances such as plastics, ceramics, and resins.[2] If improperly disposed of or incinerated in unregulated settings, these substances pose significant environmental and health risks, including soil and water contamination as well as atmospheric dispersion.[3] Such exposure has been associated with severe health complications, particularly affecting waste handlers, including neurological damage and respiratory diseases.[4]

Given these concerns, to minimize the generation of e-waste, two primary approaches can be considered (Fig. 1). When an entire electronic device is no longer functional, valuable materials such as metals and plastics can be extracted from its components for recycling. Alternatively, if only a specific component is defective or malfunctioning, that faulty unit can be selectively removed and replaced, enabling the reusing of the remaining functional components. While recycling contributes to reducing e-waste, reusing functional components offers an additional advantage by lowering production costs in the industry, thereby providing both environmental and economic benefits. Thus, the development of efficient recycling and reusing strategies for electronic devices has become a critical challenge in modern society, reflecting both sustainability and economic viability. One of the primary obstacles in these strategies is the difficulty of component separation due to the use of adhesives in device assembly.[5] As a first step, devices must be manually disassembled without causing damage to the intricate electronic structures, allowing for the recovery and reuse of functional components while discarding malfunctioning or defective parts. In this process, achieving clean and efficient disassembly from the substrate through appropriate external stimuli is essential. Advancements in such disassembly techniques can significantly mitigate the environmental and health impacts of e-waste while also contributing to environmental, social, and governance (ESG) goals. Furthermore, from a practical perspective, reusing layers and enabling the recycling of high-value materials contribute to reducing production costs, improving resource efficiency, and ultimately enhancing the economic viability of the process.[6] As industries increasingly prioritize cost-effective and scalable solutions, these technologies are becoming not only environmentally beneficial but also economically indispensable.

Adhesives as a barrier to electronic device disassembly

Adhesives used in electronic devices primarily serve a critical mechanical role by securely affixing functional components or layers. Additionally, depending on their placement, the components they bond, or the specific device in which they are

Department of Material Science and Engineering, Research Institute of Advanced Materials, Seoul National University, Seoul 08826, Republic of Korea. E-mail: minsang@snu.ac.kr

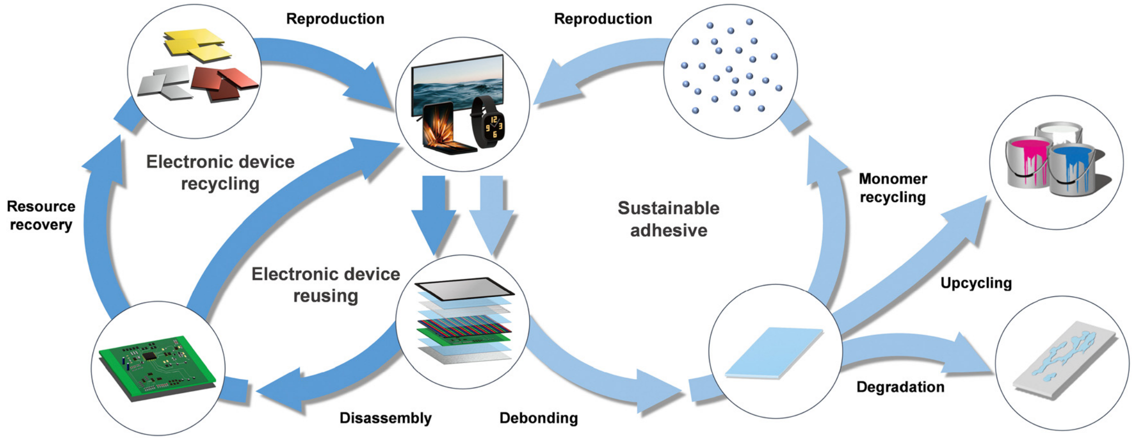

Fig. 1 The recycling and reusing process of electronic devices and the future direction approach for sustainable adhesives using debonding strategies.

applied, adhesives can also impart additional functionalities, such as high optical clearance,[7] stress relaxation,[8] electrical insulation,[9] and electrical conductivity.[10] As a result, adhesives constitute an essential element in electronic device assembly. In particular, adhesives featuring inert C–C bonds are commonly employed due to their exceptional chemical resistance, moisture resistance, durability, and high adhesion strength, ensuring stable performance even in extreme environments.[11,12] While these characteristics are crucial for enhancing the structural stability of electronic devices, they simultaneously pose a significant challenge in the recycling and reusing process, as they hinder the efficient disassembly and separation of components in electronic waste management.

To address this challenge, extensive research has been conducted on adhesive removal for electronic device disassembly. In particular, numerous studies have explored practical methods for removing adhesives used in bonding single-layer components, such as printed circuit boards (PCBs), with transesterification reactions at temperatures exceeding 140 °C.[13] However, research on practical adhesive debonding strategies specifically aimed at disassembling multi-layer structures into individual layers remains significantly limited.[11] Unlike single-layer systems, multi-layer electronic devices, such as display modules, lithium-ion batteries, and solar cells, which consist of multiple functional layers require precise separation methods. Display modules use adhesives to assemble components such as polarizers, color filters, organic light-emitting diode (OLED) layers, and thin film transistor (TFT) layers. Similarly, lithium-ion battery packs employ adhesives for cell-to-cell bonding, thermal runaway protection, compression pads, electrical insulation, and pack sealing. These layers exhibit significant thermal sensitivity; for example, color filters and OLED dyes may undergo thermal bleaching at temperatures exceeding approximately 100 °C,[14,15] while excessive heat also introduces explosion risks in lithium-ion batteries.[16] This thermal constraint severely limits the applicability of conventional high-temperature adhesive removal techniques, emphasizing the urgent need for on-demand debonding strategies to alternative recycling and reusing tailored specifically for multi-layer systems.

Existing debonding strategies

Currently, several approaches have been proposed for adhesive removal in multi-layer disassembly. In multi-layer structures, pressure-sensitive adhesive (PSA), which exhibit high adhesion under light pressure, are commonly used. Methods for PSA removal include elevating the temperature to reduce viscosity or weaken intermolecular forces, applying mechanical force such as scratching, or using solvents for dissolution.[16] However, these methods present significant limitations, including high energy consumption, environmental concerns, and thermal degradation and physical damages to the components. Additionally, they can lead to a reduction in the quality of recycled products and increase process complexity. Residual adhesive left on components may act as a contaminant during reassembly, potentially affecting electrical and optical performance and ultimately causing product malfunctions.

To overcome these challenges, fundamental research is required to develop effective and easily removable adhesives that facilitate efficient disassembly. As part of these efforts, various on-demand debonding systems have been proposed (Fig. 2). These systems enable precise, stimulus-activated separation from the substrate, allowing disassembly to occur only when necessary. Such on-demand responsiveness is a key advantage over traditional methods, offering tailored performance in complex multi-layer devices and minimizing damage to reusable components. To ensure that this on-demand functionality remains effective in extended-use strategies, debondable adhesives should be validated through comprehensive environmental stability testing that reflects realistic and long-term operational conditions. Currently, reported stimuli include thermal, photocuring, magnetic, and electric triggers, which offer potential solutions to the limitations of conventional removal methods. By integrating these techniques, more efficient and environmentally friendly disassembly processes can be developed, providing a strategic direction for sustainable electronic waste management.

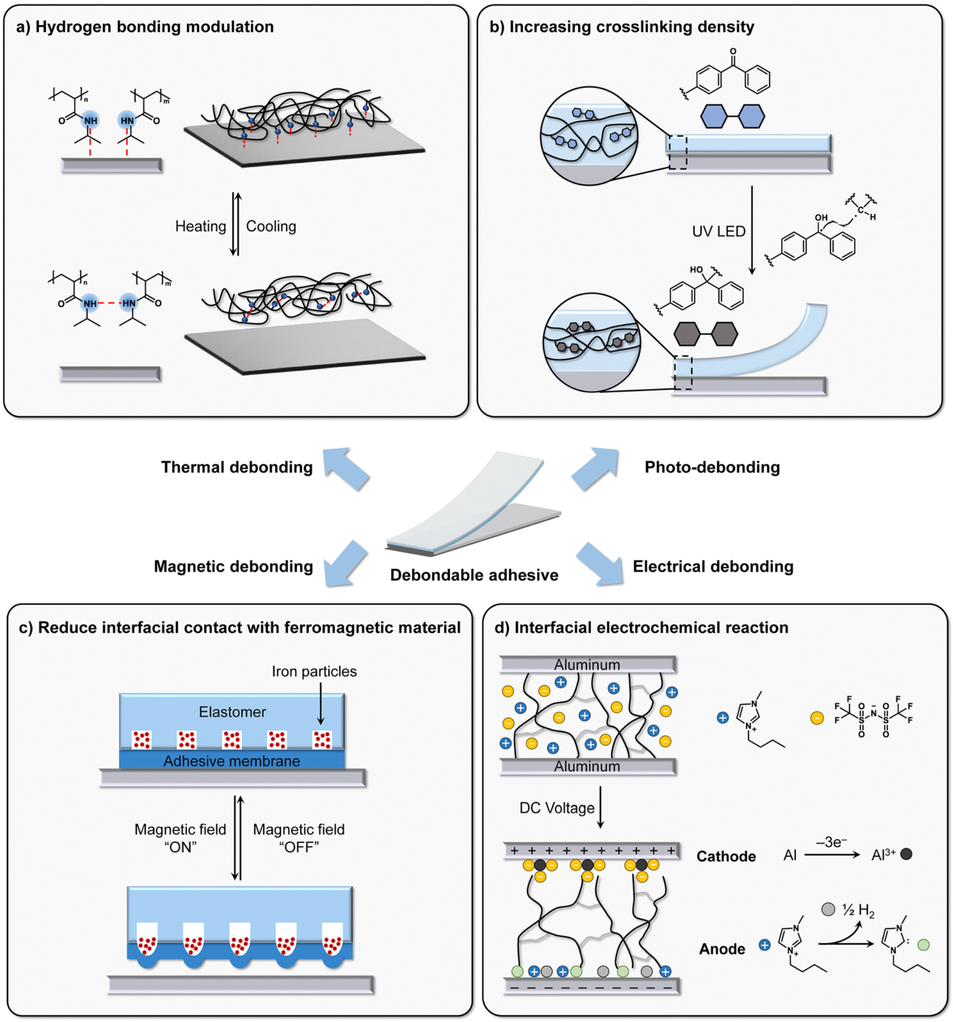

Fig. 2 Existing debonding strategies to reduce adhesion from the substrate surface for easy removal of adhesive: (a) thermal debonding strategy by hydrogen bonding modulation, (b) photo-debonding strategies through increasing crosslinking density, (c) magnetic debonding strategy by reducing interfacial contact using ferromagnetic material, and (d) electrical debonding strategy using interfacial electrochemical reaction.

Thermally debondable adhesives

Among the on-demand debonding approaches, thermally debondable adhesives, alongside photo-debondable adhesives have both received notable interest.[16] Thermally debondable adhesives primarily utilize hydrogen-bond modulation or dynamic covalent chemistry to soften or sever bonds at specific temperature ranges, thereby lowering adhesion.

For hydrogen bonding modulation, adhesives are formulated with low critical solution temperature (LCST) monomers to enable temperature-responsive adhesion. For instance, adhesives incorporating *N*-isopropylacrylamide (NIPAAM) exhibit enhanced inter- and intramolecular hydrogen bonding at 80 °C, reducing substrate interaction.[17] To lower the debonding temperature, poly(*N*-vinyl caprolactam) (PVCL)–poly(ethylene glycol) (PEG) blends are applied to undergo phase transition at a lower temperature of 50 °C, resulting adhesion reduction.[18] However, this study demonstrates that the reduction in adhesion is limited, and cohesive failure may leave residues, restricting their applicability in disassembly.

Research has also been conducted on dynamic covalent bonding to modify the adhesive network and reduce adhesion. Dynamic covalently bonded adhesives fabricated using polyglutaramide and polysuccinamide undergo cleavage of dicarboxamide linkages at temperatures above 200 °C, resulting in their conversion into cyclic imides and amines. This process leads to a reduction in network crosslinking density and changes in chain mobility, ultimately causing a decrease in adhesion. Although the dynamic covalent bonds are reversible and allow re-adhesion upon cooling, the need for extremely high temperatures remains a significant limitation.[19] Similarly, hot-melt thermoplastic polyurethane adhesives exhibited oxime-carbamate dynamic crosslinking around 100 °C, affecting lap shear strength.[20] Additionally, adhesives with ladder-like poly(silsesquioxanes) and alkyl crosslinkers demonstrated switchable adhesion *via* Diels–Alder reaction between 90 °C and 135 °C.[21] Although these approaches are customizable, the high activation temperatures may damage sensitive functional layers. As such, developing thermally responsive adhesive with lower activation thresholds is an ongoing focus, particularly to align with on-demand debonding objectives that require both material safety and operational efficiency.

Photo-debondable adhesive

Photo-debondable adhesives have gained significant attention due to their efficient, contactless, and remote stimulation capabilities, which can be controlled temporally and spatially. The ability to easily tune factors such as wavelength, intensity, and exposure time makes photoirradiation an ideal technique for on-demand adhesive removal that minimizes or avoids exposure to sensitive substrates. Most photo-debondable adhesives use crosslinking strategies to increase internal cohesion by UV irradiation, reducing adhesion for clean removal without residue.[22] Currently, this strategy has been applied as dicing tape for semiconductor wafers and also shows potential for use in the transfer of microscale materials such as micro-LEDs and graphene-based 2D materials.[23–25] However, the requirement for sufficient substrate transparency or targeted irradiation limits the application to specific materials.

One approach involves preparing PSA by incorporating diacrylate oligomers, obtained through acrylate functionalization of thermally cured polyurethane end groups, together with a photoinitiator, to induce additional crosslinking under UV irradiation and reduce adhesion strength.[26,27] Another method involves post-modification of polyacrylates with glycidyl methacrylate (GMA) and acrylic acid to achieve crosslinking.[28] While these methods allow for crosslinking density control by adjusting the substitution ratio, they require mixing different polymers or additional post-modification processing steps, presenting limitations.

To address these challenges, monomers containing UV-responsive sites are copolymerized to develop reversible and irreversible photo-debondable adhesives. In the reversible method, phase transition behaviors are induced by varying wavelengths of UV irradiation. A commonly employed strategy involves the incorporation of azobenzene groups, which facilitate phase transitions from solid to liquid through *cis–trans* isomerization. However, their applicability in optical devices is limited due to inherent color constraints.[29] In contrast, reversible photodimerization using anthracene[30] or coumarin monomers[31] enables adhesion control *via* switching between 254 nm and 365 nm light. For irreversible methods, benzophenone monomers are used in the Norrish type II reaction to create optically clear adhesives, allowing for residue-free substrate reuse in foldable displays.[22] Other UV-responsive sites, such as azide[32] or alkoxyphenyacyl groups,[33] have also been applied to PSA for adhesion reduction under UV stimuli.

Magnetically and electrically debondable adhesives

Magnetically and electrically debondable adhesives offer rapid adhesion response to stimuli, enabling the design of reversible adhesives. Magnetically debondable adhesives are typically developed by embedding ferromagnetic materials (*e.g.*, carbonyl iron or pure iron) into patterned PDMS, allowing them to respond to magnetic forces.[34,35] This method enables debonding within seconds while maintaining adhesion even after multiple cycles, demonstrating potential for reversible adhesive applications. However, the incorporation of ferromagnetic materials necessary for debonding may interfere with sensitive electronic components such as PCB circuits, touch layers, TFT layers, and semiconductor materials, while also reducing optical clarity.

The debonding mechanism of electrically debondable adhesives has been explored in only a limited number of studies. One such study reported that incorporating organic salts or ionic liquids enables ion migration toward the electrode interfaces under applied voltage, where interfacial electrodelamination occurs *via* carbene-induced degradation and hydrogen gas evolution at the cathode, and metal oxidation accompanied by metal ion migration at the anode.[36] These systems provide effective functionality at low temperatures and can be applied to various adhesives, such as acrylate, epoxy, and urethane, through the incorporation of ionic liquids.[37] Utilizing this strategy, the adhesive can be applied not only for mounting and dismounting components in high-speed aircraft but has also been practically demonstrated to enable the separation of aluminum-shelled battery cells in electric vehicles and smartphone battery cells within a few seconds. However, they necessitate a metal substrate to conduct current, making them unsuitable for adhesion to materials such as PET or glass. Both magnetic and electrical debonding strategies show significant potential for enhancing packing density and resolution, making them particularly effective for micro- and nanoscale transfer processes in silicon wafers, but limited in electronic devices.

Solvent-induced, ultrasound, and pH-triggered debondable adhesives

Alternative debonding mechanisms that rely on chemical dissolution, mechanical disruption, or ionic interactions, such as solvent, ultrasound, and pH-responsive stimuli, have garnered attention for their ability to facilitate adhesive removal. Solvent-induced debonding relies on the selective solubility of adhesives in specific solvents, promoting reversible assembly and disassembly through π–π interactions.[38] Meanwhile, pH-sensitive adhesives exploit acid–base interactions, where variations in protonation states modulate adhesion by altering electrostatic interactions[39] or inducing phase transitions.[40] Ultrasound-based debonding is utilized for acid-catalyzed degradation or as a non-destructive imaging technique for analyzing adhesive degradation.[41,42] However, the mechanical vibrations generated by ultrasound may potentially damage delicate layers, and this approach has not been extensively studied, necessitating further research to evaluate its practical applicability in electronic device disassembly. Additionally, pH-responsive stimuli require the use of solvents and acids or bases for pH modulation, which, like solvent-induced debonding, involves chemical usage that poses environmental risks and may cause chemical damage to substrates, further limiting their practical applicability.

Directions of future sustainable adhesives in electronics

Debondable adhesives based on thermal, photo, and electrical stimuli have already been commercialized and are currently available on the market, exhibiting comparable adhesion performance to that of regular adhesives. Applying commercially available debondable adhesives to electronic devices requires consideration of potential systemic barriers that could impede their commercialization. However, to the best of our understanding, no significant barriers are expected to impede their commercialization. Rather, the primary challenge lies in ensuring that the adhesive satisfies the material property requirements of the target device while also providing reliable debonding functionality. Thus, while maintaining such performance, the development of debondable adhesives depends on two critical factors: (i) using an on-demand stimulus that reduces substrate interaction without damaging the electronic device, and (ii) ensuring complete residue-free removal of the adhesive. To minimize the risk of damage to electronic devices, the stimulus should ideally be applied under low-energy conditions and for a short duration, even though higher thermal energy, irradiation intensity, or electrical voltage can enable faster debonding. However, for certain stimuli, such as thermal or photo triggers, the system must also be designed to respond only when the applied energy exceeds a specific threshold. This ensures that debonding is not unintentionally activated by ambient environmental conditions, thereby maintaining reliable on-demand performance.

Among the debonding strategies introduced above, thermal and photo stimuli have been the most extensively studied due to their feasibility for practical applications. However, thermal stimuli pose challenges due to their limited precise on/off control, as chemical reactions may occur outside the targeted temperature range. To pass stability tests under high temperature (60 °C or more and 105 °C or less) conditions, debonding should not occur at excessively low temperatures.[7] However, activation above 100 °C risks thermal degradation, narrow debonding temperature range is less suitable for achieving a realistic on-demand debonding operation.[14]

Given these challenges, photo-debondable adhesives emerge as one of the most promising on-demand system, offering precise and rapid adhesion control with wide wavelength selectivity. Here, ensuring that the overall irradiation dosage remains within a controlled range is sufficient to prevent degradation of sensitive layers. Thus, this capability enables the development of reusable adhesives, facilitating multiple attachment and detachment cycles, but dust and impurities introduced during reattachment can cause defects, generating malfunction of recycled electronics. Given that adhesive costs constitute extremely minor fraction of electronic device production, adopting irreversible photo-debondable adhesives with single-use, on-demand separation provides both economic and technical advantages. From a practical standpoint, photo-debonding allows for significant reduction in adhesion within seconds and offers controllability in terms of irradiation area, location, and on/off switching. These advantages make it one of the most favorable options in terms of both process efficiency and economic viability.

However, its applicability remains limited by the requirement that at least one of the bonded substrates must be optically transparent to allow light transmission to the adhesive layer. In cases where light cannot sufficiently reach the adhesive due to the non-transmissive materials, alternative debonding stimuli must be employed. Additionally, achieving rapid debonding typically requires high-intensity UV irradiation, which can pose a risk of damaging adjacent components, particularly those sensitive to UV exposure. Therefore, considering both economic and practical constraints, on-demand debonding strategies that enable selective, rapid, and clean separation under mild and broadly applicable stimuli should be continuously researched.

In addition to enabling efficient disassembly, addressing the environmental impact of adhesive waste itself is critical for achieving true sustainability. Debonded adhesives composed of C–C backbones are inherently non-degradable, which contributes to environmental pollution. Therefore, beyond recycling electronic devices, it is essential to incorporate pathways for adhesive degradation, monomer recycling, and upcycling to achieve ultimate sustainability. Improper disposal of adhesives may lead to the formation of "stickies," which can contaminate paper and plastic recycling streams and cause machinery fouling during processing. To promote recyclability and degradability across different adhesive systems, various approaches have been investigated, including backbone modification for acrylic adhesives,[43] vitrimer-based dynamic bonding for epoxy adhesives,[44] and chemical recycling *via* aminolysis and acidolysis for polyurethane adhesives.[45] Integrating these recycling and degradation strategies into debondable adhesive systems will be essential for future progress. Ultimately, future studies should focus on developing adhesive systems that combine efficient debonding with controlled degradation capabilities, advancing environmentally responsible adhesive technologies.

Data availability

As this is an opinion paper, the data supporting the arguments presented in this study can be found in the cited references.

Author contributions

The article was written with contributions from all authors.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by "Development of PFAS-free, eco-friendly, and highly reliable module materials for automotive foldable displays (RS202400419769)" funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea).

References

1 I. Ilankoon, Y. Ghorbani, M. N. Chong, G. Herath, T. Moyo and J. Petersen, *Waste Manage.*, 2018, **82**, 258–275.

2 E. R. Rene, M. Sethurajan, V. Kumar Ponnusamy, G. Kumar, T. N. Bao Dung, K. Brindhadevi and A. Pugazhendhi, *J. Hazard. Mater.*, 2021, **416**, 125664.
3 Y. Han, S. Zhang, D. Kang, N. Hao, J. Peng, Y. Zhou, K. Liu and Y. Chen, *Water, Air, Soil Pollut.*, 2025, **236**, 144.
4 Q. Song and J. Li, *Environ. Pollut.*, 2015, **196**, 450–461.
5 A. Sierra-Romero, K. Novakovic and M. Geoghegan, *Langmuir*, 2022, **38**, 15476–15493.
6 C. P. Baldé, R. Kuehr, T. Yamamoto, R. McDonald, E. D'Angelo, S. Althaf, G. Bel, O. Deubzer, E. Fernandez-Cubillo, V. Forti, V. Gray, S. Herat, S. Honda, G. Iattoni, D. S. Khetriwal, V. Luda di Cortemiglia, Y. Lobuntsova, I. Nnorom, N. Pralat and M. Wagner, *Global E-waste Monitor 2024*, International Telecommunication Union (ITU) and United Nations Institute for Training and Research (UNITAR), Geneva/Bonn, 2024.
7 Y. Park, J. Kim, D. Kim, S. Lee, D. Hwang and M. S. Kwon, *Soft Sci.*, 2024, **4**, 28.
8 Y. Kwon, S. Lee, J. Kim, J. Jun, W. Jeon, Y. Park, H.-J. Kim, J. Gierschner, J. Lee, Y. Kim and M. S. Kwon, *Nat. Commun.*, 2024, **15**, 2829.
9 Z. Su, H. Wang, K. Tian, W. Huang, C. Xiao, Y. Guo, J. He and X. Tian, *Compos. Sci. Technol.*, 2018, **155**, 1–10.
10 T. Wang, C. H. Lei, A. B. Dalton, C. Creton, Y. Lin, K. A. S. Fernando, Y. P. Sun, M. Manea, J. M. Asua and J. L. Keddie, *Adv. Mater.*, 2006, **18**, 2730–2734.
11 Y. Li and C. P. Wong, *Mater. Sci. Eng.: R: Rep.*, 2006, **51**, 1–35.
12 J. T. Abrahamson, Hollis Z. Beagi and F. Salmon, *Luminescence: OLED Technology and Applications*, 2020, vol. 63.
13 Z. Zhang, A. K. Biswal, A. Nandi, K. Frost, J. A. Smith, B. H. Nguyen, S. Patel, A. Vashisth and V. Iyer, *Nat. Sustainability*, 2024, **7**, 616–627.
14 M. Jung, Y. Noh, D. Suh and S. E. Ahn, *Adv. Mater. Technol.*, 2018, **3**, 1800203.
15 Y. Li, J. Zhu, M. Yang, W. Cheng, C. Wang and C. Cooper, *SID Int. Symp. Dig. Tech. Pap.*, 2023, **54**, 1012–1014.
16 K. R. Mulcahy, A. F. R. Kilpatrick, G. D. J. Harper, A. Walton and A. P. Abbott, *Green Chem.*, 2022, **24**, 36–61.
17 J. Hwang, D. Lim, G. Lee, Y. E. Kim, J. Park, M. J. Baek, H. S. Kim, K. Park, K. H. Ku and D. W. Lee, *Mater. Horiz.*, 2023, **10**, 2013–2023.
18 M. M. Feldstein, K. A. Bovaldinova, E. V. Bermesheva, A. P. Moscalets, E. E. Dormidontova, V. Y. Grinberg and A. R. Khokhlov, *Macromolecules*, 2014, **47**, 5759–5767.
19 F. Van Lijsebetten, T. Maiheu, J. M. Winne and F. E. Du Prez, *Adv. Mater.*, 2023, **35**, e2300802.
20 S. Wang, Z. Liu, L. Zhang, Y. Guo, J. Song, J. Lou, Q. Guan, C. He and Z. You, *Mater. Chem. Front.*, 2019, **3**, 1833–1839.
21 S. H. Kang, J. Y. Seo, H. J. Oh, J.-H. Lee, A. S. Lee and K.-Y. Baek, *Mater. Chem. Front.*, 2023, **7**, 679–688.
22 D. Kim, H. Kim, W. Jeon, H. J. Kim, J. Choi, Y. Kim and M. S. Kwon, *Adv. Mater.*, 2024, **36**, 2309891.
23 M. Nakatani, S. Fukamachi, P. Solís-Fernández, S. Honda, K. Kawahara, Y. Tsuji, Y. Sumiya, M. Kuroki, K. Li, Q. Liu, Y.-C. Lin, A. Uchida, S. Oyama, H. G. Ji, K. Okada, K. Suenaga, Y. Kawano, K. Yoshizawa, A. Yasui and H. Ago, *Nat. Electron.*, 2024, **7**, 119–130.
24 C. Guo, Z. Pan, C. Li, S. Zou, C. Pang, J. Wang, J. Hu and Z. Gong, *npj Flex. Electron.*, 2022, **6**, 44.
25 D. K. Hohl and C. Weder, *Adv. Opt. Mater.*, 2019, **7**, 1900230.
26 S.-W. Kim, Y. H. Ju, S. Han, J. S. Kim, H.-J. Lee, C. J. Han, C.-R. Lee, S.-B. Jung, Y. Kim and J.-W. Kim, *J. Mater. Chem. A*, 2019, **7**, 22588–22595.
27 Y. H. Ju, C. J. Han, K. S. Kim and J. W. Kim, *Adv. Mater. Technol.*, 2021, **6**, 2100776.
28 C. Hwang, J.-H. Back, D. Ahn, H.-J. Paik, W. Lee and Y. Yu, *Polym. Chem.*, 2022, **13**, 193–200.
29 H. Akiyama and M. Yoshida, *Adv. Mater.*, 2012, **24**, 2353–2356.
30 Y. Zhou, C. Zhang, S. Gao, W. Li, J. J. Kai and Z. Wang, *ACS Appl. Mater. Interfaces*, 2021, **13**, 50451–50460.
31 Q. Chen, Q. Yang, P. Gao, B. Chi, J. Nie and Y. He, *Ind. Eng. Chem. Res.*, 2019, **58**, 2970–2975.
32 R. Abu Bakar, Y. Li, O. P. Hewitson, P. J. Roth and J. L. Keddie, *ACS Appl. Mater. Interfaces*, 2022, **14**, 30216–30227.
33 Y. M. Tseng, A. Narayanan, K. Mishra, X. Liu and A. Joy, *ACS Appl. Mater. Interfaces*, 2021, **13**, 29048–29057.
34 P. Testa, B. Chappuis, S. Kistler, R. W. Style, L. J. Heyderman and E. R. Dufresne, *Soft Matter*, 2020, **16**, 5806–5811.
35 C. Linghu, C. Wang, N. Cen, J. Wu, Z. Lai and J. Song, *Soft Matter*, 2018, **15**, 30–37.
36 M. Wu, S. Chen, Y. Mei, L. Liu and Y. Wei, *ACS Appl. Mater. Interfaces*, 2022, **14**, 41456–41467.
37 Q. Yue, J. Lv, S. Huang, Y. Guo, Y. Wang, J. Liu, S. Sun, M. Wang, S. Wang and Y. Wei, *Adv. Funct. Mater.*, 2025, 2423865.
38 Z.-H. Wang, B.-W. Liu, F.-R. Zeng, X.-C. Lin, J.-Y. Zhang, X.-L. Wang, Y.-Z. Wang and H.-B. Zhao, *Sci. Adv.*, 2022, **8**, eadd8527.
39 B. Jin, G. Zhang, J. Lian, Q. Zhang, X. Zhan and F. Chen, *J. Mater. Chem. A*, 2019, **7**, 12266–12275.
40 R. La Spina, M. R. Tomlinson, L. Ruiz-Perez, A. Chiche, S. Langridge and M. Geoghegan, *Angew. Chem., Int. Ed.*, 2007, **46**, 6460–6463.
41 D. Ginzburg, F. Ciampa, G. Scarselli and M. Meo, *Smart Mater. Struct.*, 2017, **26**, 105018.
42 H. Tachi and K. Suyama, *J. Photopolym. Sci. Technol.*, 2017, **30**, 253–257.
43 K. R. Albanese, Y. Okayama, P. T. Morris, M. Gerst, R. Gupta, J. C. Speros, C. J. Hawker, C. Choi, J. R. de Alaniz and C. M. Bates, *ACS Macro Lett.*, 2023, **12**, 787–793.
44 D. Santiago, D. Guzmán, J. Padilla, P. Verdugo, S. De la Flor and À. Serra, *ACS Appl. Polym. Mater.*, 2023, **5**, 2006–2015.
45 G. Rossignolo, G. Malucelli and A. Lorenzetti, *Green Chem.*, 2024, **26**, 1132–1152.