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Biodegradable organic semiconductors: design strategies, degradation mechanisms, and performance trade-offs

Vittoria Vigorito, † Pietro Moiraghi, † Giulio Zagari, Matteo Rurali, Sara Ruggieri, Ignacio Olmedo Alegre, Martina Crosta * and Luca Beverina *

Organic semiconductors (OSCs) are uniquely positioned to enable next-generation electronic technologies due to their intrinsic mechanical flexibility, solution processability, and chemical tunability. These characteristics make them particularly attractive for applications such as flexible, wearable, and biointegrated devices, while also providing a versatile platform for addressing emerging challenges in sustainable electronics. In this context, the integration of biodegradability into OSCs represents a promising strategy to mitigate the growing impact of electronic waste and to enable devices with controlled and programmable lifetimes. This review provides a comprehensive overview of recent advances in biodegradable OSCs, focusing on the interplay between molecular design, degradation pathways, and electronic performance. Strategies to impart degradability—such as the incorporation of cleavable bonds, side-chain engineering, and copolymer and terpolymer design—are discussed in relation to their impact on material properties. The main degradation mechanisms, including hydrolytic, oxidative, and enzymatic processes, are critically examined, together with the role of environmental factors and morphology in governing degradation kinetics. A central theme of this work is the inherent trade-off between biodegradability and electronic performance. While the introduction of labile functionalities enables controlled degradation, it often disrupts π-conjugation and limits charge transport. Current approaches aimed at balancing these competing requirements, as well as emerging strategies such as dynamic covalent systems and circular material design, are highlighted. Overall, this review outlines key challenges and future directions for the development of biodegradable OSCs, emphasizing the need for integrated design approaches that simultaneously address performance, degradability, and scalability toward sustainable electronic technologies.

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Introduction

Organic semiconductors (OSCs) are a versatile class of carbon-based materials that combine semiconducting functionality with mechanical flexibility and solution processability, arising from their extended π-conjugated structures.[1] Since the seminal work of Shirakawa, Heeger, and MacDiarmid demonstrating high conductivity in doped polyacetylene,[2] OSCs have evolved into a mature field underpinning technologies such as organic light-emitting diodes (OLEDs) and organic photovoltaic devices (OPVs).[3,4] Despite exhibiting lower charge carrier mobilities than inorganic semiconductors,[3,5,6] OSCs offer unique advantages that make them particularly attractive for next-generation electronic systems.

A key strength of OSCs lies in their intrinsic mechanical flexibility and light weight, enabling conformable, stretchable, and lightweight devices that are difficult to achieve with conventional inorganic materials.[4,7] In addition, their solution processability allows fabrication through scalable and low-temperature techniques, including printing and roll-to-roll manufacturing, which are compatible with large-area and flexible substrates.[8,9]

These features open opportunities for applications such as flexible electronics, wearable systems, and biointegrated devices.[10–14] Furthermore, the synthetic tunability of OSCs provides precise control over electronic structure, intermolecular interactions, and morphology, enabling the rational design of materials with tailored optoelectronic and mechanical properties.[4,9,15]

Beyond these technological advantages, OSCs are uniquely positioned to address emerging challenges related to sustainability and end-of-life management of electronic devices.

University of Milano-Bicocca, Department of Materials Science, Via R. Cozzi 55, 20125, Milano, Italy. E-mail: luca.beverina@unimib.it, martina.crosta@unimib.it
† These authors contributed equally.

The growing volume of electronic waste has driven increasing interest in materials that can degrade or be recycled under controlled conditions.[16–18] In this context, OSCs offer a distinctive platform for integrating biodegradability directly into functional materials, owing to their molecular design flexibility and compatibility with organic and bio-derived building blocks.[19] By incorporating cleavable bonds or environmentally responsive functionalities, OSCs can be engineered to undergo controlled degradation while maintaining electronic performance during operation (Fig. 1).

This capability is particularly relevant for applications requiring temporally limited functionality, such as transient electronics and biomedical devices. Transient electronic systems are designed to operate for a defined period and subsequently degrade into benign byproducts, minimizing environmental impact and eliminating the need for device retrieval.[11,20–22] In biomedical contexts, biodegradable OSCs enable the development of implantable sensors and therapeutic devices that safely resorb in physiological environments after fulfilling their function.[16,20] More broadly, the integration of degradability into OSCs aligns with circular economy principles, enabling new strategies for sustainable electronics that combine high functionality with environmentally responsible disposal.

However, achieving this balance remains a central challenge, as the introduction of degradable functionalities often compromises electronic performance. Understanding and optimizing the interplay between molecular structure, degradation pathways, and device properties is therefore critical for advancing the field. In this review, we discuss the current strategies for imparting biodegradability to OSCs, the mechanisms

Vittoria Vigorito

Vittoria Vigorito (born 2001, Monza, Italy) received her BSc in Materials Science, and her MSc in Materials Science and Nanotechnology, from the University of Milano-Bicocca, Italy. In 2025, she began her PhD in the group of Prof. Alberto Paleari at the Department of Material Science of the University of Milano-Bicocca. Her research focuses on the development of infrared-emitting scintillators for potential application as dosimeters in FLASH radiotherapy. Outside academia, she is passionate about animals, follows rhythmic gymnastics, and enjoys hands-on activities such as drawing and design.

Pietro Moiraghi

Pietro Moiraghi (born 2001, Monza, Italy) received his BSc and MSc in Materials Science from the University of Milano-Bicocca. Currently, he is carrying out a PhD in Materials Science and Nanotechnology at the University of Milano-Bicocca in the groups of prof. Fasoli and Scotti. His main research topic involves the study of liquid scintillation formulations loaded with high-Z metal oxide nanoparticles for rare events search. Besides the lab, he enjoys baking, chess, and running.

Martina Crosta

Martina Crosta (born 1996, Milan, Italy) received her BSc in Chemistry from the University of Milano-Bicocca, Italy, and MSc in Organic Chemistry from Uppsala University, Sweden. With a thesis on boron- and nitrogen-doped molecular graphenoids, she obtained her PhD degree in Organic Chemistry from the University of Vienna, Austria. In 2025, she joined the group of Prof. Beverina at the University of Milano-Bicocca as a post-doctoral researcher within the EU-funded project GRETA. Her research interests include the synthesis of π-conjugated and heteroaromatic compounds, organic semiconductors for sustainable technologies, and green chemistry approaches. Outside the laboratory, she enjoys throwing pottery, knitting, and swimming.

Luca Beverina

Luca Beverina (born 1975, Milan, Italy) received his MSc and PhD in Materials Science from the University of Milano-Bicocca. Following a postdoctoral appointment at the Georgia Institute of Technology (Atlanta, USA), he joined the University of Milano-Bicocca, where he is now Full Professor of Organic Chemistry and ViceRector's for the Third Mission and Relationships with businesses. His research focuses on the design and synthesis of conjugated materials for organic electronics and biophotonics, with particular emphasis on sustainable materials and green chemistry. He has co-authored more than 150 peer-reviewed publications and 20 patent applications. Outside academia, he enjoys trekking, climbing, and following Grand Sumo.

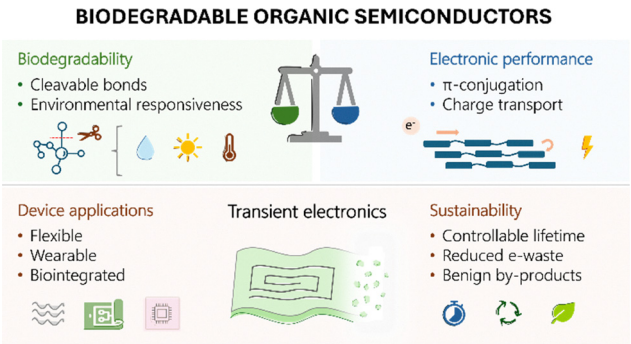

Fig. 1 Biodegradable organic semiconductors: interplay between biodegradability and electronic performance, with applications in transient electronics and sustainable technologies.

governing their degradation, and the resulting trade-offs with electronic performance, highlighting opportunities for the development of next-generation sustainable electronic materials.

Recycling

The widespread use of electronic devices has resulted in an unprecedented increase in electronic e-waste, or waste electrical and electronic equipment (WEEE). This growth poses significant challenges for proper disposal and contributes to the depletion of key chemical elements required in manufacturing. In 2019, WEEE reached 53.6 Mt worldwide. Disposing of WEEE in landfill sites is obviously considered an inefficient strategy and a threat to both human health and the environment.[16–18] Consequently, there is a growing interest in designing strategies to minimize e-waste, including achieving degradation and ideally closed-loop recycling of OSCs.[23]

Life cycle assessment (LCA) is an environmental management tool used to calculate the environmental and human health impacts of products, including photovoltaic devices. Studies have applied LCA to compare OPV solar panels with conventional silicon technologies, evaluating potential cradle-to-grave impacts. Results show that OPVs have the potential for lower environmental footprints and shorter energy and carbon payback times during production compared to silicon. Beyond manufacturing, baseline cradle-to-grave impacts for OPVs used in long-term applications (like rooftop arrays) and short-term applications (like portable chargers) were found to be on average 55% and 70% lower than silicon devices, respectively.[24] These findings suggest that the environmental benefits of OPVs can extend throughout their entire life cycle. Integrating OPVs into simpler devices that leverage their flexibility can lead to further impact reductions. For example, OPV charging units have demonstrated life-cycle impacts that are reduced by 39–89% relative to their silicon-based counterparts.[24] Achieving sustainable (green) electronics involves using abundant materials (including biomolecules), developing novel production schemes with non-toxic solvents, and implementing eco-design principles that incorporate end-of-life options like biodegradation.[16] For organic electronics, it is crucial to design built-in sustainability into materials selection, processing, and device architectures to facilitate a circular approach.[24] This includes ensuring ease of dismantling and recycling.[25]

Historically, limited attention has been dedicated to the end-of-life scenarios for electronic equipment, with the focus primarily on device performance.[16] For conventional photovoltaic technologies, the infrastructure for disposal is often lacking, and landfilling serves as a default solution. Similarly, the disposal routes for commercially used OPV panels remain uncertain.[24]

The recycling of multi-material composites, which are components in many electronic devices, is still an immature area, requiring new solutions. Existing recycling methods for composites can be broadly classified into material recycling (*e.g.*, crushing), thermal recycling (*e.g.*, pyrolysis), and chemical recycling (*e.g.*, solvolysis). However, significant challenges persist, particularly in preserving material properties after recycling and in developing effective methods for multi-material composites. Often, recycling processes break down the composite into its constituent materials, causing a loss of the original composite properties. Moreover, the recovered materials frequently exhibit inferior performance, restricting their reuse to down-cycling applications. Consequently, most end-of-life composites are either buried or incinerated.[26]

The increasing volume of end-of-life composite materials necessitates greater attention from government, industry, and academia. A crucial requirement for new composite products should be an effective method for waste management and recycling.[26] Ultimately, to address the environmental challenges associated with e-waste, especially for emerging technologies like organic electronics, it is vital to invest further in recycling technologies capable of handling all device components and to integrate design-for-recycling principles from the outset.[25]

While refurbishment and recycling of electronic devices have been identified as economically and environmentally viable solutions for WEEE, a promising complementary route toward sustainability for electronics is based on biodegradable materials and devices.[17]

Addressing the end-of-life stage for OSCs and electronics requires developing specific recycling and degradation strategies. However, recycling OSCs faces unique challenges due to the material properties and current technological limitations. Organic-based devices are usually made up of several components with different physical and chemical properties (conductors, semiconductors, dielectrics, substrates, encapsulations), and current designs do not facilitate the dismantling and recovery of materials.[25] Moreover, conventional treatments utilize harsh chemicals (*e.g.* acid leaching), which destroy functional components and require additional procedure for waste management.[27] For example, acidic hydrolysis of imine bonds has been observed to degrade the functional building blocks like naphthalene diimide (NDI) and diketopyrrolopyrrole (DPP).[22,28] Another important challenge is related to the actual performances of the recyclable devices,

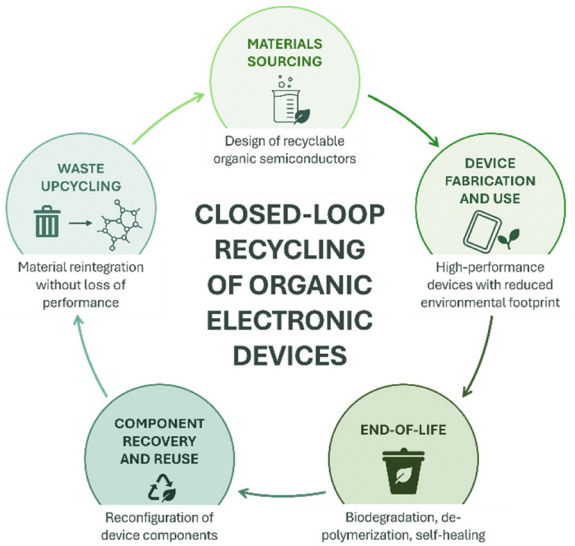

Fig. 2 Schematic illustration of the closed-loop recycling strategy for organic electronic devices.

which may still be low compared to materials not designed for recycling.

Nonetheless, recently significant progress has been made in the recycling of OSCs and the devices that use them, mainly in the area of closed-loop recycling; this refers to the circular process where materials are reused an indefinite number of times in order to produce new devices without loss of performance (Fig. 2). This minimizes waste and consumption of raw materials. OSCs offer unique opportunities for closed-loop recycling owing to their molecular tunability and solution processability, with recent studies highlighting three principal recycling strategies:

1. Component recovery and reuse
2. Materials design
3. Waste upcycling

For the first approach, Park *et al.*[29] reported the possibility of recycling each component of an organic flexible electronic device; they employed a ''recyclable organic flexible'' (ROF) device made of PEDOT:PSS, P3HT and an ion gel as dielectric. Through the use of eco-friendly solvents (water, acetone and anisole) and selective dissolution, the authors were able to recapture the single material components of the ROF device and reconfigure them into other devices, cycling through an inverter, a temperature sensor and an electrochemical transistor in depletion mode (*d*-ECT). The device electrodes did not show considerable degradation even after five iterations of the recycling process.

Kim *et al.*[30] studied a device made of a blend of PEDOT:PSS, polyurethane and PEG, exploiting self-healing properties in order to recover both mechanical and electrical properties even after 20 cycles.

Another strategy, related to the design of materials, exploits the use of reversible bonding in the design of materials in order to enable controlled disassembly in the appropriate conditions; these include imine or ester functionalities. For example,

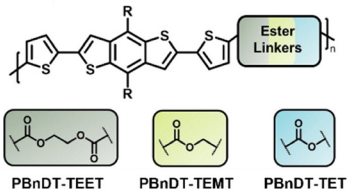

Fig. 3 Chemical structure of depolymerizable benzodithiophene-based polymers incorporating ester linkers. Adapted with permission from ref. 23. Copyright 2024, Wiley-VCH GmbH.

Megret-Bonilla *et al.*[23] incorporated some depolymerizable ester units into a benzodithiophene-based conjugated polymer, to yield polymers like PBnDT-TEET, PBnDT-TEMT, and PBnDT-TET (Fig. 3).

While all three polymers could depolymerize under methanolysis, PBnDT-TEET demonstrated the highest recyclability potential, yielding a single dimethyl ester-functionalized product with an excellent 92% isolated yield. This recovered material could then be repolymerized to reobtain PBnDT-TEET, albeit with a lower yield of 36%. While this work establishes a framework for recyclable OSCs, a central challenge remains the simultaneous realization of effective recycling and high device performance. Indeed, PBnDT-TEET showed a power conversion efficiency (PCE) of only 0.03% in solar cell, which is markedly lower than state-of-the-art values exceeding 20%.[31–33]

A different approach involves waste upcycling, that is the process of converting waste into new functional high-value materials. As reference example, Lo *et al.*[34] demonstrated that waste Styrofoam can be sulfonated to synthesize PEDOT:PSS, creating electronics-grade material from plastic waste. The obtained material was subsequently integrated into a hybrid solar cell and demonstrated performances similar to those of commercial PEDOT:PSS.

Degradation and biodegradation

A viable end-of-life option for appropriately designed organic electronic materials is biodegradation, particularly *via* composting.[16,17] Di Mauro *et al.*[16] studied the biodegradability of bio-sourced and synthetic organic electronic materials in industrial compost conditions (thermophilic at 58 °C and mesophilic at 25 °C), following the ASTM D5338 protocol. Under these conditions, the bio-sourced pigment eumelanin, extracted from cuttlefish ink, showed biodegradation. Under mesophilic conditions (25 °C), Sepia melanin reached a mineralization level of 4.1% in 97 days. Under thermophilic conditions (58 °C), the mineralization level for Sepia melanin was significantly higher, reaching 37% after 98 days. This demonstrates that temperature is a major factor influencing the rate of melanin biodegradation, being 9 times higher at 58 °C than at 25 °C. Biodegradation in compost is carried out by a community of microorganisms and is a multi-step process involving initial depolymerization followed by mineralization into H_2O and CO_2. In contrast to eumelanin, two synthetic organic

electronic materials tested, copper(II) phthalocyanine (Cu–Pc) and polyphenylene sulfide (PPS), did not biodegrade under these composting conditions. Cu–Pc even caused inhibition of microbial respiration in the compost. It is important to distinguish between biodegradability in composting conditions (a man-made ecosystem) and bioresorbability, which refers to degradation and absorption of materials within a physiological environment (like body fluids), relevant for transient electronics or implants. Much of the work claiming biodegradability of organic electronic devices actually refers to testing in aqueous electrolytic solutions akin to bioresorbability conditions.[16]

Environmental concerns about persistent waste have intensified research into degradable and biodegradable materials as possible alternatives to conventional plastics. The issue of "white pollution" is becoming increasingly significant, making it imperative to reduce polymeric waste and protect the environment.[35]

It is crucial to understand the concepts of degradability and biodegradability to avoid terminological misunderstandings.[36] Although these terms are frequently used interchangeably, they represent distinct processes with significant differences in environmental context, mechanisms and practical outcomes. This differentiation is crucial for proper material classification and environmental management.

The term Degradability refers to the general breakdown of materials through various mechanisms.[35] Biodegradability, on the other hand, indicates the decomposition that takes place by the action of biological agents, such as bacteria, fungi and algae.[37] Biodegradability is a multifaceted property, thus no single definition exists.[38] Also for this reason, the environmental context in which degradation occurs (soil, compost, seawater, anaerobic digestion) is decisive and should always be specified.[39] In this framework, the academic bibliography on environmental biotechnology emphasizes also that biodegradation and bioremediation, by their very definition, have distinct meanings and, consequently, require differentiated methodological approaches. The former refers in fact to a naturally occurring process, whereas the latter to a man-made process.

Another distinction that is worth making is the one between biodegradable and bio-based materials. Indeed, the latter only refers to the origin of the material, indicating that it contains organic carbon of renewable origin, derived from agricultural, plant, animal, fungal, microbial, marine or forestry raw materials. However, this does not imply that all bio-based polymers are necessarily biodegradable.[36,37,39]

Bio-based polymers, both natural and synthetic, are increasingly being explored as functional components in organic semiconducting devices. Serving as substrates, dielectrics, and even active semiconducting or charge-transport layers, they have in some cases showed performance approaching that of devices built on conventional materials.[40]

The design of both bio-based and biodegradable conjugated polymers remains an ongoing challenge in the field. There are instances in which the biodegradability of bio-based conjugated systems was reported, such as for carotenoid-derived poly(azomethine)s possessing imine linkages that provide both conjugation and controlled degradability.[41] However, many sources that discuss bio-based conjugated polymers do not comment on their biodegradability, instead focusing on renewable sourcing and sustainable synthetic methods.[42,43]

Degradation type and mechanisms

As shown in Fig. 4, degradation of materials can occur through different mechanisms, including abiotic degradation and biotic degradation (or biodegradation).[36]

An example of abiotic mechanism is chemical degradation, which is caused by agents such as oxygen, water, alkaline substances, acids and solvents; hydrolytic degradation is a variant of such mechanism. Other abiotic mechanisms include photodegradation, hydro-degradation and thermo-oxidative degradation.

Biodegradation instead, is the process of decomposition of an organic substance by the action of living organisms that produce extracellular enzymes. It is thus triggered at physiological or biologically benign conditions.[44] This process can be classified either according to the oxygen presence or to the extent of fragmentation achieved. In the first case it is possible to distinguish between aerobic degradation, occurring in the presence of oxygen, and anaerobic degradation, which occurs in the absence of oxygen.[36,37] In the second case, two degradation mechanisms can be described type I and type II (Fig. 5).[19]

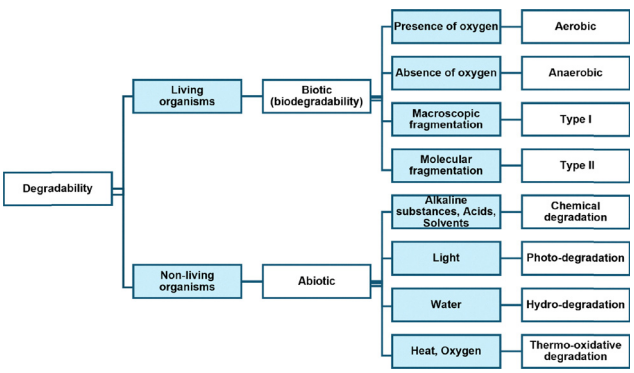

Fig. 4 Scheme illustrating degradability classification and terminology (white) according to different parameters (light blue). A primary distinction can be made on the base of the environment where the degradation process takes place, whereas a secondary distinction can be made on the base of the agents involved and the extent of fragmentation achieved.

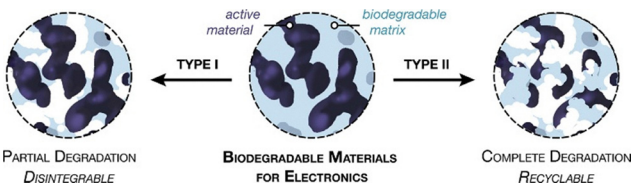

Fig. 5 Degradation mechanisms: type I and II. Type I degradation (left) consists of a partial breakdown of the material, resulting in its fragmentation. Type II Degradation (right) consists of a full molecular cleavage enabling the complete degradation of the material and potentially recycle. Reproduced with permission from ref. 19. Copyright 2018, American Chemical Society.

Type I and type II degradation

Type I degradation refers to a partial breakdown of the material, which is typically characterized by macroscopic fragmentation and a loss of structural integrity, without the occurrence of complete chemical cleavage at the molecular level. In other words, while the material undergoes a visible physical disintegration, its chemical backbone remains, at least in part, intact.[19] This preliminary decomposition does not guarantee complete biological assimilation or conversion into simple substances. Materials that only fragment may leave behind persistent intermediate debris, such as microplastics, which may remain in the environment for a long time.[36,39] Nevertheless, this stage of degradation is often sufficient to significantly reduce, or even eliminate, the need for complex and costly recycling processes in large-scale applications such as electronic devices.[45,46]

Type II degradation, on the other hand, involves a complete degradation process in which the entire material undergoes molecular cleavage, ultimately resulting in the formation of smaller units such as oligomers and monomers.[19] This process frequently occurs either *in vivo* through biological or immune-mediated mechanisms, or in natural environments *via* the action of specific microorganisms enabling a further breakdown of the material.[19] At this stage, simple compounds such as carbon dioxide, water, methane, biomass and mineral salts are formed.[36,39] The standards for biodegradable materials require this complete biological assimilation, however, such achievement typically requires the adoption of tailored synthetic strategies during the material design stage. For instance, some of them aim at introducing labile bonds or functional groups susceptible to cleavage under physiological or environmental conditions.[19,47]

Electrically conductive polymers represent promising alternatives to conventional electronic materials, particularly in the context of sustainable electronics, where biodegradability can help mitigate the environmental impact of increasing e-waste.[45] Incorporating biodegradability into the design of conductive polymers could contribute to reducing the accumulation of persistent synthetic materials in landfills and natural ecosystems.

On the other side, there exist specific fields of application where biodegradability is not merely a desirable feature but rather a strict requirement. This is particularly the case in biomedical engineering and healthcare-related technologies. The use of biodegradable materials enables the creation of transient medical devices, such as temporary implants, drug delivery systems, and bioresorbable sensors, which are designed to safely degrade *in situ* after fulfilling their therapeutic or diagnostic function, thus avoiding the need for invasive surgical removal procedures and minimizing long-term complications for patients.[11,48,49]

Although the fundamental mechanisms governing the degradation of electrically conductive polymers are often similar, whether intended for electronic or biomedical applications, the degradation kinetics and profiles can vary significantly depending on several factors.[47] In this context, both biodegradation rate and the nature of the resulting byproducts must be carefully assessed to ensure biocompatibility and environmental safety.[47] Consequently, a systematic and holistic design approach is essential to achieve reliable and efficient degradation pathways tailored to the intended application.

From an application standpoint, type I biodegradable materials have found particular relevance in the biomedical field, where controlled degradation rates are highly desirable. These materials are widely employed in therapeutic applications, targeted drug delivery systems, and regenerative medicine.[47,50]

This can be achieved either by engineering the intrinsic properties of the biodegradable components – such as polymer composition, molar mass, and crystallinity – or by incorporating stimulus-responsive materials capable of degrading in response to specific external or physiological stimuli, including changes in pH, temperature and humidity.[45] Such an approach enables the design of systems with tunable lifetimes and tailored functionality according to the therapeutic or diagnostic needs.

Once partial or complete degradation has occurred, the resulting byproducts can follow different metabolic or disposal pathways, depending on the application context. In the case of *in vivo* biomedical applications, these degradation products are generally processed by biological systems through various mechanisms, such as phagocytosis by immune cells, enzymatic metabolization or bioabsorption.[19]

Type II materials instead have attracted growing interest in the context of sustainable electronics and in the field of security systems owing to their complete degradability.[45,51] Among the inherently degradable materials, natural polymers such as cellulose have been extensively investigated.[52] Other examples include plant-based fibers such as jute, cotton, banana and bamboo that can provide a valid alternative to traditional dielectric materials. They exhibit in fact high dielectric constants (k) thanks to the presence of hydroxyl groups conveying polarity.[53] Moreover, owing to their flexibility, organic materials can be successfully incorporated in combination with inorganic materials, which instead exhibit poor mechanical properties.[51]

The selection of the appropriate degradation mechanism and trigger is crucial and should be tailored to the final application. For example, environmental monitoring devices designed for operation in open ecosystems should ideally be degradable under soil or marine conditions, to minimize the environmental footprint and facilitate natural disposal.[54]

Finally, it should also be noted that biodegradation is an extremely complex and multi-parameter process, and reproducing realistic degradation conditions in a laboratory setting presents significant challenges.[45]

Molecular design strategies to impart biodegradability

The degradability of semiconducting polymers intended for transient electronics is the result of a complex and finely balanced interplay between intrinsic material properties and external environmental conditions. Achieving controlled degradation requires careful molecular design that incorporates cleavable bonds, optimizes hydrophilicity, and modulates polymer morphology and aggregation. At the same time, the

chemical, physical, and biological stimuli encountered during the material's operational life or disposal phase – such as solvent polarity, pH, enzymatic activity, light exposure, and oxygen availability – play a decisive role in determining the rate and mechanism of degradation.

In the following sections, we provide a more detailed discussion of the main factors affecting polymer biodegradability, as previously outlined.

A primary strategy in the design of degradable materials involves the strategic incorporation of labile chemical bonds within the polymer backbone.[23,55–57] Among the most employed are imine (IM) bonds. These bonds are particularly useful because their π-electrons can contribute to maintaining the continuous conjugation along the polymer chain necessary for semiconducting properties.[58] While imine bonds exhibit stability under neutral pH conditions, they are readily cleaved when exposed to acids, due to their acid–labile nature which makes them easily hydrolysable.[59]

As an alternative to imine bonds, other cleavable linkages can be employed to enhance polymer biodegradability. Ester, amide, and anhydride bonds, for instance, are prone to hydrolytic degradation, making them effective for environmentally responsive materials.[60] Likewise, disulfide bonds and oxidation-sensitive moieties offer degradation routes through reductive or oxidative mechanisms.[48,61] The selection of these alternative bonds enables the design of polymers with tailored degradation behaviours suited to various applications.

Side-chain engineering plays a significant role in the biodegradability of semiconducting polymers, particularly by influencing the kinetics of degradation and the overall morphology and processability of the material.[62,63] While the primary degradation mechanism often relies on labile bonds incorporated into the polymer backbone, the side chains affect how quickly and effectively this backbone degradation can occur. The structure and properties of the side chains, including the branching point and the overall molar mass, can affect how polymer chains aggregate in solution, which in turn impacts the rate of degradation. Reducing aggregation can facilitate faster degradation.[22]

Chiong *et al.*[22] recently proposed a study on the influence of side-chain engineering on DPP-based polymers (Fig. 6). Among the analyzed parameters, the impact of hydrophilicity was investigated by incorporating triethylene glycol (TEG) or modified branched alkyl chains with ether functionalities (C_4E). Degradation lifetimes were studied by means of UV-vis spectroscopy both in solution and thin-films. Increased hydrophilicity was found to accelerate degradation by facilitating water diffusion into the polymer matrix, leading to degradation times of 10 and 14 days for C_4E and TEG, respectively. This effect was observed at room temperature in chloroform, with a molar excess of trifluoroacetic acid (TFA) and water. Chloroform, unlike toluene and chlorobenzene, enabled enough water dissolution for the hydrolysis of imine bonds. A positive effect on degradation was observed in thin films due to the improved water diffusion in the hydrophobic polymer substrates. In the latter case, a 50% degradation was observed in 3 and 21 days for C_4E and TEG, respectively.

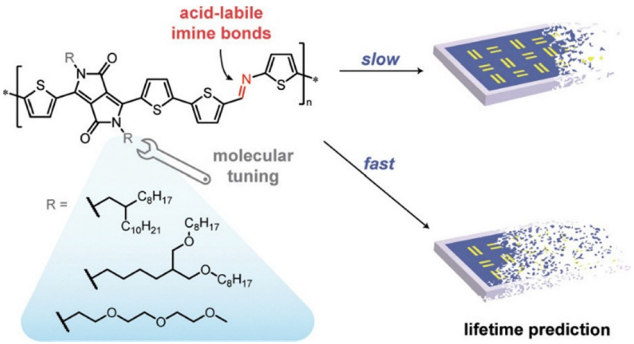

Fig. 6 Molecular design of imine-containing DPP polymers with different side chains, from top to bottom: pDPP(C1)-TIT, pDPP(C4E)-TIT, pDPP(10TEG)-TIT. Reproduced with permission from ref. 22. Copyright 2022, American Chemical Society.

Terpolymerization consists of incorporating three different monomer units into a polymer chain. This strategy is often presented as a versatile approach to tailor both the degradability and the electrical performance of semiconducting polymers.[64,65]

In another work by Chiong *et al.*,[64] two imine-based monomers (benzothiadiazole-imine-benzothiadiazole (BTiBT) and benzothiadiazole-imine-phenyl (BTiPh)) were synthesized to be copolymerized with indacenodithiophene (IDT) (Fig. 7). In this case, terpolymerization was used to directly influence the morphology of the resulting polymer, as the BTiPh fragment was expected to show more significant backbone twisting with respect to the BTiBT fragment. By varying the ratio and the type of monomers, it was possible to introduce structural disorder and reduce the crystallinity of the polymers, thus accelerating the rate of degradation. The IDT-based polymers, despite exhibiting only short-range order, showed charge carrier mobilities comparable to those of the semicrystalline, long-range ordered polymer pDPP(C4E)-TIT. Remarkably, however, they underwent degradation orders of magnitude more rapidly in both solution and thin films, even under comparatively mild acidic conditions.

The observation of faster degradation in less ordered polymers is consistent with solution-phase degradation kinetics being strongly dependent on the aggregation state of the polymer chains.[66] In thin films, morphology plays a dual role, influencing both electronic performance and the efficiency of solid-state degradation.[67,68]

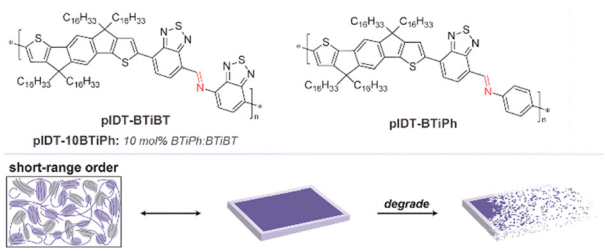

Fig. 7 Molecular design of imine-containing IDT terpolymers. Adapted with permission from ref. 64. Copyright 2023, The Royal Society of Chemistry.

This highlights that all of the above aspects are closely interconnected and must be considered when designing degradable semiconducting polymers.

Environmental factors influencing degradation

Environmental factors play a crucial role in triggering degradation and influencing the stability of electronic devices and materials. These factors encompass a range of abiotic conditions, including solvation, temperature, light, and mechanical force. Abiotic factors are important for biodegradable features, alongside enzymatic reactivities (Fig. 8).

The chemical environment significantly impacts material behaviour and degradation. pH changes can act as an endogenous trigger to activate release mechanisms in responsive systems, and local pH changes can generate electrochemical responses that dissolve polymers. The rate of degradation for azomethine-containing polymers, for instance, is dependent on the strength of the acid used during hydrolysis, with the rate tending to increase as the pK_a of the acid decreases. In the work of Brindhadevi *et al.*[69] the degradation of fluorene using hausmannite nanoparticles was investigated across a range of pH values between 5 and 9. In 2022 Gutiérrez *et al.*[70] presented a synthesis of magnetite nanoparticles and diimide-dopamine ligands, that were subsequently bonded in basic conditions and through irradiation between 120–130 °C at 3 bar. The increase in pressure and temperature was shown to convey chemical resistance to extreme aqueous pH conditions.

Hydrolysis, often initiated by moisture in the air, causes certain bonds like anhydride bonds to undergo chain scission.[51] Controlling humidity levels can tune degradation rates.[71] Degradation *via* hydrolysis in natural environments like seawater at room temperature is an example of environmental depolymerization.[72] For azomethine-containing polymers, the rate of degradation varies depending on the solvent used for hydrolysis. Solution degradation studies reveal a dependence on solvent polarity; the degradation rate tends to increase as the polarity of the solvent decreases. Calculations suggest that solvents with higher polarity may stabilize protonated imine intermediates, potentially affecting the degradation rate. Highly hygroscopic solvents, like THF, can contain a greater concentration of water, leading to an increased rate of hydrolysis.[67]

The presence of oxygen is a critical environmental factor, particularly for the stability of OPVs. Oxygen exposure, especially during illumination, can facilitate photochemical reactions and lead to the formation of photodegraded products. This means photodegradation mechanisms can differ significantly between ambient air and inert (oxygen-free) environments.[73]

Light (solar irradiance or illumination) can also trigger degradation, especially in photoactive materials. Photovoltaic materials in OPVs are subjected to illumination, which triggers photochemical reactions, changes their photo-physical properties, and can introduce traps leading to device degradation. Light-induced molecular structural changes at the sub-nanometer scale and morphological changes at the nanometer scale occur under illumination.[73] Brindhadevi *et al.*[69] have evaluated the influence of different irradiation sources, specifically sunlight and UV light, on the photocatalytic degradation efficiency of fluorene. The experiments were conducted over exposure times ranging from 1 to 5 hours, revealing a correlation between the duration of illumination and degradation efficiency. Specifically, the degradation percentage increased from 40% to 56% in water and from 44% to 67% in soil after 360 minutes of exposure to sunlight and UV radiation. However, extending the irradiation period beyond 360 minutes led to a reduced degradation rate, likely due to the accumulation of intermediate compounds and by-products generated during the photocatalytic process.

The degradation times of polyanhydrides are affected by temperature.[54] One clear example of the effect of the temperature is shown in the work of Park *et al.*,[28] where they investigated the degradation of thin films of imine-based semiconducting polymers and decided to use heating at 70 °C in acidic solution to accelerate degradation. Overall, also mechanical stresses and pressure can act as abiotic trigger for degradation as shown by Lee *et al.*[11]

Enzymatic reactivities are essential for features like biodegradation. Studies evaluated polymer biodegradability by incubating films with enzymes like cholesterol esterase, observing increased release of degradation products in the enzyme's presence. The combined use of nanotechnology and microorganisms can accelerate natural bioremediation processes.[70]

The selection of substrates is another key aspect in the design of sustainable organic electronic devices. Accounting for the largest fraction of total mass of materials in the device, the use of biodegradable substrates such as cellulose, paper, silk, hydrogels and biopolymers can enable environmentally benign end-of-life scenarios.[74–80] Their porous and hydrophilic nature can promote the diffusion of water, oxygen, enzymes, and microorganisms into the device architecture, thereby accelerating the degradation of active components and facilitating material recovery.[77] At the same time, it is critical that the biodegradable substrate remains compatible with the conditions for device fabrication, including solution-based deposition techniques and thermal treatments usually required for semiconductor processing.

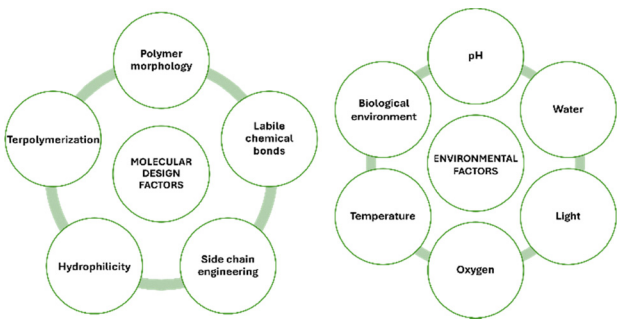

Fig. 8 Scheme illustrating the main parameters affecting the degradability of semiconducting polymers. As in the discussion above, the factors can be divided into (left) Molecular design factors and (right) environmental factors.

Biodegradation processes

Several degradation and biodegradation processes relevant to OSCs and transient electronics can be found in the literature, which primarily rely on hydrolysis (especially of imine and ester linkages), enzymatic degradation (particularly for natural polymers), and oxidative degradation (including photo-oxidation and ROS-induced mechanisms).

Hydrolysis

Hydrolysis represents one of the primary degradation pathways in biodegradable OSCs, involving the cleavage of covalent bonds through reaction with water to yield oligomers or monomeric species.[45] This mechanism is particularly relevant for polymers incorporating hydrolysable linkages, and has been widely exploited to design materials with controlled degradability.

As previously discussed, imine (–C═N–) linkages have emerged as especially effective in semiconducting systems, as they enable degradation while largely preserving π-conjugation along the polymer backbone.[22,67] Under acidic conditions, protonation of the imine nitrogen shifts the equilibrium toward bond cleavage, leading to the regeneration of the corresponding amine and aldehyde building blocks.[54,67] This reversible chemistry provides a basis for triggered degradation strategies and, in some cases, potential recyclability.[23] Importantly, imine bonds have demonstrated sufficient stability under neutral conditions and during post-polymerization processes, making them compatible with device fabrication.[58,67,81,82]

A range of imine-based semiconducting polymers has been developed using building blocks derived from common conjugated systems such as diketopyrrolopyrrole (DPP) and naphthalene diimide (NDI).[28] In these materials, hydrolysis can be induced under relatively mild conditions, as demonstrated by studies showing rapid degradation in the presence of water and acid, often monitored through changes in optical absorption associated with disruption of interchain interactions.

The incorporation of imine linkages into high-performance semiconducting polymers has also enabled systematic investigations of the trade-off between electronic properties and degradability. For example, in NDI-based terpolymers, increasing the fraction of imine units leads to a progressive decrease in electron mobility, attributed to disruption of the donor–acceptor architecture and introduction of electronic disorder.[28] Nevertheless, moderate imine contents can still yield mobilities sufficient for device operation, particularly when favourable packing motifs are retained. These findings highlight the importance of balancing chemical lability with structural order in the design of degradable OSCs.

Alternative synthetic strategies have been explored to decouple degradable functionality from polymerization methods. In particular, modular approaches based on Stille cross-coupling have been used to incorporate imine-containing linkers into conjugated backbones. In detail, the approach reported by Chiong *et al.*[22] involves pre-installing the acid–labile imine bond within a ditin-functionalized thiophene–imine–thiophene (TIT) monomer unit prior to polymerization, rather than generating the degradable linkage as a direct product of the coupling reaction connecting donor and acceptor units. Because the degradable bond resides entirely within this separate building block, the same TIT monomer can be coupled with a range of structurally distinct donor or acceptor cores *via* standard Stille cross-coupling, without requiring redesign of the polymerization protocol for each new backbone structure. This strategy expands the chemical space available for degradable OSCs beyond condensation-based systems.[22]

Hydrolysis has also been investigated in composite systems, where semiconducting polymers are embedded within biodegradable matrices. In such architectures, the degradation of the matrix and the semiconductor can occur on different timescales, allowing independent tuning of mechanical properties and electronic functionality. For instance, DPP-based semiconducting polymers incorporated into polycaprolactone (PCL)-based elastomeric matrices exhibit gradual degradation over weeks under acidic aqueous conditions, while maintaining biocompatibility *in vitro* (Fig. 9).[83] These systems illustrate how hierarchical material design can be used to control degradation behaviour in complex devices.

In contrast to imine-based systems, ester linkages are widely used in biodegradable polymers due to their susceptibility to hydrolysis under acidic, basic, or enzymatic conditions.[23,45,53,56] Their incorporation into conjugated backbones is generally limited as ester functionalities disrupt π-conjugation and significantly reduce charge transport properties.[54,56] As a result, ester-based degradation strategies are more commonly applied to supporting materials or as cleavable units in partially conjugated systems.

Overall, hydrolysis-based degradation in OSCs is governed by a combination of molecular design, morphology, and environmental conditions. Effective implementation requires the integration of hydrolysable motifs that enable controlled bond cleavage while preserving sufficient electronic functionality, highlighting the central challenge of balancing degradability with device performance.

Oxidation

OSCs are inherently susceptible to oxidative degradation when exposed to oxygen, particularly under illumination. This process

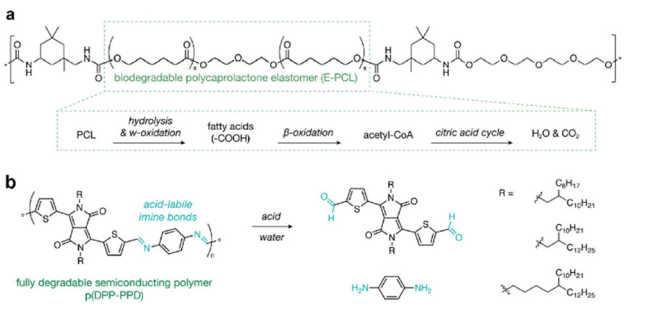

Fig. 9 (a) Structure of the PCL-based elastomeric matrix, with the known biodegradation mechanism of PCL being highlighted; (b) structure of the degradable polymer, with the degradation scheme. Adapted with permission from ref. 83. Copyright 2019, American Chemical Society.

represents one of the primary pathways limiting device stability and lifetime, as it induces irreversible chemical modifications that disrupt π-conjugation and deteriorate electronic performance.[84]

Oxidative degradation typically proceeds through photoactivated pathways involving the generation of reactive oxygen species (ROS). Upon light absorption, excited states in the semiconductor can transfer energy or electrons to molecular oxygen, leading to the formation of superoxide radicals ($O_2^{\bullet -}$), hydroxyl radicals ($^{\bullet}OH$), and singlet oxygen ($^1O_2$).[84] These highly reactive species attack vulnerable sites in the polymer backbone, resulting in chain scission, oxidation of functional groups, and loss of conjugation, ultimately impairing charge transport properties.

The dominant degradation mechanism depends strongly on the physical state of the material and its electronic structure. While singlet oxygen-mediated pathways are often invoked, experimental evidence—particularly from studies on poly(3-hexylthiophene) (P3HT)—indicates that radical-driven mechanisms prevail in the solid state.[85] In this context, degradation kinetics are influenced by exciton generation rates and their interaction with oxygen, leading to a radical chain process that governs the evolution of chemical damage within the material.[85]

The electronic structure of OSCs plays a crucial role in determining their susceptibility to oxidation.[86] The spatial distribution and energy alignment of frontier molecular orbitals (HOMO and LUMO) influence exciton dissociation and the probability of charge transfer to oxygen. Modifications to the electronic structure, such as through doping or molecular design, can therefore alter degradation pathways by either promoting or suppressing ROS formation.[87]

Environmental factors further modulate oxidation processes. Light intensity and spectral distribution are key parameters, with higher-energy (*e.g.*, UV) irradiation significantly accelerating degradation rates.[85] Oxygen concentration also affects reaction kinetics, with rapid increases in degradation rate observed at low partial pressures before reaching saturation behaviour at higher concentrations. Humidity, although not directly causing degradation, can act as a catalytic factor by influencing oxygen uptake and facilitating secondary reactions, particularly during prolonged exposure. Temperature contributes by enhancing oxygen diffusion and reaction rates, thereby accelerating overall degradation kinetics.

The temporal evolution of oxidative degradation is also an important consideration. In model systems such as P3HT, early stages of degradation are characterized by limited structural disruption, whereas prolonged exposure leads to more pronounced chemical transformations, including thiophene ring opening and accumulation of oxidation products at the surface. High-resolution analytical techniques, such as MALDI-TOF mass spectrometry, have enabled the identification of specific low-molecular-weight degradation products, providing insight into the underlying reaction pathways.[84,89]

Recent studies have further highlighted the sensitivity of OSC stability to processing conditions and material preparation. For example, variations in synthesis conditions of perylene diimide (PDI)-based systems can significantly influence the stability of radical species and, consequently, the degradation of transport capabilities under ambient conditions (Fig. 10).[90]

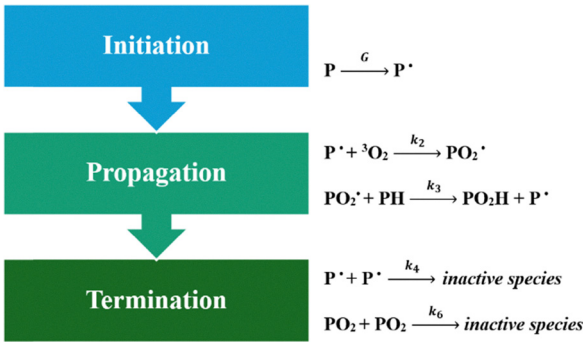

Fig. 10 Kinetic scheme of polymer degradation by a radical chain mechanism where *G* is the generation rate of excitons and P stands for the polymer chain. Adapted from ref. 85 and 88.

These findings underscore the importance of controlling both molecular design and processing parameters to mitigate oxidative degradation.

Overall, oxidative degradation in OSCs arises from a complex interplay between photoexcitation, oxygen diffusion, electronic structure, and environmental conditions. Understanding these coupled factors is essential for the rational design of materials with improved operational stability, particularly in applications such as organic photovoltaics and field-effect transistors, where long-term performance is critical.

Enzymatic degradation

Enzymatic degradation represents an important biodegradation pathway involving the enzyme-catalysed cleavage of susceptible chemical bonds within polymeric materials.[53] While polymers derived from natural sources readily undergo enzymatic breakdown in biological environments, synthetic polymers—particularly OSCs—are generally far less susceptible to enzymatic attack.[53,91] This limited degradability arises from their chemical structure and dense packing, which restrict enzyme accessibility. As a result, enzymatic degradation in OSCs is typically confined to a surface erosion process, as the relatively large size of enzymes prevents penetration into the bulk of the material. Consequently, degradation rates are strongly dependent on polymer morphology, with increased crystallinity and cross-linking density reducing water uptake and limiting enzymatic access.[19] Compared to hydrolytic and oxidative degradation pathways, enzymatic degradation remains less explored in semiconducting systems and is primarily relevant for materials designed for biomedical applications, where biocompatibility and controlled resorption are critical. In this context, several studies have demonstrated that the incorporation of hydrolysable linkages, such as esters, can enhance susceptibility to enzymatic cleavage.

Early examples include the work of Rivers *et al.*,[92] who reported pyrrole–thiophene–pyrrole oligomers incorporating ester linkages along the backbone (Fig. 11).

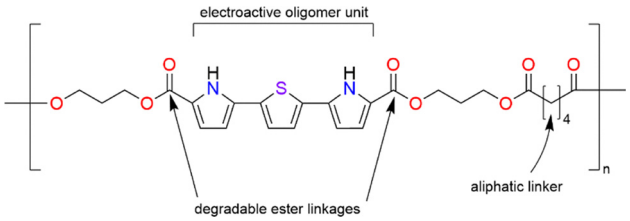

Fig. 11 Chemical structure of the pyrrole–thiophene–pyrrole oligomers alternated by degradable ester linkages and aliphatic linkers. Adapted from ref. 92.

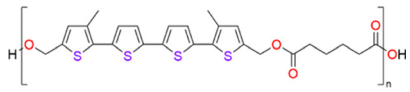

Fig. 12 Chemical structure of the quaterthiophene-*co*-adipic acid polyester. Adapted from ref. 56.

Although these materials do not possess fully conjugated structures, they demonstrate that partial retention of electrical conductivity can be achieved alongside enzymatic degradability. Similarly, Guimard *et al.*[56] investigated a quaterthiophene-*co*-adipic acid polyester (QAPE) (Fig. 12), showing that incubation with cholesterol esterase (CE) led to increased release of degradation products compared to control samples. These results indicate that enzymatic cleavage of ester bonds can contribute to polymer degradation, although concurrent non-enzymatic hydrolysis may also play a role.

More complex systems have been developed to integrate biodegradability with improved mechanical and electrical properties. For instance, Xu *et al.*[93] designed a conductive polyurethane elastomer (DCPU) incorporating biodegradable segments such as polycaprolactone (PCL), where degradation was accelerated in the presence of lipases compared to buffer solutions alone. The degradation rate was found to depend on polymer composition, highlighting the role of molecular design in modulating enzymatic susceptibility. Importantly, these systems demonstrated good cytocompatibility, confirming their potential for biomedical applications (Fig. 13).

In addition to synthetic polymers, naturally derived or bio-inspired materials have also been explored. Irimia-Vladu *et al.*[94] reported that certain organic pigments and dyes, such as indigo and related compounds, can undergo enzymatic degradation

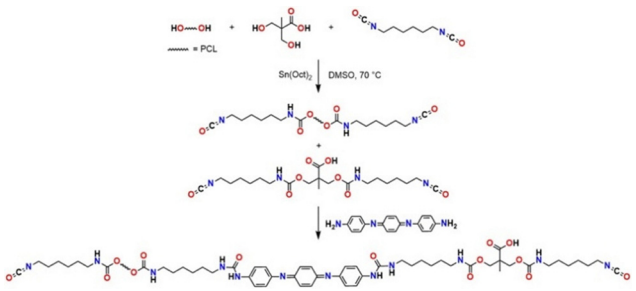

Fig. 13 Schematic synthetic pathway of DCPU. Adapted from ref. 93.

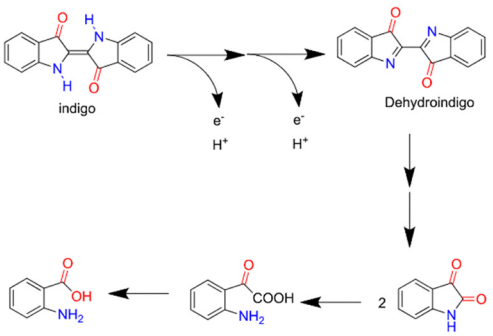

Fig. 14 Proposed scheme of degradation of indigo. Adapted from ref. 94.

mediated by biological catalysts including laccases and peroxidases (Fig. 14). However, the strong intermolecular interactions and low solubility of these materials can limit their accessibility to enzymatic processes, resulting in relatively slow degradation kinetics.

Overall, enzymatic degradation in OSCs remains a relatively underdeveloped strategy compared to hydrolysis and oxidation, primarily due to the inherent incompatibility between highly conjugated structures and enzymatic accessibility. Nevertheless, it offers unique opportunities for biomedical and transient electronic applications, where degradation under physiological conditions is required. Future developments will likely focus on designing semiconducting polymers with tailored architectures that balance enzymatic degradability, electronic performance, and structural accessibility, thereby enabling more efficient and predictable biodegradation pathways.

Other degradation processes

Another possible application for semiconducting polymers has been demonstrated in the work of Tang *et al.*,[61] wherein a self-sacrificially degradable pseudo-semiconducting polymer (PSP) was designed for incorporation into a multifunctional nanoparticulate system for deep-tissue bioimaging and cancer therapy. The PSP architecture incorporates strategically positioned ''soft blocks'' with disulfide linkages integrated within the polymer backbone (Fig. 15). This structural modification

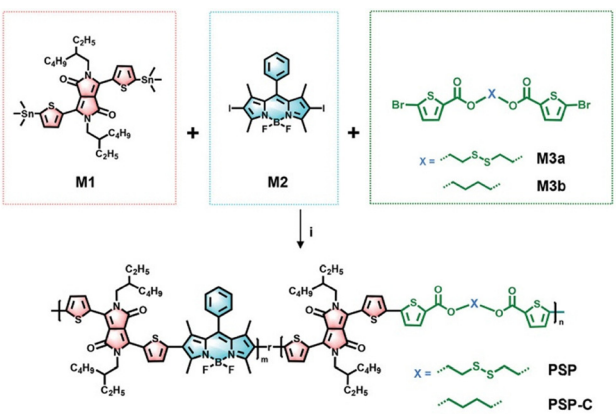

Fig. 15 Illustration of the components and synthetic approach of a pseudo-semiconducting polymer. Adapted with permission from ref. 61. Copyright 2022, Wiley-VCH GmbH.

enables the preservation of semiconductor functionality while introducing susceptibility to biodegradation mechanisms in physiological environments. The engineered PSP was further co-assembled with an amphiphilic polyester functionalized with pendant doxorubicin moieties (PEDOX).

The degradation pathway exploits the differential concentration of glutathione (GSH) between tumoral and normal tissues. The mechanism proceeds *via* thiol-disulfide exchange reactions wherein GSH, an intracellular antioxidant present at elevated concentrations within tumor microenvironments, cleaves the disulfide bonds incorporated within the PSP backbone. The self-sacrificial degradation mechanism not only facilitates eventual clearance from biological systems but also functions as an integral component of the therapeutic strategy.

Another example of the relevance of biodegradable OSCs in biomedicine can be found in the work of Bettinger *et al.*,[50] which evaluates the potential application of melanin thin films as semiconducting substrates for regenerative medicine approaches, particularly in neural and cardiac tissue reconstruction. Melanins are naturally occurring pigments exhibiting electronic conduction properties. The hydration-dependent conductivity profile renders melanin particularly suitable for *in vivo* tissue engineering applications where physiological hydration is inherently maintained.

The melanin thin films prepared in this work were studied under physiologically relevant hydrated conditions and demonstrated electrical conductivity of $7.00 \pm 1.10 \times 10^{-5}$ S cm^{-1} that enhanced Schwann cell proliferation and PC12 neurite extension *in vitro*.

Histological assessment was conducted by examining the biomaterial–tissue response of melanin implants placed in close proximity to peripheral nerve tissue. Melanin films induced an inflammation response that was comparable to silicone implants *in vivo*. A significant finding of the *in vivo* investigation was the substantial resorption of melanin implants observed after an 8-week implantation period. This degradation timeframe is compatible with the temporal requirements for regenerative medicine scaffold functionality, allowing sufficient persistence for therapeutic efficacy while preventing long-term foreign body complications.

These results suggest that solution-processed melanin thin films have the potential for use as a biodegradable semiconducting biomaterial for use in tissue engineering applications.

Synthetic and processing strategies compatible with biodegradability

Apart from intrinsic degradability and recyclability of organic semiconductors and devices, the synthetic and processing methods employed during their manufacture strongly influence their overall environmental footprint and end-of-life behavior.

Conventional conjugated polymers are typically prepared by transition-metal-catalyzed reactions (*e.g.*, Stille or Suzuki polymerizations) and subsequently processed using halogenated or other hazardous organic solvents.[95] These approaches generate large quantities of hazardous waste and may leave residual catalysts, solvents, or processing additives trapped within the final material, potentially compromising biodegradability, biocompatibility, and environmental safety.

Consequently, increasing attention has been devoted to developing green-chemistry-compliant synthetic and processing strategies for truly sustainable organic electronics. Alternative solvents with reduced toxicity or derived from renewable feedstocks have been explored to mitigate solvent impacts.[96,97] Furthermore, recent advances demonstrate that aqueous synthesis and water-based processing, enabled by micellar catalysis,[98,99] biodegradable surfactants[100] and self-emulsifying polymers,[101] can provide a viable alternative to conventional solvent-intensive protocols. For a more comprehensive discussion on the synthesis and processing of π-conjugated derivatives in aqueous media, we refer the interested readers to our recent review.[102] At the same time, emerging methodologies—including enzymatic,[103] electrochemical,[104,105] and photochemical[106] polymerization—offer opportunities to reduce or eliminate transition-metal catalysts, minimize solvent consumption, and improve the overall sustainability of polymer production.

Trade-offs between biodegradability and performance

The comparative analysis reported in Table 1 highlights a clear and persistent trade-off between biodegradability and electronic performance in organic semiconductors. A general performance hierarchy emerges, in which fully conjugated backbones such as P3HT-, DPP-, and NDI-based systems exhibit the highest charge carrier mobilities, lowest turn-on voltages, and superior operational stability, but rely predominantly on oxidative degradation pathways that do not lead to true biodegradability.[84,85] At the opposite end of the spectrum, ester- and anhydride-based systems display excellent hydrolytic degradability, yet suffer from severe disruption of π-conjugation, resulting in poor charge transport and limited device applicability.[23,53,54,56] Between these two extremes, imine-based polymers represent the most effective compromise currently available, as they retain a significant degree of conjugation while enabling chemically triggered degradation; however, the progressive incorporation of imine linkages inevitably introduces electronic disorder and reduces mobility, as quantitatively demonstrated in recent studies.[28,59,67,81] The table further shows that secondary design strategies, such as side-chain engineering and terpolymerization, provide additional degrees of freedom to modulate degradation kinetics without fully sacrificing electronic performance. In particular, increased side-chain hydrophilicity enhances water uptake and accelerates hydrolysis, while terpolymerization allows for controlled incorporation of degradable units and morphological tuning, leading to intermediate performance levels that are often sufficient for practical applications.[22,28,64,67] Stimuli-responsive motifs such as disulfide bonds offer a complementary approach by enabling targeted degradation under specific conditions, although at the

Table 1 Comparative overview of structural motifs in biodegradable organic semiconductors, highlighting degradation mechanisms, biodegradability, and qualitative impact on key electronic performance parameters (charge mobility, turn-on voltage (V_{on}), and operational stability)

Structural motif/ design strategy	Typical degradation mechanism	Biodegradability level	Representative mobility ($cm^2\ V^{-1}\ s^{-1}$)	Key references	Critical assessment/trade-offs
Imine (–C═N–) linkages	Acid-catalyzed hydrolysis	High (triggered, controllable)	10^{-3}–10^{-1}	22, 28, 54 and 67	Best compromise between degradability and electronic performance; mobility decreases with increasing imine content
Ester linkages (backbone)	Hydrolysis (acid/ base/enzymatic)	High	10^{-5}–10^{-3}	23, 53 and 56	Highly effective degradability but incompatible with high-performance conjugated backbones
Disulfide (–S–S–) bonds	Reductive cleavage (stimuli-responsive)	Moderate–high	10^{-4}–10^{-2}	61	Enables targeted degradation; introduces electronic disorder and environmental sensitivity
Anhydride linkages	Rapid hydrolysis	High (fast degradation)	10^{-6}–10^{-4}	51 and 54	Excellent degradability but insufficient stability for most OSC applications
Side-chain hydrophilicity (*e.g.* glycol chains)	Facilitated hydrolysis (water diffusion)	Moderate–high	10^{-3}–10^{-1}	22 and 64	Effective secondary strategy to tune degradation; impacts morphology and transport
Terpolymerization/ random copolymers	Depends on incorporated labile units	Tunable	10^{-3}–10^{-1}	28 and 64	Promising balance between performance and degradability *via* controlled disorder
Fully conjugated backbones (*e.g.* P3HT, DPP, NDI)	Oxidation/ photo-oxidation	Low (non-biodegradable)	10^{-2}–1	73, 84 and 85	Benchmark systems; excellent performance but poor sustainability
Dynamic covalent systems (emerging)	Reversible bond cleavage	Potentially high	10^{-4}–10^{-2}	23 and 67	Promising strategy to decouple performance and degradability; still underdeveloped
Polymer blends/composite systems	Phase-selective degradation	Moderate (component-dependent)	10^{-3}–10^{-1}	25 and 26	Enables partial preservation of performance; complexity in morphology and recycling

expense of increased environmental sensitivity and moderate reductions in stability.[61] Overall, the trends summarized in Table 1 emphasize that no single design strategy simultaneously maximizes degradability and electronic performance, and that current research efforts are largely focused on identifying optimal compromises. Importantly, these approaches also differ in synthetic accessibility: simpler strategies such as imine condensation are relatively scalable, whereas terpolymerization and dynamic covalent systems require more complex synthetic control, potentially limiting their practical implementation. Consequently, future advances in biodegradable OSCs will depend not only on improving structure–property–degradation relationships, but also on developing synthetically efficient routes that can bridge the gap between laboratory-scale demonstrations and scalable device fabrication. Across all systems, a clear trade-off emerges in which mobilities above $\sim 10^{-1}$ $cm^2\ V^{-1}\ s^{-1}$ are currently only accessible in non-biodegradable fully conjugated systems, whereas biodegradable systems typically operate in the 10^{-3}–10^{-1} $cm^2\ V^{-1}\ s^{-1}$ regime.

Conclusions

Biodegradable OSCs represent a rapidly emerging class of functional materials that aim to reconcile electronic performance with environmental sustainability. As highlighted throughout this review, significant progress has been made in understanding and engineering the degradation behaviour of OSCs, particularly through the integration of chemically labile motifs and the control of material–environment interactions. These advances are enabling the development of transient and recyclable electronic systems with potential applications ranging from wearable sensors to implantable biomedical devices and environmentally benign disposable electronics.

From a materials design perspective, the incorporation of cleavable bonds such as imine, ester, disulfide, and anhydride linkages has proven to be an effective strategy to impart degradability while preserving semiconducting functionality. Among these, imine-based systems have emerged as particularly promising due to their ability to maintain π-conjugation while enabling acid-triggered hydrolysis. However, a recurring theme across the literature is the intrinsic trade-off between electronic performance and degradability. Increasing the density of degradable linkages often disrupts backbone conjugation and reduces charge carrier mobility, highlighting the need for more sophisticated molecular design strategies that balance these competing requirements.

Beyond the chemical structure of the semiconductor, side-chain engineering, polymer morphology, and environmental conditions play a decisive role in governing degradation kinetics and mechanisms. Increased hydrophilicity, reduced aggregation, and tailored morphology can significantly accelerate degradation by facilitating the diffusion of water and reactive species into the material. At the same time, external factors such as pH, temperature, light, and oxygen concentration critically influence both abiotic and biotic degradation pathways. These findings underscore the importance of adopting a holistic design approach in which molecular structure, processing conditions, and application environment are considered simultaneously.

In parallel with material design, important advances have been achieved in end-of-life strategies, including closed-loop

recycling, component recovery, and waste upcycling. While these approaches demonstrate the potential for circular organic electronics, they remain limited by challenges associated with multi-material device architectures, incomplete material recovery, and performance degradation upon reuse. Biodegradation, particularly under composting or physiological conditions, offers a complementary pathway for sustainable disposal, although standardized protocols and realistic testing environments are still lacking.

Despite these encouraging developments, several key challenges remain. First, achieving high-performance biodegradable OSCs with charge carrier mobilities comparable to state-of-the-art materials is still an open problem. Second, the lack of standardized definitions and testing methodologies for biodegradability complicates the comparison of results across studies. Third, the scalability and industrial compatibility of degradable materials and fabrication processes need to be addressed to enable real-world implementation.

Looking forward, future research should focus on the development of new molecular design paradigms that decouple electronic performance from degradability, for example through dynamic covalent chemistry, supramolecular interactions, or hybrid material systems. Greater emphasis should also be placed on quantitative structure–property–degradation relationships, supported by predictive modelling and advanced characterization techniques. Finally, the integration of life cycle assessment and eco-design principles at the early stages of material development will be essential to fully realize the promise of sustainable organic electronics.

In conclusion, biodegradable OSCs hold significant potential to transform the field of printed and flexible electronics by introducing new functionalities alongside environmentally responsible end-of-life scenarios. Continued interdisciplinary efforts bridging organic chemistry, materials science, and device engineering will be crucial to advance this field toward practical and scalable technologies.

Author contributions

V. V. and P. M. writing original draft. G. Z., M. R., S. R., I. O. A. investigation. M. C. conceptualization, visualization. L. B. writing, review and editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

The article is a review and does not contain original data.

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