

Review

Beyond Green Synthesis: Materials for Environmental Preservation and Resource Recovery

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Abstract: Growing concerns about resource depletion, pollution, climate change, and waste production have made sustainable and green materials an essential subject of study. Unlike traditional materials, which are often linked to energy-intensive manufacturing, hazardous chemicals, and poor end-of-life management, sustainable materials are designed to reduce environmental burdens while maintaining practical functionality. This narrative review examined literature published predominantly between 2014 and 2026 and evaluated 72 references related to bio-based, waste-derived, recycled, and hybrid materials for environmental applications. Recent studies have reported the development of these materials for water treatment, air pollution control, catalysis, carbon management, climate mitigation, and resource recovery. However, the sustainability of a material should not be assessed solely based on its renewable origin or green synthesis technique. The true environmental value must be evaluated based on functional performance, durability, reusability, scalability, and total environmental benefit. This overview encapsulates recent progress in sustainable and green materials from a function-centric viewpoint, emphasizing essential material classifications, design methodologies, and ecological applications. Emphasis is placed on the interconnections between material supply, structure, characteristics, and practical performance, alongside contemporary concerns of lifecycle impact, regeneration, and real-world applicability. This review presents a comprehensive framework integrating functional performance, life-cycle burden, durability, regeneration and reusability, scalability, and real-world applicability to facilitate the rational design and assessment of sustainable materials for environmental preservation, climate mitigation, and the advancement of the circular economy.

Keywords: sustainable and green materials; environmental protection; pollution control; resource recovery; circular economy; climate mitigation

1. The Importance of Sustainable and Green Materials Currently

The importance of environmentally responsible materials has grown in light of the present environmental concerns, such as climate change, depletion of resources, accumulation of pollution, and the increase of waste output, which need solutions beyond the conventional material production and utilization. For decades, traditional materials have been a cornerstone of industrial and technological development, but are often associated with fossil-based feedstocks, energy-intensive processing, toxic chemicals, and poor end-of-life management, all of which contribute to greenhouse gas emissions and long-term environmental burdens. On the other hand, environment-friendly materials have received increasing attention, not only because they can be made from renewable, recycled, or waste-derived resources, but also because they can actively contribute to environmental protection and resource recovery



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through pollutant removal, catalytic conversion, gas capture, water treatment, and circular utilization [1,2]. Most significantly, the value of these materials today should not be evaluated solely on their green origins or synthesis pathways, but on their real-world functionalities, performance, durability, reusability, and overall environmental benefits in practical applications. This move mirrors a broader shift in materials research from avoiding harm during the production process to designing material systems that directly enable cleaner technologies, reduce environmental impacts, and promote more sustainable resource use.

Global environmental issues, such as climate change and the accumulation of pollutants, require a transition to more environmentally friendly materials. Hublikar et al. [3] showed that functionalized biochar-metal oxide nanocomposites could be applied in wastewater treatment to achieve 95–99% destruction of resistant pollutants via advanced oxidation processes. Similarly, Mukherjee et al. [4] reported a zwitterionic lignin-chitosan composite (ZLC) as a sustainable platform for the removal of 80–90% of a variety of pollutants, including heavy metals, synthetic dyes, and per- and polyfluorinated substances (PFAS), and exhibited strong antifouling properties. In the work of Ruiz-Caldas et al. [5], the authors documented an effort to promote a circular economy by effectively obtaining cellulose nanocrystals (CNCs) from post-consumer textile blends, showing the potential to transform waste into high-value nanomaterials. Chen et al. [6] showed that enzymatic hydrolysis is a greener alternative to the conventional harsh chemical isolations for extracting ribbon-like CNCs. Similarly, Zhong et al. [7] reported that incorporating recycled nanomaterials into composite films significantly enhances mechanical strength and UV-blocking properties. On the other hand, Taher and Rianjanu [8] noted that although adsorption technologies had made good progress, future studies should focus on technology transfer to bridge the gap between academic discoveries and practical implementation in industry.

Taken together, these studies indicate that sustainable and green materials are developing at different levels of technological maturity. Nanocomposites, lignin-based biocomposites, and nanocellulose-based materials are still mainly at the laboratory or early demonstration stage, while adsorption technologies, biochar-based treatment systems, and waste-derived materials are closer to practical application. However, materials requiring chemical activation, metal functionalization, high-temperature processing, or complex purification may have higher environmental burdens. Therefore, their sustainability should be assessed based on performance, reusability, regeneration, scalability, and life-cycle impact rather than green origin alone.

Although there are many studies on the preparation, characterization, or evaluation of environmentally responsible materials for a single function, most existing research has not focused on linking the material's performance to tangible environmental benefits, resource circularity, and comprehensive sustainability assessment. To further clarify the research gap, representative existing reviews are compared in Table 1 according to their major focus and limitations. As summarized in the table, the relationship among material synthesis conditions, functional performance, reusability, and environmental impact has not been sufficiently discussed in an integrated manner. This creates a research gap regarding whether environmentally responsible materials are truly sustainable beyond their renewable or waste-derived nature. Hence, the novelty of this study lies in the integrated evaluation of environmentally responsible materials from both functional and sustainability perspectives. The originality of this review lies in its combined assessment of the performance-sustainability-scalability relationships of environmentally responsible materials, rather than evaluating them only by material origin, synthesis route, or single-function performance. This study highlights the material's actual performance, durability, reusability, and potential environmental benefits in real-life applications, in contrast to conventional assessments based solely on the green source or synthesis technique. To improve the analytical depth of the review, the revised manuscript further contrasts the major limitations and trade-offs of different sustainable material categories, including performance versus environmental burden, renewability versus feedstock variability, high functionality versus complex processing, and laboratory performance versus scalability. This review contributes a combined assessment framework that links material performance, sustainability indicators, and scalability, including functional efficiency, durability, reusability, life-cycle burden, regeneration requirements, and practical applicability. To avoid a purely descriptive discussion, this review evaluates different material categories using common criteria, including functional performance, sustainability benefits, life-cycle burden, scalability, technology maturity, and practical limitations. This evaluative approach is further supported by recent focused reviews on bio-based nonwoven materials and bio-based flame-retardant functionalization, which emphasize that sustainable materials should be assessed not only by renewable origin, but also by processing feasibility, durability, functional performance, circularity, and end-use applicability [9,10]. More importantly, the value of these materials today should not be assessed solely by their green origin or synthesis techniques, but by their actual functions and overall environmental benefits in practical applications. This change mirrors a broader movement in materials research, from avoiding harm in material production to designing material systems that can directly enable cleaner technologies, reduce environmental impact, and support more sustainable resource use.

Table 1. Brief comparison of existing reviews and the research gap addressed in this study.

Existing Review	Focus	Limitation	Ref.
Kader et al.	Systematic review of recycled waste substrates and their environmental applications.	Mainly focused on recycled waste substrates; limited discussion on durability, regeneration, scalability, and integrated sustainability assessment.	[2]
Taher and Rianjanu	Emerging trends and future perspectives in adsorption technologies for water and wastewater treatment.	Focused primarily on adsorption technologies; the link between material performance, technology transfer, and overall environmental benefit was not fully integrated.	[8]
Tazmeen and Mir	Green material options in the construction sector.	Sector-specific review; limited coverage of broader environmental applications such as pollution control, carbon management, and resource recovery.	[11]
Ram et al.	Catalytic pyrolysis of organic solid wastes for sustainable biofuel production.	Mainly process- and energy-conversion-oriented; limited discussion of sustainable materials as multifunctional systems for environmental preservation.	[12]
Trivedi et al.	Biochar-based materials for pollutant removal in wastewater treatment.	Application-specific review focused on wastewater treatment; less emphasis on cross-sector sustainability criteria such as life-cycle burden, regeneration, and scalability.	[13]
Arfasa and Tilahun	Life-cycle impacts of biochar, MOFs, and biomass adsorbents for wastewater and carbon management.	Strong focus on life-cycle assessment; limited integration with material design, functional performance, durability, and practical implementation.	[14]
Present review	Sustainable and green materials for environmental preservation, climate mitigation, and resource recovery.	This review addresses the above gaps by integrating material origin, functional performance, durability, regeneration, life-cycle burden, scalability, and real-world applicability into a comprehensive assessment framework.	

2. Sustainable and Green Materials-Definition and Scope

Sustainable and green materials can be defined as materials that are extracted, synthesized, used, and disposed of in a way that minimize environmental impact and meet the functional requirement for real-world application [11]. Generally, such materials have one or more of the following desirable properties: (1) they are derived from renewable, recycled, or waste-derived resources; (2) they are synthesized using low-energy, low-toxicity, or environmentally benign processes; and (3) they have favorable end-of-life properties, e.g., biodegradability, reusability, recyclability, or regenerability [15]. However, labeling a substance as sustainable or green should not be limited to its source or preparation technique. It needs to be assessed more comprehensively for its functional efficacy, durability, life-cycle consequences, and capacity to deliver concrete environmental benefits during use, such as pollution removal, carbon reduction, resource recovery, or waste valorization. Therefore, in this review, sustainable and green materials are considered in a wide but application-oriented sense, including bio-based, recycled, waste-derived, and other environmentally responsible functional materials that can contribute significantly to environmental protection and resource recovery. In this context, current sustainability assessment frameworks, such as life cycle assessment (LCA), circular economy indicators, and techno-economic assessment (TEA), provide useful tools for evaluating sustainable and green materials. LCA can quantify environmental burdens across the material life cycle; circular economy indicators can assess resource efficiency, recyclability, and material circularity; and TEA can evaluate economic feasibility and scalability for practical implementation.

Figure 1 provides a comprehensive framework for understanding eco-friendly materials from a circular economy perspective. The top section explains the difference between “green materials” that have a low immediate environmental impact (non-toxic, low emission) and “sustainable materials” that focus on long-term resource management and social responsibility. It also demonstrates that the ideal intersection between the two is the ultimate goal for future generations. The lower section depicts the entire cradle-to-cradle life cycle starting from sustainable sourcing and green processing to low carbon logistics and durable use and finally stresses waste

management strategies such as recycling and biodegradation to effectively avoid landfilling and close the resource loop. To make the framework more scientifically applicable, Figure 1 also incorporates measurable sustainability indicators, including carbon footprint, resource efficiency, recyclability, and durability. These indicators help connect the conceptual definition of sustainable and green materials with practical criteria for evaluating their environmental performance and long-term applicability.

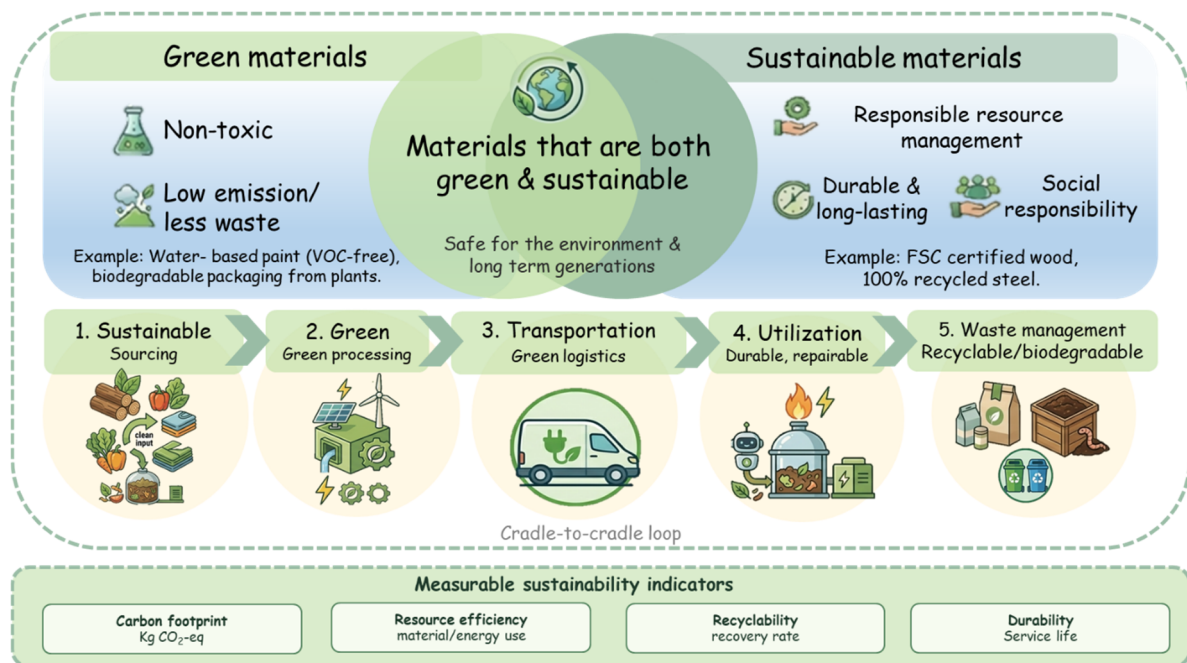


Figure 1. Sustainable and green materials: definition and span of the lifetime.

3. Main Classifications of Material

Sustainable and green materials are broadly classified based on origin, processing pathways and functional performance into several categories, namely bio-based materials, waste-derived and recycled materials, green functional composites and smart and advanced materials (Figure 2). The categories present several techniques to minimize environmental effect while retaining or boosting material efficiency and application.

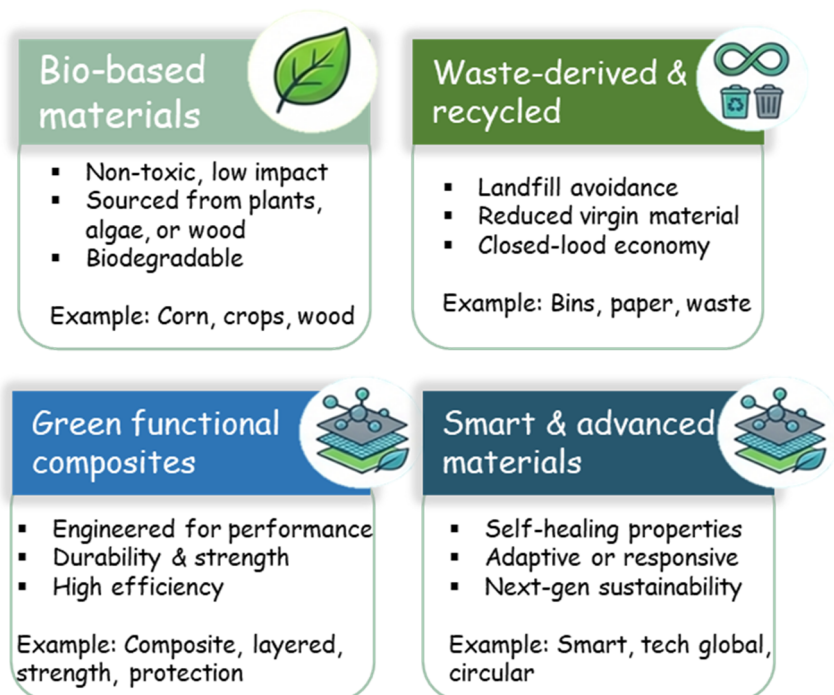


Figure 2. Main types of green and sustainable materials.

3.1. Bio-Based Products

Bio-based materials are an important class of environmentally friendly materials derived from renewable biological resources such as plants, algae, and agricultural residues. Compared to petroleum-based materials, renewable materials offer advantages such as reduced dependence on fossil resources. Examples include cellulose, lignin, starch, and protein-based polymers, which are commonly employed in environmental applications due to their adjustable features, such as surface functionality and porosity. However, their sustainability should be judged not only by their origin but also by their performance, stability, and overall life-cycle impact.

Recent advances in sustainable materials science are a disruptive movement toward circularity and green innovation in several scientific areas. Chen [16] identified potato peels with 50–60% starch and rice straw with 32–47% cellulose as promising untapped agricultural residues for biopolymer manufacturing to address the worldwide plastic challenge. Başarır et al. [17] tackled the possibility of zero-waste devices in the field of green electronics by developing edible and biodegradable wearable capacitive pressure sensors from cellulose and pectin with the sensitivity of 0.0294 kPa^{-1} and the fast response time of 118 ms, which were completely degradable by fungi within 16 weeks. In the context of end-of-life management, McGuire et al. [18] reported a fundamental breakthrough in chemical circularity by discovering a linear free-energy relationship in recycling catalysis, showing that 6-atom repeat-unit polyesters depolymerize about 100 times faster than 7-atom analogs using a commercial zinc(II) catalyst. Regarding renewable energy, Wu et al. [19] reported record advances in the molecular engineering of hybrid materials for perovskite solar cells, achieving 27% power conversion efficiency with great operational stability. Finally, Ram et al. [12] reviewed advances in catalytic pyrolysis, an important method for converting organic solid waste, such as biomass and plastics, into sustainable biofuels. Bio-based materials use agricultural waste and biomass feedstocks to enable sustainable breakthroughs, such as biodegradable plastics and edible electronics, within a circular bioeconomy enabled by efficient chemical recycling methods [20]. Recent review evidence also suggests that agricultural waste-derived resources, such as coconut shells, rice husk ash, and palm oil fuel ash, can serve as bio-based alternatives for sustainable construction materials, supporting both resource utilization and carbon footprint reduction [21]. To synthesize the advantages and limitations of representative bio-based products, Table 2 summarizes their main benefits and key limitations from the perspectives of sustainability and application maturity.

Table 2. Summary of representative bio-based products, benefits, and limitations.

Material	Main Benefit	Limitation
Cellulose, lignin, starch, and protein-based polymers	Renewable feedstocks with adjustable surface functionality and biodegradability.	Performance stability, moisture sensitivity, and life-cycle impact still require further evaluation.
Agricultural residue-derived biopolymers	Valorize biomass wastes and reduce dependence on fossil-based resources.	Feedstock variability, collection, pretreatment, and scalability remain key challenges.
Cellulose/pectin-based biodegradable electronics	Provide biodegradable and low-waste alternatives for emerging green electronics.	Mostly at the laboratory stage; long-term durability and practical deployment remain limited.
Chemically recyclable bio-based or biodegradable polymers	Support circularity through depolymerization and material recovery.	Recycling efficiency depends on catalyst, polymer structure, processing cost, and system integration.
Biomass-derived fuels through catalytic pyrolysis	Convert organic wastes into value-added fuels and chemicals.	May require high-temperature processing and catalysts, leading to possible energy and environmental burdens.

3.2. Waste-Derived and Recycled Materials

Waste-derived and recycled materials are an important class of ecologically responsible materials, as they help reduce waste output and the need for virgin resources. They are based on industrial residues, agricultural by-products, municipal waste, and post-consumer items, thereby contributing to the shift toward a circular economy by transforming waste into valuable resources [22]. These materials can be used for adsorption, catalysis, environmental remediation, and resource recovery through various processing methods. Despite the challenges such as feedstock unpredictability and contamination, they are critical for sustainable materials engineering and efficient resource management [23]. The textile industry could decrease GWP and water consumption simultaneously by 33.1% and 43.9%, respectively, by integration of closed-loop water recycling and renewable

energy [24], but trade-offs were also observed, such as an increase in freshwater ecotoxicity by 14.1% due to chemical additives required for advanced recycling processes.

Breen et al. [25] validated that the combination of microwave (MW) assisted heating and heterogeneous catalysis greatly improved the efficacy of plastic upcycling and was able to produce 95% of bis(hydroxyethyl) terephthalate (BHET) monomer from polyethylene terephthalate (PET) in only 15 to 45 min. It also enabled Fenton-type oxidative degradation of low-density polyethylene (LDPE) into valuable carboxylic acids (71% yield). Sharma et al. [26] emphasized that biochar and hempcrete were representative carbon-negative materials for carbon sequestration, noting that biochar-augmented concrete formulations could sequester approximately 59 kg of CO₂ per ton, accelerate cement hydration, and enhance mechanical strength. Finally, Palaniappan et al. [27] reported that agricultural residues such as banana stem fibers could be used as high-performance reinforcements in lightweight biocomposites. Their results showed a 41% reduction in density and 35% improvement in flexural strength, indicating the suitability of these materials for sustainable structural applications in automotive and aerospace sectors. These results represent complementary environmental advantages of waste-derived and recycled materials. The 95% BHET recovery indicates high potential for plastic circularity by converting PET waste back into valuable monomers, thereby reducing dependence on virgin petrochemical resources. The sequestration of approximately 59 kg CO₂ per ton demonstrates the climate-mitigation potential of carbon-negative construction materials. In addition, the 35% improvement in flexural strength indicates that agricultural residue-based composites can provide mechanical reinforcement, potentially reducing material consumption through lightweight, more efficient structural design. Therefore, these examples suggest that waste-derived materials can simultaneously contribute to resource recovery, carbon reduction, and performance enhancement. From a circular economy perspective, agricultural waste-derived materials provide a useful bridge between waste valorization and low-carbon material development. Agro-wastes such as coconut shells, rice husk ash, and palm oil fuel ash can partially replace conventional construction resources and improve mechanical properties, while also reducing the environmental burden associated with raw material extraction and waste disposal. However, their practical use still requires further validation of material consistency, long-term durability, life-cycle performance, and standardized application guidelines [21].

3.3. Functional Composites of Green

Green functional composites are a class of materials that consist of sustainable components, e.g., bio-based or recycled materials, with functional matrices to enhance performance while remaining environmentally compatible. They are used to improve mechanical properties, thermal stability, and durability, and to provide functions such as pollutant absorption and thermal insulation. Examples include biochar-cement composites, natural fiber reinforced polymers, recycled plastic-wood composites, biochar-polymer systems, and fly ash-based products. Such composites relate to circular economy ideas, but their performance is limited by materials compatibility and long-term stability.

The present studies in sustainable materials science indicate a significant trend toward the use of renewable resources and high-performance nanostructures for environmental and industrial applications. Åhlén et al. [28] demonstrated that the synthesis of biobased porous organic frameworks (POFs) from renewable monomers such as lignin and cellulose could provide a cheap and carbon-neutral alternative to standard fossil-fuel-based synthesis. Oliaei et al. [29] studied the processing issues of these materials and found that a green modular polymerization strategy enabled the fabrication of highly reinforced degradable biocomposites with fiber loadings >50 wt%, which exhibited significant improvements in mechanical properties and dispersion compared to conventional melt processing. Moreover, Hu et al. [30] and Tian et al. [31] confirmed that integrating framework materials with biopolymers to fabricate 3D covalent organic framework (COF) foams and membranes enhanced hydrophilicity and photothermal conversion, needed for high-rate water evaporation and effective gas separation. Although these advanced green functional composites show strong potential, most reported examples remain at the laboratory demonstration stage. Biobased porous organic frameworks, degradable lignocellulose biocomposites, and COF-based foams or membranes have mainly been demonstrated through controlled material synthesis and performance tests. Their pilot-scale production and commercial applications remain limited because long-term durability, cost, reproducibility, process scalability, and real-world performance still require further validation. Therefore, future development should focus not only on high functional performance but also on the feasibility of scale-up and practical implementation.

Green functional composites combine sustainable materials with functional matrices to improve performance and environmental compatibility, and recent advances in biobased frameworks and green polymerization open the way for the development of high-performance, renewable materials for environmental and industrial applications.

3.4. Smart or High-Performance Sustainable Materials

Smart or advanced sustainable materials are engineered materials that are meant to provide better functionality, such as responsiveness, adaptability, or multi-functionality, with little environmental impact. These materials often exhibit stimulus responsiveness (e.g., to temperature, pH, or light), self-healing capabilities, or high surface reactivity for applications in energy storage, carbon capture, environmental remediation, and catalysis. Combining innovative material design with sustainability principles, they allow for more efficient resource use and contribute to next-generation low-carbon technology. In addition to AI-assisted material design, smart and high-performance sustainable materials also include self-healing materials, adaptive materials, smart coatings, and responsive biomaterials. Self-healing polymers can extend service life, improve durability, and reduce material replacement, thereby supporting circular material use [32]. Adaptive or stimuli-responsive polymers can respond to external triggers such as temperature, pH, light, electric fields, magnetic fields, or biological signals, enabling tunable functions for advanced environmental and engineering applications [33]. Smart coatings can provide anti-fouling, anti-corrosion, and protective functions, thereby extending the lifetime of marine and industrial facilities [34]. In addition, stimulus-responsive hydrogels and responsive biomaterials can be designed for pollutant adsorption, ion exchange, oil-water separation, pathogen control, and regeneration in environmental and wastewater treatment systems [35]. These examples show that smart sustainable materials are not limited to computational design but also encompass functional systems that enhance durability, adaptability, efficiency, and environmental performance.

Zeng [36] reviewed the use of AI techniques to advance sustainable material design, and showed that data mining, hybrid modeling, and multicriteria optimization could be effectively applied to predict material properties, accelerate the discovery of novel sustainable materials, and reduce energy consumption and waste generation in the process of material design. Based on this, Xian et al. [37] showed that AI revolutionized sustainable materials development from predictive and generative models for accelerated material discovery to adaptive synthesis optimization and intelligent recycling, with a focus on battery materials, thermal management, energy conversion materials, and catalysts for green energy applications through the entire lifecycle. Consistent with these results, Xue et al. [38] showed that the application of AI in sustainable materials such as bioplastics, bamboo, and recycled metals in smart production systems led to 25% reduction in energy consumption and 30% increase in waste reduction, suggesting a new concept of smart eco-innovation to achieve near-zero-waste circular manufacturing. Together, these three studies indicate that innovative sustainable materials are a game-changing strategy to upscale environmental protection and resource efficiency combined with AI-powered design and lifetime management.

4. Environmental Applications

Figure 3 provides an overview of the main application areas of environmentally responsible materials in the sectors related to sustainability. These materials have been extensively investigated for water and wastewater treatment, air pollution management, gas treatment, carbon capture and reduction, waste-to-energy conversion, and circular resource recovery. These applications exemplify the wide potential of advanced materials to contribute to the solution of environmental problems, as well as to promote sustainability and resource efficiency. The next subsections describe various application areas in more detail.

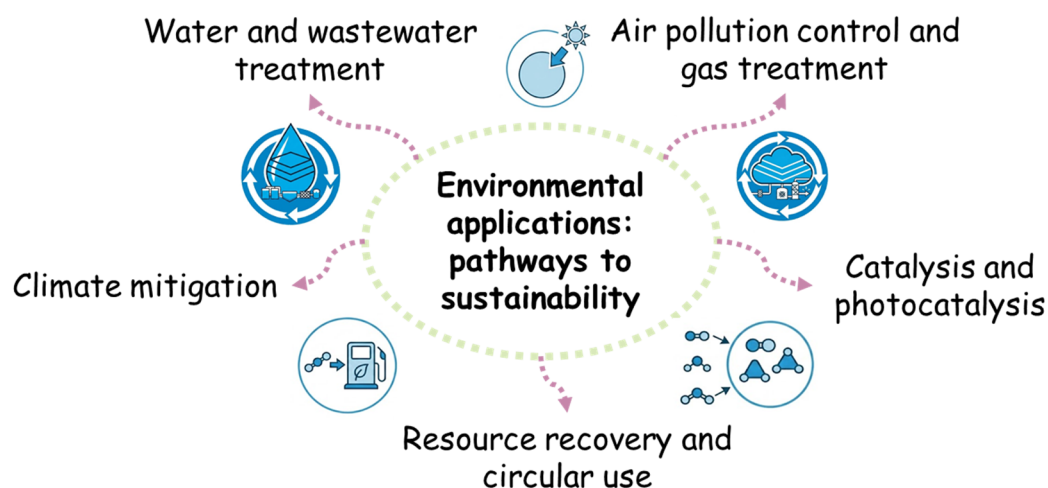


Figure 3. Main environmental application areas of environmentally responsible materials.

4.1. Water and Wastewater Treatment

Water and wastewater treatment is a set of physical, chemical, and biological processes used to remove impurities and make water safe for release, reuse, or drinking. Traditional techniques such as filtration, coagulation-flocculation, adsorption, membrane separation, and sophisticated oxidation processes. Environmental responsibility has meant a greater focus on reducing chemical inputs, lowering energy use, and controlling secondary pollution, such as sludge formation. Sustainable techniques encompass the use of eco-friendly materials such as biochar, biopolymers, and green functional composites that not only enable effective removal of pollutants but also promote resource recovery (e.g., nutrients or valuable metals). In addition, looking ahead, the focus is on environmentally responsible treatment systems that prioritize life-cycle performance, scalability, and the use of renewable or waste-derived materials to support circular water management and reduce environmental impact.

The study by Agaton [39] highlighted that nature-based solutions (NbS), namely constructed wetlands and other green infrastructure systems, represent a strong and sustainable alternative for aquatic remediation with microplastic capture efficiencies of up to 100% and 99%, respectively. Wang et al. [40] focused on the application of specific low-cost materials and reported distinctive mineralogical and catalytic properties of sludge-derived biochar (SDB), which substantially enhanced hybrid treatment setups and microbial fuel cells (MFCs) for improved nutrient removal and power density. Regarding physical application, El Barkaoui et al. [41] emphasized that high-quality biochar should be manufactured from carbon-rich feedstock and, ideally, used as an intermediate layer between inert substrates to minimize clogging and flotation in vertical-flow systems. These biochar-amended wetlands provided multifunctional ecological benefits, as Yang and Yang [42] showed the dual capability of biochar-based systems for effective wastewater treatment and climate change mitigation through biomass carbon sequestration and greenhouse gas emission reduction. Finally, Trivedi et al. [13] recommended the use of biochar as a global cornerstone for wastewater treatment. They highlighted the versatility of biochar and that the modified version could be engineered to capture different pollutants, such as heavy metals and pharmaceuticals, through multi-pathway mechanisms, including ion exchange and surface complexation. To better synthesize the practical performance of sustainable materials for water and wastewater treatment, Table 3 summarizes representative performance indicators, including pollutant removal efficiency, adsorption or treatment function, and regeneration or practical considerations.

In summary, biochar-based nature-based solutions are a wide, affordable, and sustainable option for advanced wastewater treatment with significant environmental and climate benefits.

Table 3. Summary of representative performance indicators for sustainable materials in water and wastewater treatment.

Material/System	Target Application	Performance Indicator	Regeneration/Practical Consideration	Ref.
Constructed wetlands and green infrastructure	Microplastic removal	Microplastic capture efficiency up to 99–100%.	Long-term clogging control and field-scale monitoring are required.	[39]
Sludge-derived biochar	Nutrient removal and microbial fuel cell enhancement	Improved nutrient removal and power density in hybrid treatment systems.	Feedstock variability and possible secondary contamination should be controlled.	[40]
Biochar-amended constructed wetlands	Wastewater treatment and carbon mitigation	Pollutant removal combined with biomass carbon sequestration and greenhouse gas reduction.	Biochar placement, hydraulic stability, and service lifetime affect practical performance.	[41,42]
Modified biochar adsorbents	Heavy metals, pharmaceuticals, and organic pollutants	Pollutant adsorption through ion exchange, surface complexation, and pore filling.	Regeneration efficiency, adsorbent reuse, and spent-material disposal remain key issues.	[13]

4.2. Gas Treatment and Air Pollution Control

Air pollution control and gas treatment are methods and techniques used to eliminate or minimize dangerous pollutants from industrial emissions and ambient air with the aim of safeguarding human health and the environment. Conventional techniques include adsorption, catalytic oxidation, filtration, and scrubbing systems for the removal of particulate matter, volatile organic compounds (VOCs), sulfur oxides (SO_x), nitrogen oxides (NO_x), and carbon dioxide (CO₂). From an environmental perspective, greater attention has been paid to the use of sustainable materials, such as biochar, functional carbon materials, and green composites, which can efficiently

trap pollutants while reducing energy consumption and secondary waste generation. Furthermore, innovative materials with large surface area, adjustable porosity, and catalytic activity are being developed to improve gas separation, carbon capture, and pollutant conversion. Such approaches allow cleaner industrial operations, resource recovery, and transition to low-carbon and circular environmental systems.

Makoś-Chelstowska et al. [43] suggested that approximately 1.3 billion metric tons of agri-food waste produced annually could be transformed into sustainable biosorbents for the removal of volatile organic compounds (VOCs) from air and industrial gases within a circular economy paradigm. Meanwhile, Alayaki et al. [44] reported that metal-rich biochar could significantly improve urban air quality by adsorbing up to 76% of volatile organic compounds (VOCs) emitted from asphalt surfaces, while improving infrastructure longevity. Additionally, Papchenko et al. [45] have reported that renewable biopolymer membranes made from Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) provide a sustainable alternative for industrial CO₂/CH₄ separation with mechanical and transport properties similar to those of fossil-based materials. Budhathoki et al. [46] showed that the combination of artificial intelligence and high-throughput atomistic simulations might be used to screen more than 100,000 materials to design mixed-matrix membranes that reduce the cost of carbon capture to less than \$50/ton CO₂.

To compare the maturity of these approaches, Table 4 summarizes their relative industrial applicability for gas treatment and air pollution control. All examples indicate that biosorbents and biochar-based systems are relatively closer to practical environmental application, whereas advanced membranes and AI-screened materials still require further validation, scale-up, and techno-economic assessment before widespread industrial deployment. These advances together help the WHO air quality standards, intended to reduce pollutants such as PM_{2.5} and SO₂, achieve net-zero emissions and climate stability [47,48].

Table 4. Relative industrial applicability of sustainable materials and tools for gas treatment and air pollution control.

Technology/Approach	Main Function	Relative Maturity/Industrial Applicability	Key Limitation	Ref.
Agri-food waste biosorbents	VOC adsorption from air and industrial gases	Laboratory to early pilot stage; promising due to low-cost and abundant agri-food waste feedstocks.	Regeneration, adsorption stability, and performance under real gas mixtures require further validation.	[43]
Metal-rich biochar for asphalt-related VOCs	VOC adsorption and urban air-quality improvement	Early practical demonstration; relatively closer to field application in urban infrastructure systems.	Long-term field durability, pollutant saturation, and environmental safety need further assessment.	[44]
Renewable biopolymer membranes	CO ₂ /CH ₄ gas separation	Laboratory to pilot stage; potential sustainable alternative to fossil-based polymer membranes.	Scale-up, membrane lifetime, selectivity stability, and cost competitiveness remain key challenges.	[45]
AI and high-throughput screening tools	Discovery and cost prediction of carbon-capture materials	Research and design-stage tool; useful for accelerating material discovery but not a direct treatment technology.	Requires experimental validation, material fabrication, and industrial-scale testing before practical deployment.	[46]

4.3. Catalysis and Photocatalysis

Catalysts have been widely used in industry and environmental applications such as pollution degradation and emissions control. Photocatalysis, driven by light (mainly UV or visible), can be used to degrade organic contaminants, air pollutants, and microorganisms. For environmental reasons, there is increasing interest in developing sustainable catalysts based on bio-based, waste-derived, or low-toxicity materials that reduce energy consumption and avoid secondary pollution. In addition, advanced materials such as modified carbon-based materials, semiconductors, and hybrid composites have increased surface activity, stability, and reusability. These techniques are advantageous for greener chemical processes, more efficient pollutant removal, and the development of sustainable environmental and energy systems.

Cordero-Lanzac et al. [49] indicated that the production of green methanol from CO₂ and renewable hydrogen using an Indium-Cobalt catalyst could abate up to 1.75 tons of CO₂ per ton of methanol produced if renewable energy is used to power the process, although the economic profitability was highly sensitive to hydrogen prices and carbon taxation. The study by Banerjee et al. [50] pointed out some main advantages of using organic polymeric materials for solar-to-chemical energy conversion in comparison with conventional inorganic

semiconductors. “soft photocatalysis” based on organic polymers gives the unique ability to tune the molecular level, their study found. In particular, the enhancement of crystallinity of two-dimensional carbon nitrides, such as poly(triazine imide) (PTI) and poly(heptazine imide) (PHI), may improve charge-carrier mobility and lifetime, resulting in superior hydrogen-evolution performance compared with conventional linear polymers, such as the melon polymer. Sherpa et al. [51] found that a new ruthenium metal-organic framework integrated with three-dimensional graphitic carbon nitride (RuMOF@CN) exhibited outstanding photocatalytic hydrogen evolution rate of 55,802.5 $\mu\text{mol g}^{-1} \text{h}^{-1}$ under 450 nm illumination. The great performance is related to the development of Schottky junction for strong light absorption, efficient charge separation and improved electron transport. The study also shows that the RuMOF component functions as an effective electron-trapping site and the 3D structure of g-C₃N₄ enhances the specific surface area and active sites for the reaction.

Despite these impressive performance values, their practical application still depends on economic feasibility, long-term stability, and scalability. For green methanol production, the reported CO₂ reduction potential indicates strong climate-mitigation value, but economic applicability remains sensitive to renewable hydrogen cost, catalyst cost, energy consumption, and carbon-pricing conditions [49]. For photocatalytic hydrogen production, the high hydrogen evolution rate demonstrates excellent laboratory-scale activity; however, long-term catalyst stability, reusability, noble-metal dependence, light penetration, reactor scale-up, and continuous operation still require further validation [50,51]. Therefore, catalytic and photocatalytic systems should be evaluated not only by peak conversion or hydrogen production rates but also by cost, durability, operational stability, and scalability [52].

4.4. Recovery of Resources and Circular Use

Resource recovery and circular use involve the systematic extraction of valuable materials, water, and energy from waste streams and their reintegration into productive systems, thereby reducing dependence on virgin resources and lowering waste generation. In the context of a circular economy, products and materials retain their value for as long as feasible, with the aim of reducing waste generation and resource use. Resource recovery has become particularly essential for managing wastewater, biomass, and industrial residues in environmental systems. Commonly recoverable outputs include nutrients such as nitrogen and phosphorus, reusable water, metals, and energy carriers. Recent assessments have underlined that wastewater should no longer be considered merely as a disposal burden, but rather as a resource platform for water, materials, and energy in more circular production systems [53]. From an environmental responsibility point of view, these approaches focus on minimizing waste production, low energy consumption, and the use of sustainable or waste-derived products like biochar and functional composites. In addition, water reuse and energy recovery have the potential to further improve the environmental and economic performance of treatment systems, while industrial wastewater streams may also provide chances for metal recovery, especially where dissolved or concentrated metallic species are present [54]. To provide a clearer comparison of different recovery routes, Table 5 summarizes representative quantitative indicators and environmental advantages for nutrient, metal, and energy recovery.

Table 5. Comparison of representative resource recovery routes and their environmental advantages.

Recovery Route	Representative Quantitative Indicator	Main Environmental Advantage	Key Limitation	Ref.
Nutrient recovery	Struvite crystallization is a mature phosphorus recovery route that has been applied from laboratory to pilot and full-scale systems	Reduces eutrophication risk and supports fertilizer substitution by recovering phosphorus as reusable struvite.	Product purity, Mg/P ratio, pH control, and recovery cost affect practical use.	[55]
Metal recovery	Electrochemical metal recovery can enhance mass-transfer and Cu recovery kinetics by 3.5–4.3 times compared with single-mode operation.	Recovers valuable metals and reduces heavy-metal discharge from industrial wastewater.	Performance depends on wastewater composition, metal concentration, energy input, and electrode stability.	[56]
Energy recovery	The extractable energy embedded in wastewater has been estimated at approximately 2.7 kWh/m ³ , while the specific energy consumption of most wastewater treatment plants is generally below 1 kWh/m ³	Offsets external energy consumption and reduces greenhouse-gas emissions from wastewater treatment.	Energy recovery depends strongly on organic loading, anaerobic digestion efficiency, and facility scale.	[57]

Overall, nutrient recovery is most directly linked to fertilizer substitution and eutrophication control; metal recovery is more valuable for industrial wastewater and resource conservation; and energy recovery provides the strongest contribution to reducing the operational energy burden of wastewater treatment. These solutions are very much in line with ecologically responsible design in terms of their low energy consumption, low emissions, and substitution of traditional materials with sustainable or waste-generated resources. Within this framework, biochar and waste-based functional materials have received growing attention as they are versatile for soil application, pollutant removal, composite production, and other value-added applications. They are representative examples of waste-to-functional products instead of waste-to-residues [58]. Figure 4 presents a conceptual diagram illustrating the resource recovery and circular-use pathways for converting waste streams into valuable products. The valorization of waste streams into fertilizers, reusable water, recoverable metals, energy, and functional materials generally promotes circular economy concepts, mitigates environmental loads, and improves the sustainability and efficiency of industrial and environmental processes.

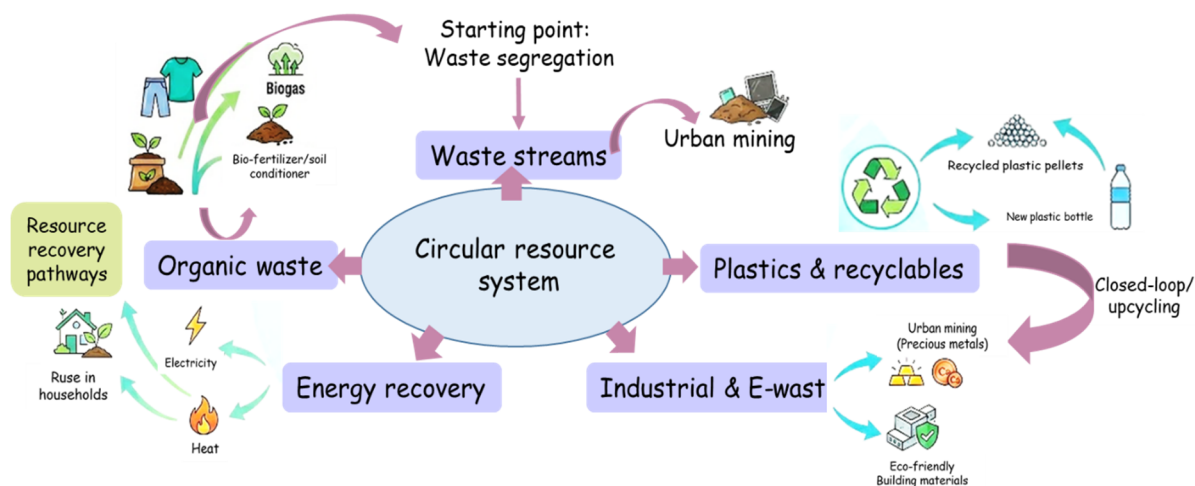


Figure 4. Schematic illustration of resource recovery and circular use pathways for converting waste streams into value-added products.

4.5. Climate Mitigation

Climate mitigation is also achieved through the use of sustainable technologies and materials in environmental systems, in addition to environmental factors. Biochar and other biomass-derived materials can play a significant role in this regard, serving as long-term carbon sinks for sequestration while also enhancing soil quality and assisting in ecosystem restoration. Their use in wastewater treatment and pollution management enhances environmental performance by adsorbing impurities and reducing secondary emissions associated with conventional treatment technologies. Incorporating renewable energy systems, such as solar and geothermal technologies, into environmental infrastructure is another way to lower the carbon intensity of treatment and resource recovery processes. The statistic also underscores the need to use waste-derived materials within a circular framework, in which emissions from one process are offset by turning waste into valuable products. In combination with carbon capture, storage, and utilization (CCS/CCU), these solutions enhance the overall potential for greenhouse gas mitigation. Together, these environmental applications strengthen the transition to carbon-neutral, climate-resilient systems by linking emissions reduction, carbon sequestration, and sustainable resource management into a comprehensive climate mitigation strategy.

Sustainable materials contribute directly to climate mitigation through carbon storage, CO₂ capture, and substitution of high-carbon materials. For example, biochar and biomass-derived materials can act as long-term carbon sinks, while carbon-capture materials such as polymeric membranes, biochar-based adsorbents, MOFs, and biomass adsorbents can reduce CO₂ emissions from industrial and environmental systems. In addition, recycled and waste-derived materials can lower embodied emissions by replacing virgin or energy-intensive resources. Therefore, sustainable materials support climate mitigation through carbon sequestration, emission reduction, and circular resource use. In addition to these material-based pathways, risk assessment, governance, and AI-based modeling can support the planning and optimization of climate-mitigation strategies. Cardenas [59] tackled the challenge of improving the success of climate change mitigation by studying mitigation risk, which they define as the deviation from intended goals and the uncertainty associated with those outcomes. They noted that the literature lacks conceptual clarity, often employing terms such as risk perception, risk acceptance, and agents' concerns

interchangeably, leaving crucial causes of mitigation failure understudied. To enhance the specification of mitigation actions, the authors identified three key research gaps: first, the identification and operationalization of agents' concerns; second, the influence of risk perception and acceptance on the weighting of concerns; and third, the impacts of disparities in power relations. Moreover, Shobanke et al. [60] highlighted the revolutionary role of artificial intelligence (AI) and machine learning (ML) in improving energy systems and climate change modeling. They reviewed existing literature and identified significant progress in optimization and predictive analytics, essential for tackling global energy transitions and developing strategic responses to climate change, including optimization in energy systems: research that uses AI and ML to find the best strategies to manage and transition energy infrastructures, and predictive analytics in climate change: research that uses machine learning algorithms to interpret strategic responses to climate change and improve climate change assessments.

In conclusion, effective climate change mitigation depends on improving conceptual clarity about mitigation risks, in particular by addressing agents' concerns, risk perceptions, and power imbalances, and simultaneously leveraging AI and ML to optimize energy systems and improve predictive climate modeling for more informed and reliable decision making.

5. Sustainability Assessment beyond Performance

The functional performance of a material should not be the only metric in assessing its sustainability. High adsorption capacity, catalytic activity, selectivity, or stability can indicate technological potential, but these measures alone do not tell us if a material is truly sustainable. In particular, a bio-based origin should not be considered an inherent sign of environmental advantage, as sustainability needs to be assessed from a life-cycle perspective rather than solely from the renewability of the feedstock [61]. Life-cycle thinking expands the assessment from the point of manufacture to the entire chain of raw material extraction, production, use, and end-of-life management, thereby offering a more balanced basis for sustainability claims [14]. To make the proposed framework more operational, Table 6 summarizes key assessment dimensions, measurable indicators, and decision uses for evaluating the sustainability of materials beyond their functional performance.

Table 6. Operational metrics for evaluating sustainable materials [14,62,63].

Assessment Dimension	Operational Metric	Decision Use
Functional performance	Removal efficiency, adsorption capacity, catalytic activity, or mechanical strength	Identifies whether the material meets application requirements.
Life-cycle burden	Carbon footprint, energy use, water use, and chemical consumption	Compares environmental impacts across production, use, and end-of-life stages.
Resource circularity	Waste-derived content, recyclability, recovery rate, and material reuse potential	Evaluates contribution to circular economy and resource conservation.
Durability and regeneration	Service life, number of reuse cycles, regeneration efficiency, and capacity retention	Assesses long-term applicability and replacement frequency.
Scalability and TEA	Technology readiness level, process complexity, production cost, and scale-up feasibility	Determines whether laboratory performance can be translated into practical application.
Environmental risk	Leaching risk, secondary emissions, toxicity, and spent-material disposal	Prevents hidden environmental burdens during use or end-of-life management.

To strengthen this assessment, commonly used sustainability tools should be considered explicitly. Life Cycle Assessment (LCA) provides a standardized method for quantifying environmental impacts across the material production, use, and end-of-life stages [64]. Techno-Economic Assessment (TEA) evaluates process cost, economic feasibility, and scale-up potential, which are essential for translating laboratory materials into practical applications [65]. Environmental Product Declaration (EPD), usually based on product-category rules and LCA results, provides transparent and comparable environmental information for material products [66]. Therefore, integrating LCA, TEA, and EPD can provide a more rigorous basis for assessing whether a material is not only high-performing, but also environmentally credible, economically feasible, and practically scalable. To provide a more quantitative basis for sustainability assessment, Table 7 summarizes representative numerical indicators reported in the reviewed literature, including emission reduction, resource recovery, carbon sequestration, energy recovery, regeneration burden, and techno-economic feasibility.

Table 7. Representative quantitative indicators for sustainability assessment beyond material performance.

Assessment Aspect	Representative Numerical Indicator	Sustainability Implication	Ref.
Emission and water reduction	Closed-loop water recycling and renewable energy integration reduced GWP by 33.1% and water consumption by 43.9%, although freshwater ecotoxicity increased by 14.1%.	Shows that environmental improvement may involve trade-offs between carbon reduction, water saving, and chemical-related impacts.	[24]
Plastic circularity	Microwave-assisted catalytic PET upcycling achieved 95% BHET monomer recovery.	Indicates strong potential for resource recovery and reduced dependence on virgin petrochemical feedstocks.	[25]
Carbon sequestration	Biochar-augmented concrete was reported to sequester approximately 59 kg CO ₂ per ton.	Demonstrates the potential of waste-derived construction materials for carbon storage and low-carbon building applications.	[26]
Energy recovery	Extractable energy embedded in wastewater has been estimated at approximately 2.7 kWh/m ³ , while the energy consumption of most wastewater treatment plants is generally below 1 kWh/m ³ .	Suggests that wastewater can be treated as an energy resource rather than only a treatment burden.	[57]
Catalytic carbon reduction	Green methanol production from CO ₂ can abate up to 1.75 tons of CO ₂ per ton of methanol when renewable energy is used.	Highlights climate-mitigation potential, but feasibility depends strongly on renewable H ₂ cost, energy demand, and carbon pricing.	[49]
Regeneration burden	Adsorbent regeneration may require chemical solvents, pH adjustment, thermal treatment, or repeated washing.	Shows that regeneration performance and secondary pollution should be considered together with initial adsorption capacity.	[63]
Techno-economic feasibility	TEA evaluates cost, scale-up potential, and process feasibility, especially for technologies moving from laboratory to industrial application.	Supports practical decision-making by linking material performance with economic viability and scalability.	[65]

A synthesis of the LCA-related studies indicates that the environmental advantage of sustainable materials is highly context-dependent. Waste-derived and bio-based materials can reduce environmental burdens when they replace virgin resources, enable carbon storage, or support circular resource use. However, these benefits may be reduced or even offset when material preparation requires high energy input, chemical activation, solvent-intensive processing, long-distance transportation, or frequent regeneration[14]. The reviewed studies also show that improvements in one impact category may create trade-offs in another, such as reduced GWP but increased freshwater ecotoxicity due to chemical use[24]. Therefore, a generalizable insight from LCA studies is that sustainable materials should be evaluated through full life-cycle trade-offs rather than by renewable origin, waste-derived source, or single performance indicator alone[63].

In this larger context, one important aspect is the consumption of energy and resources in material synthesis. Many bio-based and waste-derived materials need to be pre-treated, thermally converted, chemically activated, purified and dried before they can be used for their intended use [13]. Thus, a renewable feedstock may nonetheless bear significant environmental consequences if its conversion method is energy- or chemically-intensive. Similarly, the source of raw materials should be carefully evaluated, as feedstocks from waste are in general more attractive than purpose-grown biomass, but their sustainability is still dependent on collection, transport, contamination level, preprocessing requirements, and land-related implications along the supply chain. The sustainability of a material after its initial use depends on the regeneration, reusability and risk of secondary contamination. A material that is good in a single cycle but needs harsh solvents, high regeneration temperatures, or frequent replacement may be of only limited overall advantage. Additionally, the use of activation agents, surface modifiers or other processing chemicals may lead to secondary emissions or hazardous residues during synthesis, regeneration or disposal [67,68]. Hence, a comprehensive sustainability assessment should consider not only the material performance during operation, but also durability, regeneration burden, waste generation, and end-of-life handling.

Finally, in practical terms, a material cannot be labeled sustainable without considering scalability and economic feasibility. The multistep preparation processes, precisely regulated circumstances or expensive reagents that are difficult to recreate at industrial size are the basis of many products reported at laboratory scale. Thus, from the point of view of review, the most meaningful evaluation is not only to identify the best performing material, but also to identify materials that can achieve acceptable performance with lower life-cycle burden, simpler processing requirements, and more realistic techno-economic viability. Such fair discussion contributes to the scientific rigor of the review and makes its results more relevant for future translation into real applications.

6. Current Challenges

Although the interest in green synthesis and bio-based materials is expanding, there are still significant hurdles that limit their practical sustainability. A frequent problem is the notion that a renewable or biomass-based material is automatically environmentally friendly. In fact, sustainability cannot be determined solely by feedstock origin, as synthesis, use, regeneration, and disposal can still pose significant environmental consequences. A key difficulty is also that many so-called green materials are nevertheless energy-intensive in respect to processing, chemical activation, solvent use, or multistep modification. These limitations may offset the environmental benefits expected from renewable precursors. Regeneration and reuse are also ongoing challenges, as some materials exhibit strong initial performance but require harsh treatment, high energy inputs, or frequent replacement, and may pose secondary pollution risks. Another disadvantage is the difference between laboratory performance and practical use. Many materials are evaluated solely under simplified conditions, whereas real systems have complex matrices, changing operating environments, and economic constraints. Future development should go beyond green synthesis and place greater emphasis on life-cycle burden, regeneration efficiency, scalability, and techno-economic feasibility to more reliably identify environmentally responsible materials.

In addition to technical limitations, practical implementation is also constrained by standardization, regulation, market adoption, and supply chain issues. The lack of unified testing methods and reporting standards makes it difficult to compare material performance across studies. Regulatory concerns related to safety, toxicity, leaching, and product certification may further slow the use of waste-derived or bio-based materials. Moreover, market adoption depends on cost competitiveness, durability, reliability, and compatibility with existing industrial systems. Supply-chain variability, especially in biomass, agricultural residues, recycled plastics, and industrial wastes, can also affect material consistency and scalability. Therefore, future challenges should be addressed from both technical and practical implementation perspectives.

Industrial-scale implementation also faces practical challenges related to feedstock variability, cost, and processing complexity. For example, agricultural waste-derived materials such as coconut shells, rice husk ash, and palm oil fuel ash can support low-carbon construction, but their composition and quality may vary depending on source, season, collection method, and pretreatment process [21]. Similarly, biochar-based construction materials require controlled pyrolysis conditions and consistent feedstock quality to ensure stable carbon storage, mechanical performance, and product reliability [69]. In plastic upcycling, high BHET recovery from PET demonstrates strong circularity potential, but industrial adoption still depends on catalyst cost, product purification, solvent use, and process integration [25]. For CO₂-based green methanol, the environmental benefit is clear, but techno-economic feasibility remains highly sensitive to the cost of renewable hydrogen, catalyst performance, energy demand, and carbon pricing policies [49]. These examples show that scale-up depends not only on material performance but also on feedstock control, process simplicity, cost competitiveness, and supply-chain reliability. Some sustainable technologies still involve environmental trade-offs. Biochar and sludge-derived materials may contain heavy metals or other contaminants depending on feedstock and production conditions. In addition, activated adsorbents, biochar materials, and advanced recycling processes may require high temperature, chemicals, catalysts, solvents, or repeated regeneration, which can increase energy demand and secondary emissions. Therefore, these technologies should be assessed not only by performance or waste-derived origin, but also by contamination risk, energy intensity, regeneration burden, and secondary pollution.

7. Future Perspectives

Future research should go beyond the development of bio-based or waste-derived materials and aim to produce truly ecologically responsible material systems. This implies that material design should combine not just functional performance, but also low-impact synthesis, decreased chemical use, effective regeneration, and safe end-of-life management. In this respect, life-cycle thinking should be introduced at an earlier stage of material development and not merely at the end as a final judgment. Another significant approach is to translate the achievement at the laboratory size to practical applications. Future studies should pay more attention to the material

stability in complicated actual matrices, long-term reuse performance, scalability and economic feasibility. At the same time, more efforts are needed to standardize the performance evaluation, regeneration protocols, and sustainability standards, so that materials may be evaluated more equitably across research. Future research should also place greater emphasis on quantitative and data-driven sustainability assessment. AI-assisted sustainability assessment can help predict material performance, environmental impacts, and optimal design conditions from large datasets [70]. Digital twins may be used to simulate material production, regeneration, and end-of-life pathways under real operating conditions, supporting process optimization and scale-up [71]. Carbon accounting tools can further quantify carbon storage, avoided emissions, and carbon footprint reduction across the material life cycle [72]. In addition, standardized sustainability indicators, such as carbon footprint, resource efficiency, recyclability, durability, regeneration efficiency, and techno-economic feasibility, should be more widely applied to improve comparability between studies [62].

This will assist in moving the field beyond “green synthesis” as an idea to ecologically responsible materials that are technically successful, scalable, and truly sustainable for environmental protection and resource recovery.

8. Conclusions

In summary, the development of bio-based, waste-derived, and green-synthesized materials has offered new prospects for environmental protection and resource recovery, yet green synthesis alone is not sufficient to qualify a material as ecologically responsible. This review points out that material sustainability evaluation needs to be carried out in a broader context, including life-cycle burden, energy required for synthesis, demand for chemicals, regeneration and reusability, secondary pollution, scalability, and economic feasibility. Thus, the most promising materials are not just those with the highest laboratory performance, but those that deliver effective performance with a smaller environmental impact and greater practical feasibility. Future research should focus on three practical directions. First, standardized sustainability indicators, such as carbon footprint, resource efficiency, recyclability, durability, and regeneration efficiency, should be applied to improve the comparison between studies. Second, long-term durability, reusability, and regeneration performance should be evaluated under realistic operating conditions rather than only under laboratory settings. Third, integrated Life Cycle Assessment (LCA) and Techno-Economic Assessment (TEA) should be used to verify whether sustainable materials are environmentally beneficial, economically feasible, and scalable for practical applications. Transitioning from green synthesis to environmentally responsible material design will be crucial for translating new materials into credible, sustainable, real-world applications.

Author Contributions

Conceptualization, A.C.; methodology, W.-H.C.; formal analysis, A.C. and W.-H.C.; investigation, A.C. and W.-H.C.; writing—original draft preparation, A.C. and W.-H.C.; writing—review and editing, W.-H.C.; supervision, W.-H.C.; funding acquisition, W.-H.C. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The original contributions presented in this study are included in the review. Further inquiries can be directed to the corresponding author.

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Conflicts of Interest

Given the role as Associate Editor, Wei-Hsin Chen had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal. The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT (OpenAI) to improve the language and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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