sustainability

Review

Eco Breakthroughs: Sustainable Materials Transforming the Future of Our Planet

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Abstract: Interest in the sustainable materials sector is growing and accelerated. These materials are designed to reduce the use of non-renewable resources, limit greenhouse gas emissions, and be recyclable or biodegradable, making them highly attractive to both academia and industry. Constantly updating on innovations in this field is essential to speed up the transition to a circular economy and significantly reduce environmental impact. The paper analyzes the current status and future trends of the scientific literature for seven sustainability-related materials categories, such as sustainable materials, green materials, biomaterials, eco-friendly materials, alternative materials, material recycling and material recovery from complex products, and sustainable applied materials. Next, it assesses the impacts, benefits, and challenges associated with sustainable materials from the scientific literature according to six research fields (impact on the environment, performance and durability, economic efficiency, health and safety, social sustainability, and implementation and use). Furthermore, the paper outlines recent advances in sustainable material design, including biomimicry, nanotechnology, additive manufacturing, 3D printing, and sustainable composite materials. Additionally, a bibliometric analysis of 545 studies on sustainable materials published between 1999 and 2023 was conducted based on eight criteria, namely trend, source, author, country, keywords, thematic, co-citation, and content. The findings show that the sustainability-related materials categories have a particular distribution among the domains. Also, the thematic map analysis outlines that biopolymers, nanocellulose, and biocomposites are critical research areas for developing sustainable materials.

Keywords: sustainable materials; environmentally friendly materials; eco-friendly paints; healthy environment; recyclable materials; biodegradable materials; green composites; biomaterials; alternative materials; sustainable applied materials

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1. Introduction

Sustainable materials are essential in building a greener and more responsible future. The choice of these materials contributes significantly to protecting the environment and creating healthy and efficient living and working spaces. Knowing these materials and how they are created and developed is useful for minimizing the negative impact on the environment, conserving natural resources, reducing carbon emissions and the CO_2 footprint, and reducing polluting waste.

In addition, through well-designed policies oriented toward the objectives of sustainable development, significant savings can be achieved, in the medium and long term, at the level of the individual as well as society, in the sense of improved thermal insulation and the obligation to generate a healthy environment for the occupants of newly built buildings.

In a world where sustainability is becoming increasingly important, various fields are rapidly adapting to integrate sustainable and environmentally friendly materials.

These innovative and environmentally friendly materials reduce the impact on nature and bring long-term economic and social benefits.

Sustainable materials are changing how buildings are designed and erected in construction and architecture. Eco-friendly concrete, FSC (Forest Stewardship Council) certified wood, and natural insulating materials such as cellulose fibers are becoming standards in residential and commercial building development. Infrastructure projects now incorporate recycled asphalt and green concrete, helping to reduce carbon emissions and increase the sustainability of structures. Renovations and restorations also benefit from paints without volatile organic compounds (VOC-free paints) and eco-friendly finishes, reducing waste and protecting occupant health.

The construction industry has recognized the need for more sustainable building practices [1]. Sustainable building materials are a key aspect of this transition, as they can help minimize the environmental impact of construction projects and improve the overall sustainability of buildings. One aspect of sustainable building materials that has received growing attention is the material criteria used in building sustainability assessment tools. These tools often include a material category that assesses the environmental performance of the materials used in construction. The weight given to this category can range from 10% to 20% of the overall assessment score, indicating its significance [2]. The material requirements in these tools are also becoming more stringent as their scope expands, reflecting the increasing importance of sustainable materials. However, there is still a lack of consensus on the specific categories, numbers, and definitions of criteria that should be used to evaluate sustainable building materials. This lack of a unified set of criteria can make it challenging for architects, engineers, and the building industry to select the most sustainable materials for their projects consistently.

The automotive industry is making significant strides toward sustainability by using natural fibers such as hemp and flax to manufacture vehicle components. These materials reduce the weight of cars and improve fuel efficiency. In addition, parts and components made from recycled materials such as plastic and metal are becoming more common. The development of more efficient and durable batteries supports the transition to electric vehicles, helping to reduce pollution. Furthermore, the industry is exploring the use of recycled and biodegradable materials for interior components, such as seat fabrics and trim, to further enhance vehicle sustainability [3]. Adopting closed-loop manufacturing processes, where materials are recovered and reused, is another critical strategy in the automotive sector's shift toward a more circular and environmentally responsible approach [4].

Sustainable fashion is gaining ground through natural and organic fibers such as organic cotton, hemp, and bamboo. Recycled materials such as recycled polyester offer an environmentally friendly alternative to traditional textiles. Eco-friendly paints and dyes, obtained from natural sources and energy-efficient dyeing technologies, reduce the negative impact on the environment while creating safe clothes. Sustainable fashion also involves implementing closed-loop systems, where garments are designed for disassembly and reuse, minimizing waste. Additionally, ethical labor practices and fair wages for workers are critical components of sustainable fashion [5]. The industry continuously explores innovative solutions, such as using agricultural waste as raw materials and developing biodegradable synthetic fibers, further enhancing the fashion sector's sustainability [6,7].

Sustainable packaging is revolutionizing the way products are packaged and transported. Biodegradable and compostable cornstarch plastic and cellulose packaging are eco-friendly alternatives that break down quickly without polluting the environment. Recyclable packaging, such as cardboard and glass, reduces waste, while reusable packaging, such as containers and bags, promotes responsible use of resources. In addition, using refillable and deposit-return systems for packaging further contributes to a more circular and sustainable approach to product packaging. The increased focus on sustainable packaging helps minimize waste, conserve natural resources, and reduce the overall environmental impact of product distribution and consumption [8,9].

In the electronics sector, sustainability is increasing through employing recycled metals and plastics in device manufacturing. Energy-efficient devices with low power consumption and long-lasting batteries are becoming market standards. Managing e-waste through recycling and reuse helps reduce environmental impact and conserve valuable resources. Additionally, the development of modular and repairable electronics allows for easier maintenance and extends the lifespan of devices, further contributing to sustainability. Incorporating renewable and recyclable materials in electronics production and improved e-waste management are critical steps in minimizing the environmental footprint of the electronics industry [10,11].

Sustainable packaging plays an essential role in the food industry, where compostable and biodegradable materials are increasingly used. Sustainable agricultural practices, including using sustainable agricultural materials and energy-efficient equipment, contribute to greener food production. Food products grown and packaged using organic methods are becoming increasingly popular with consumers [12].

The renewable energy sector benefits from sustainable materials for constructing solar panels and wind turbines. These materials include recycled metals and plastics, which improve sustainability and energy efficiency. Energy storage systems, such as sustainable and recyclable batteries, support the transition to renewable energy sources, reducing dependence on fossil fuels.

The authors propose the following six research fields to analyze the utility of sustainable materials, taking into account their associated impacts, benefits, and challenges:

- Impact on the environment;
- Performance and durability;
- Economic efficiency;
- Health and safety;
- Social sustainability;
- Implementation and use.

The paper's contributions are as follows:

- Discusses comprehensively the current status and future trends of the scientific literature for seven sustainability-related materials categories, such as sustainable materials, green materials, biomaterials, eco-friendly materials, alternative materials, material recycling and material recovery from complex products, and sustainable applied materials;
- Assesses the impacts, benefits, and challenges associated with sustainable materials from the scientific literature according to six research fields, namely impact on the environment, performance and durability, economic efficiency, health and safety, social sustainability, and implementation and use;
- Outlines recent advances in sustainable material design, including biomimicry, nanotechnology, additive manufacturing, 3D printing, and sustainable composite materials;
- Conducts a bibliometric analysis of 545 studies that focus on sustainable materials that were published in 299 sources between 1999 and 2023;
- Performs a quantitative and a qualitative literature analysis based on eight criteria, namely trend, source, author, country, keywords, thematic, co-citation, and content;
- Examines in-depth 545 publications by highlighting the challenges and implications regarding the six research fields mentioned above.

The paper comprises six sections. Section 2 presents the current status and future trends in the scientific literature for seven sustainability-related materials categories, such as sustainable materials, green materials, biomaterials, eco-friendly materials, alternative materials, material recycling and material recovery from complex products, and sustainable applied materials. Section 3 discusses the systematic analysis and review of published studies and research in the sustainable materials domain. Section 4 shows the results and findings. Sections 5 and 6 describe the discussion and conclusions.

2. Literature Review

2.1. Sustainable Materials

The demand for sustainable materials has increased in tandem with regulations and current tendencies. Sustainable materials can be found in the environment as raw materials. They are renewable, natural, and carbon neutral, while synthetic materials are harmful [13]. Yet, some natural materials cannot be considered renewable. For example, iron or aluminum are abundant in the environment and can be recycled often.

Sustainable materials play a pivotal role within the construction industry, primarily aiming to mitigate natural resource depletion and minimize waste generation [14]. Critical components such as steel, glass, and environmentally friendly substitutes for concrete are indispensable for realizing eco-conscious structures [15]. Green materials' significance, abundance, reduced toxicity, and economic viability are paramount in catalyzing sustainable development initiatives [16].

Nevertheless, attaining a sustainable materials ecosystem necessitates comprehensive measures beyond mere consumption reduction and technological advancement. It mandates the elongation of product lifecycles, enhancement of manufacturing efficiency, and implementation of robust recovery mechanisms, all underpinned by robust governance frameworks and educational initiatives [17].

Many studies on sustainable materials put an urgent need for eco-friendly practices and forward-thinking strategies. Titirici et al. [18] dive deep into sustainable carbon materials, urging a shift from traditional sources to renewable alternatives. Their work not only highlights the practical benefits but also emphasizes the moral imperative of these materials in driving renewable energy efforts and environmental conservation. Meanwhile, Anbarzadeh and Tahavvori [19] steer the conversation toward green engineering materials, celebrating their versatility across various industries, from energy to construction. While their specific methods remain unspecified, their paper shines a light on the transformative potential of these materials in fostering sustainable development.

Shi [20] explores the intricate nuances of sustainable materials development. With a broad perspective, the study advocates for resource efficiency, cleaner production methods, and harnessing abundant elements to steer industry toward a more environmentally conscious path. Bauer [21] takes a pragmatic approach, dissecting the environmental impact of everyday materials like steel and cement. By proposing strategies for smarter material usage, the author calls for a shift in industrial practices toward reduction, reuse, and recycling to curb emissions and energy consumption.

Scott and Letcher [22] focus on the future, where material scarcity looms large and sustainable alternatives beckon. From biomass to urban infrastructure, their discussion encompasses a wide array of materials, all underlined by the pressing need for sustainability in managing our resources. Choudhury [23] echoes this sentiment, advocating for adopting renewable and sustainable materials as the linchpin of environmental preservation. With a rallying cry to abandon harmful materials, the paper charts a course toward a greener future, where sustainable choices pave the way for a healthier planet for future generations.

Table 1 summarizes the current status and the future trend of the research conducted on sustainable materials.

Table 1. Current status and the future trend of the research conducted on sustainable materials.

Current Status	Future Trend	Domain	Reference
Use of natural raw materials like steel, glass, and eco-friendly substitutes in construction	Adoption of advanced materials to mitigate natural resource depletion and improve waste management	Construction	Ritu and Chhillar (2017) [14]
Green engineering materials highlighting versatility across industries	Development of innovative green materials for energy, construction, and sustainability applications	Energy, construction, multiple industries	Anbarzadeh and Tahavvori (2019) [19]

Table 1. *Cont.*

Current Status	Future Trend	Domain	Reference
Sustainable carbon materials urging a shift to renewable alternatives	Implementation of carbon materials for renewable energy and environmental conservation efforts	Renewable energy, sustainability	Titirici et al. (2015) [18]
Strategies for smarter material usage focusing on steel and cement	Expansion of reduction, reuse, and recycling in industrial practices to curb emissions	Industrial processes	Bauer (2012) [21]
Exploration of biomass and sustainable urban materials	Development of eco-conscious urban infrastructure and alternatives to synthetic materials	Urban planning, sustainability	Scott and Letcher (2012) [22]
Advocacy for adopting renewable and sustainable materials	Increased integration of environmentally friendly choices to drive global preservation efforts	Environmental conservation	Choudhury (2016) [23]
Emphasis on resource efficiency and cleaner production methods	Transition to abundant, eco-friendly materials for reducing environmental impact	Industrial and environmental fields	Shi (1998) [20]

2.2. Green Composites/Materials

There are many different types of natural fibers and resins and methods for strengthening fibers as alternative solutions to synthetic fibers. Moreover, natural fiber and resins are less expensive, biodegradable, and available. With such materials, synthetic polymer composites can be successfully replaced. According to Shekar and Ramachandra (2018), green composites are polymer materials made of natural fibers such as bamboo, coir, flax, and hemp. Natural fibers are categorized as animal-based (protein), such as silk and wool; vegetable-based (cellulose), such as seed, fruit, and leaf; and mineral-based, such as asbestos. Biocomposites can be used in electronics, furniture, and sports equipment [24,25].

Polymer composites can be filled with natural fillers made from biodegradable sources. For example, wood flour and fibers usually serve as organic fillers, which are also easily available and produced. Furthermore, wood flour is obtained from sawmill waste. Commercial applications of such materials are mainly window and doorframes and furniture [26].

Green composites, also known as environmentally friendly materials, have emerged as a promising area of research due to their renewable, recyclable, and biodegradable nature [27]. These composites can take various forms, including polymer-based composites utilizing natural fibers like hemp, flax, and sisal as replacements for synthetic fibers or cement-based composites employing new binders such as geopolymer and recycled aggregators. Studies have demonstrated the mechanical properties of bamboo fiber-reinforced green composites, highlighting their potential for applications across various fields. Meanwhile, Singh et al. [28] state that using biodegradable polymers from natural resources in green composites further enhances their environmental friendliness. These materials have the potential to be used in a wide range of applications, but careful consideration is needed to match the material to the specific application. Loureiro and Esteves [29] investigated the formulation of green composites using biopolymer poly (lactic acid) (PLA) and natural-based cellulosic fibers for automotive interior applications. Their study emphasized optimizing the price/quality relationship and improving thermal behavior without compromising mechanical properties. A total of 20% fiber content notably enhanced the composite's thermal behavior while maintaining mechanical integrity.

Green composites, composed of natural fibers and biodegradable polymers, have shown significant potential in industries such as automotive and construction. Recent studies emphasize the environmental benefits of using natural fibers like bamboo, flax, and hemp, which reduce dependency on synthetic materials and are easily recyclable. For example, Nachiappan et al. [30] demonstrated the use of hemp-based composites in automotive panels, highlighting reduced weight and enhanced biodegradability compared to conventional materials. Other advancements in this field focus on optimizing fiber-matrix bonding to improve durability and performance in various applications.

Teacă and Bodîrlău [31] highlighted the environmental benefits of green composites derived from renewable resources, emphasizing biopolymer matrices and bio-fillers. Their analysis employed various techniques to elucidate the structure and properties of these composites, including spectroscopy and thermal analysis methods. Khalil et al. [32] comprehensively reviewed cellulose nano-fibril-based green composites, underscoring their eco-friendly nature and promising applications. The study elucidated these materials' processing, properties, and applications, displaying their potential as sustainable alternatives. Torres et al. [33] delved into fully green composite materials, employing biopolymers as matrices and organic fillers from agroforestry wastes. Their review highlighted such composites' enhanced mechanical, thermal, and barrier properties, emphasizing their role in replacing non-degradable polymers.

Furthermore, Huda et al. [34] explored using recycled cellulose fibers from newsprint in PLA composites, demonstrating improved mechanical properties and compatibility. Their methodology involved analyzing various composite properties, including tensile and flexural moduli, crystallinity, and thermal decomposition. Pfister and Larock [35] investigated green composites utilizing a linseed oil-based resin and wheat straw, emphasizing their renewable composition and suitability for industrial applications. The study assessed the influence of different variables on composite properties, mainly focusing on water absorption and mechanical behavior.

Ashori [36] discussed the utilization of wood–plastic composites as sustainable materials in the automotive industry, highlighting their benefits, such as enhanced mechanical strength, reduced weight, and biodegradability. The study emphasized the technical advantages of incorporating plant fibers into polymer matrices.

Vázquez-Núñez et al. [37] reviewed the significance of green composites in fostering sustainability efforts, stressing their biodegradability and potential for contributing to green economies. Their analysis likely involved describing manufacturing processes and assessing the properties of raw materials used. Lastly, Zini and Scandola [38] provided an overview of green composites, focusing on the environmental benefits of utilizing natural fibers and bio-based polymers. The study underscored the shift toward waste-derived fibers and the development of new bio-based polymers for composite applications.

Table 2 resumes the current status and the future trend of the studies carried out on green materials.

Table 2. Current status and the future trend of the studies carried out on green materials.

Current Status	Future Trend	Domain	Reference
Use of natural fibers like bamboo, coir, flax, and hemp in green composites	Optimization of fiber-matrix bonding to improve durability and performance	Automotive, construction	Singh et al. (2017) [28]
Biopolymer PLA with natural cellulosic fibers for automotive interiors	Improved thermal behavior with optimized price/quality relationship and 20% fiber content	Automotive	Loureiro and Esteves (2019) [29]
Hemp-based composites for automotive panels	Development of lightweight, biodegradable alternatives to conventional materials	Automotive	Nachiappan et al. (2022) [30]
Biopolymer matrices with organic fillers from agroforestry waste	Enhanced mechanical, thermal, and barrier properties of fully green composites	Packaging, construction	Torres et al. (2019) [33]
Recycled cellulose fibers in PLA composites	Improved mechanical properties, crystallinity, and thermal decomposition analysis	Electronics, packaging	Huda et al. (2005) [34]
Linseed oil-based resin and wheat straw composites	Renewable compositions with enhanced water absorption and mechanical properties	Industrial applications	Pfister and Larock (2010) [35]
Wood–plastic composites with plant fibers	Increased biodegradability, mechanical strength, and weight reduction for sustainable alternatives	Automotive	Ashori (2008) [36]
Waste-derived fibers and bio-based polymers for green composites	Development of bio-based polymers emphasizing environmental benefits	General industries, sustainable materials	Zini and Scandola (2011) [38]

2.3. Biomaterials (Bio/Life-Inspired Materials)

Bio-based nanostructured materials represent a significant area of interest due to their diverse applications and potential for innovation. Inspired by biological systems, biomaterials are becoming popular for applications requiring high compatibility and low toxicity, such as medical devices and food packaging. Recent research [39] has focused on using bioinspired nanomaterials in drug delivery systems, which offer biodegradable controlled release mechanisms. Another promising avenue in biomaterials involves bio-based nanostructures, which mimic natural resilience and flexibility, providing enhanced material performance in biomedical applications [40]. Razavi [41] discusses the broad applications of bio-based materials and the utilization of nanotechnology in creating nanostructured materials for various biology applications. This study underscores the importance of innovations in nano-biomaterials and research on bio-based nanostructured materials, particularly in biomedical applications.

Similarly, Green et al. [42] explore the evolution of biomaterials from different environments and advocate for incorporating design strategies from biological models into synthetic materials for regenerative medicine. Their work emphasizes the significance of bioinspired materials engineering beyond human biology, reflecting the growing interest in nature-inspired solutions for material development.

Suresh Kumar et al. [43] provide an overview of biomimetic materials inspired by nature, highlighting their biological properties and diverse applications across various fields. Their review underscores the importance of understanding and utilizing biomimetic materials for advancing technological innovations. Additionally, Pavlovic [44] outlines the importance of biomaterials in bioengineering and regenerative medicine, emphasizing the need for biocompatible and biodegradable materials for various applications, including drug delivery systems and tissue scaffold fabrication.

Demirel et al. [45] discuss recent advancements in bio- and nanotechnologies for developing eco-friendly materials from renewable resources. This study highlights bio-derived materials' structural and functional characteristics, facilitating the design and synthesis of advanced nanomaterials and devices. Pradhan et al. [46] focus on utilizing nature-derived materials to fabricate functional bio-devices, emphasizing their properties and potential applications in green electronics and sustainability efforts. Their work highlights the viability of nature-derived biomaterials for real-world applications, reflecting the growing interest in green and sustainable technologies.

Furthermore, Aizenberg and Fratzl [47] explore the inspiration from nature for developing advanced materials, emphasizing the challenge of replicating biological designs in artificial structures. This study highlights the potential of biomimetic materials for creating bioinspired advanced materials with optimized structural and functional properties. Lastly, Raghavendra et al. [48] discuss the importance of biomaterials in medical sciences and their design, development, and biomedical applications. Their work emphasizes the increasing demand for bio alternatives and the essential role of biomaterials in modern medical technologies.

Table 3 abstracts the current status and the future trend of the surveys performed on biomaterials.

Table 3. Current status and the future trend of the surveys performed on biomaterials.

Current Status	Future Trend	Domain	Reference
Bioinspired nanomaterials in drug delivery systems	Development of biodegradable controlled release mechanisms	Drug delivery, biomedical sciences	Bochicchio et al. (2021) [39]
Bio-based nanostructures mimicking natural resilience and flexibility	Enhanced material performance in biomedical applications	Biomedical applications	Razavi (2018) [41]
Biomaterials for regenerative medicine	Incorporating biological design strategies into synthetic materials	Regenerative medicine	Green et al. (2016) [42]
Biomimetic materials inspired by nature	Advancing technological innovations through the utilization of biological properties	Biomedical engineering, technological innovation	Suresh Kumar et al. (2020) [43]
Eco-friendly materials from renewable resources	Design and synthesis of advanced nanomaterials and devices	Green technologies, material science	Demirel et al. (2015) [45]
Nature-derived materials for functional bio-devices	Expanding applications in green electronics and sustainability efforts	Green electronics, sustainability	Pradhan et al. (2020) [46]

Table 3. *Cont.*

Current Status	Future Trend	Domain	Reference
Inspiration from biological systems for advanced materials	Creation of bioinspired advanced materials with optimized structural and functional properties	Advanced materials engineering	Aizenberg and Fratzl (2009) [47]
Biomaterials in medical sciences	Growing use of bioalternatives in modern medical technologies	Medical sciences	Raghavendra et al. (2015) [48]

2.4. Eco-Friendly/Recyclable Materials

Environmentally friendly materials—cotton, linen, bamboo, and wood—are widely known natural materials and are used in different areas. Cotton, bamboo, silk, and linen are particularly popular in clothing production. Wood, as an eco-friendly material, is commonly used in furniture production as well as for interior design, flooring, facades, and decorations.

Recycled materials not only reduce the negative effect on raw materials [49] but also decrease pollution and water use caused by the manufacturing of raw materials [50]. This leads to reducing land waste and disposal, considering that synthetic materials are not biodegradable [51].

More widespread recyclable textile types include cotton or cotton/polyester composite, which is recycled through chemical, biochemical, or mechanical methods [52].

Recycled paper has become an important part of the paper industry. However, recycled paper contains chemicals that require monitoring to keep safe [53].

The importance of recycling and eco-design in sustainable materials management is widely recognized across various studies. Maris et al. [54] highlight the significance of recycling polymer materials to protect non-renewable resources, mitigate climate change impacts, and minimize adverse effects on human health and ecosystems. Despite the acknowledged benefits, the authors also discuss the existence of barriers to recycling, encompassing technical and social challenges. Similarly, Nowotna et al. [55] explore using natural eco-friendly building materials in modern construction, emphasizing their advantages, such as energy efficiency, cost-effectiveness, and environmental friendliness. Their methodology involves comparing selected natural materials for hydrothermal research, displaying their suitability for diverse construction applications.

Rossi et al. [56] address the urgent need for sustainable packaging solutions by introducing NeoPalea, a composite material composed of straw and biodegradable biopolymers, as a viable alternative. Their study aims to mitigate the environmental impact of packaging waste by developing a material that aligns with the characteristics of conventional polymers, thereby offering a sustainable substitute. Similarly, Lyons [57] discusses the promotion of recycling in construction to address environmental concerns, highlighting various recycled materials and their transition to standard building materials, as exemplified by the Earth Centre in Doncaster.

Furthermore, Feng et al. [58] propose a method for fabricating environmentally friendly materials using recycled waste, considering environmental protection and construction practicability. The methodology involves pulverizing recycled plastic and rubber scrap, mixing with calcium carbonate powder, and molding to create waterproof, moisture-proof, acid and alkali-resistant, lightweight, high-strength materials. Walton and Walton [59] encourage the repurposing of waste materials into art, furniture, and home decorations, promoting eco-friendly design practices. Their methodology involves exploring the history of recycled materials in design and advocating for their utilization in creative endeavors.

Pan et al. [60] also discuss strategies for recycling plastic products with high benefits, focusing on sustainability and the occasional need for property readjustment. Rahman et al. [61] emphasize the benefits of recycling waste materials for people and the environment, underlining the importance of environmental preservation and energy conservation. These studies collectively contribute to the literature on recycling and eco-design, highlighting the importance of sustainable materials management practices in mitigating environmental impacts and promoting a circular economy.

Table 4 outlines the current status and future trend of the research that has led to eco-friendly materials.

Table 4. Current status and the research led to eco-friendly materials.

Current Status	Future Trend	Domain	Reference
Natural materials like cotton, bamboo, silk, and linen used in textiles	Advanced methods for recycling cotton/polyester composites (chemical, biochemical, mechanical)	Clothing production	Maris et al. (2014) [54]
Wood is widely used in furniture, flooring, and decorations	Expanded adoption of natural eco-friendly materials for energy-efficient modern construction	Construction, interior design	Nowotna et al. (2019) [55]
Development of NeoPalea composite material for packaging	Increased use of biodegradable biopolymer packaging to replace conventional plastic waste	Packaging, material science	Rossi et al. (2020) [56]
Recycling practices in construction	Integration of recycled materials into standard building materials for environmental sustainability	Construction	Lyons (2019) [57]
Fabrication of materials from recycled plastic and rubber	Creation of lightweight, waterproof, high-strength eco-materials for environmental and construction uses	Construction, environmental protection	Feng et al. (2014) [58]
Repurposing waste into art and design	Enhanced eco-friendly practices in furniture, art, and creative design industries	Art, furniture, home design	Walton and Walton (2000) [59]
Recycling plastic products for sustainability	Optimization of recycling processes with an emphasis on adjusting properties for better performance	Plastics industry	Pan et al. (2020) [60]
Benefits of recycling for environmental preservation	Strengthening circular economy and energy conservation through innovative waste recycling strategies	Sustainability, energy conservation	Rahman et al. (2020) [61]

2.5. Alternative Materials

Using alternative materials in various fields is a growing trend, presenting opportunities and challenges. Alternative materials, including synthetic alternatives to metals and other non-renewable resources, are essential in applications where material resilience and performance are critical. Recent research [62] highlights using geopolymer concrete as a low-carbon alternative in construction. These materials, developed using waste products like fly ash, are highly durable and support the reduction of CO_2 emissions [63]. The field continues to innovate with new materials that provide functionality on par with traditional resources while supporting environmental sustainability.

In construction, there is a need for updated regulations to support the use of alternative materials [64]. In furniture design, a wide range of materials, including stone, metal, cardboard, papier-mâché, paper, plastic, and glass, are being explored for their artistic potential [65]. The application of alternative materials in hot mix asphalt, such as recycled waste tires, glass, roof shingles, and steel slag, is being investigated to address environmental concerns. In language teaching, the production of alternative materials, including picture flashcards, posters, cartoons, books, and computer-based materials, is being explored to enhance the learning experience [66].

The construction industry is undergoing significant transformations driven by sustainability concerns, leading to the exploration of alternative materials and processes. Zhang et al. [67] and Kidalova et al. [68] delve into sustainable construction materials, focusing on bricks and composites. Zhang et al. [67] emphasize the unsustainable nature of traditional fired clay bricks due to their high energy consumption and carbon footprint. They advocate adopting geo-polymerization as a more sustainable approach, particularly clay-based geo-polymers while highlighting the need to enhance clay reactivity at a lower cost.

Conversely, Kidalova et al. [68] investigate lightweight composites using renewable materials like hemp fibers and wood cellulose. They explore alternative binding agents, such as magnesium oxide and zeolite, to reduce carbon dioxide production in cement manufacturing. Both studies underscore the urgency of transitioning toward environmentally friendly construction materials to mitigate the industry's environmental impact.

Similarly, Balaguera et al. [69] and Petersen and Solberg [70] delve into the environmental assessment of construction materials, focusing on roads and wood products, respectively. Balaguera et al. [69] discuss the application of Life Cycle Assessment (LCA) in evaluating the environmental impacts of road construction, emphasizing the need to consider traditional and alternative materials such as recycled asphalt, fly ash, and polymers. They advocate for a holistic approach to road construction that balances technical, social, economic, and environmental criteria.

Petersen and Solberg [70] provide a comprehensive overview of LCAs comparing wood with alternative materials, mainly focusing on greenhouse gas emissions. Their analysis demonstrates that wood often outperforms other materials in terms of environmental impact, highlighting its potential as a sustainable building material.

Moreover, Manalo et al. [71] explore innovative materials for railway sleepers, addressing the environmental concerns associated with hardwood timber and chemically impregnated sleepers. They propose fiber composites as a viable alternative, presenting ongoing research and development efforts. Finally, King and Tansey [72] examine rapid tooling to accelerate product development and reduce time to market in the manufacturing sector. Their study explores the adaptation of selective laser sintering (SLS) for metal-based prototypes, emphasizing the potential of modular injection mold tool inserts to streamline the production process.

Table 5 shows the current status and the future trend of the studies conducted on alternative materials.

Table 5. Current status and the studies conducted on alternative materials.

Current Status	Future Trend	Domain	Reference
Use of geopolymer concrete as a low-carbon alternative in construction	Continued development of geopolymer materials, particularly clay-based geo-polymers, for enhanced sustainability	Construction	Zhang, Z. et al. (2018) [67]
Exploration of a wide range of materials in furniture design	Increased use of materials such as stone, metal, cardboard, and recycled products for artistic and sustainable designs	Furniture design	Kidalova et al. (2012) [68]
Exploration of alternative materials for educational tools	Development of more sustainable and eco-friendly educational materials	Education	Castillo, and Piantzi (2016) [66]
Use of lightweight composites made from renewable materials like hemp and wood cellulose	Continued research into alternative binding agents to reduce carbon emissions in cement manufacturing	Construction	Kidalova et al. (2012) [68]
Application of LCA to evaluate environmental impacts of road construction	Broader use of LCA to assess the environmental impacts of traditional and alternative road construction materials	Road construction	Balaguera et al. (2018) [69]
Wood compared with alternative materials in construction	Further research on the environmental benefits of wood versus alternative materials, particularly in terms of greenhouse gas emissions	Building materials	Petersen and Solberg (2005) [70]
Use of hardwood timber for railway sleepers	Research into fiber composites as a sustainable alternative to hardwood timber	Railway construction	Manalo et al. (2010) [71]
Exploration of selective laser sintering (SLS) for rapid tooling and product development	Advancements in modular injection mold tool inserts to accelerate product development and reduce time to market	Manufacturing	King and Tansey (2002) [72]

2.6. Material Recycling and Material Recovery from Complex Products

The recovery of precious and unique metals from complex products presents economic and technological challenges [73]. Innovative recycling technologies, such as bio-leaching and molecular sorting, are being developed to enhance resource efficiency and meet the demands of modern production lines. Argonne National Laboratory is working on cost-effective technologies for materials recovery, including dezincification of galvanized steel scrap and high-value-plastics recovery from obsolete appliances [74]. The problem of selecting the best sequence for material recovery in bulk recycling is addressed through dynamic programming and target material identification [75].

The quest for sustainable material recovery and recycling practices has become increasingly imperative in contemporary manufacturing and product design. Johnson and Wang [76] propose a methodology to optimize disassembly processes for material recovery opportunities (MRO) in post-consumer products. Their focus lies in enhancing the efficiency of disassembly planning and generating optimal disassembly sequences, emphasizing criteria such as material compatibility, clustering for disposal, concurrent operations, and maximizing yield. Similarly, Ignatenko et al. [77] developed a fundamental material and an optimization model of energy recovery to meet EU legislation targets. Their research explores various end-of-life vehicle (ELV) recovery scenarios, highlighting the importance of flexibility in processing options to achieve high recovery quotas effectively.

Barwood et al. [78] delve into adopting reconfigurable manufacturing systems to enhance flexibility and automation in recycling activities. They introduce the concept of a 'Reconfigurable Recycling System' (RRS), illustrated through a specially designed robotic cell for disassembling electrical car components. Tansel [79] discusses the challenges of increasingly compact and efficient product designs on recycling and materials recovery infrastructure. With municipal solid waste quantities doubling globally since 1960, effective waste management and recycling infrastructures are critical, especially given the impending scarcity of critical raw materials.

Pajunen et al. [80] advocate for a comprehensive approach to recycling, shifting the focus from end-of-life product stages to design and material development phases. Their research emphasizes the integration of life cycle and system thinking in the design phase to facilitate effective recycling. Singh and Ordoñez [81] analyze over 50 examples of products developed from discarded materials to understand resource recirculation in a circular economy context. They identify practical challenges and propose a revised model for recovery routes in society, highlighting the need for waste management to facilitate material recirculation.

Birat [82] explores the concept of the circular economy, emphasizing the importance of recycling and materials recovery in reducing the demand for virgin resources. Recycling is pivotal in achieving environmental benefits such as energy savings and reduction of greenhouse gas emissions. The circular economy approach requires detailed materials analysis to improve recycling rates and reduce ecological footprints. Tools like Life Cycle Assessment (LCA) and Materials Flow Analysis (MFA) are essential for understanding material stocks and flows over time and informing policy decisions to foster the circular economy effectively.

Table 6 summarizes the current status and the future trend of the surveys performed on material recycling and material recovery from complex products.

Table 6. Current status and the surveys performed on material recycling and material recovery from complex products.

Current Status	Future Trend	Domain	Reference
Innovative recycling technologies such as bio-leaching and molecular sorting to recover precious metals	Continued development of cost-effective and efficient recycling technologies for modern production lines	Manufacturing, recycling	Daniels (1997) [74]
Development of optimization models for material recovery in bulk recycling	Enhanced sequencing and target material identification for improved recovery rates	Recycling	Ignatenko et al. (2008) [77]
Focus on improving disassembly processes for material recovery opportunities in post-consumer products	Optimization of disassembly planning to increase efficiency and material recovery yields	Post-consumer recycling	Johnson and Wang (1995) [76]
Introduction of reconfigurable manufacturing systems for recycling flexibility	Further research into robotic systems for disassembling complex products and enhancing automation	Manufacturing, recycling	Barwood et al. (2015) [78]
Challenges in recycling due to compact product designs	Development of more efficient waste management and recycling infrastructures to address global waste increase	Waste management, recycling	Tansel (2020) [79]

Table 6. *Cont.*

Current Status	Future Trend	Domain	Reference
Advocacy for a comprehensive recycling approach integrating life cycle and system thinking	Shift toward early design phase integration to facilitate recycling and reduce waste generation	Product design, recycling	Pajunen et al. (2015) [80]
Analysis of products developed from discarded materials for resource recirculation	Development of revised recovery models for material recirculation in a circular economy context	Circular economy, waste management	Singh and Ordoñez (2016) [81]
Emphasis on the importance of recycling in the circular economy to reduce the demand for virgin resources	Increased use of LCA and MFA to improve recycling rates and ecological footprints	Circular economy, recycling	Birat (2015) [82]

2.7. Sustainable Applied Materials

Various studies have highlighted the potential of green and sustainable materials in multiple applications. Purwasasmita [16] and Anbarzadeh and Tahavvori [19] both emphasize the unique properties of these materials, including their abundance in nature, low toxicity, and economic affordability. Ismail et al. [83] and Yhaya et al. [84] further underscore the need to transition to a circular economy and the importance of coordination and concerted efforts in developing and commercializing sustainable materials. These studies collectively suggest that sustainable applied materials have the potential to contribute significantly to the advancement of a more environmentally friendly and economically viable future.

Khalid et al. [85] shed light on the significance of natural fibers reinforced polymer composite (NFRPC) materials in engineering applications. These materials offer eco-friendly attributes, lightweight properties, and notable mechanical characteristics. However, challenges persist, such as fiber quality, thermal stability, and water absorption capacity. The review highlights recent breakthroughs, including hybridization with synthetic fibers and chemical treatments, to enhance NFRPC performance. Additionally, the integration of numerical models for NFRPCs is explored, offering valuable insights for future research directions.

Titirici et al. [18] focus on developing sustainable carbon materials, emphasizing the importance of considering the entire life cycle, from precursor to end-of-life, when assessing their sustainability. By utilizing natural and renewable precursors coupled with energy-efficient synthesis processes, sustainable carbon materials can contribute to reducing greenhouse gas emissions and toxic element usage. The review highlights recent progress in synthesizing and applying sustainable carbon materials, particularly in renewable energy and environmental science fields.

Sanchez-Rexach et al. [86] examine the role of additive manufacturing (AM) in advancing sustainability within chemistry and materials science. AM offers unique capabilities for fabricating complex geometries and has potential applications in aerospace, robotics, and healthcare. However, sustainability challenges persist, particularly concerning material sourcing, recycling, and circularity. The review discusses recent developments in designing sustainable polymers for AM applications, focusing on biodegradable and biosourced polymers, and explores emerging sustainability-related applications enabled by AM technologies.

Korhonen et al. [87] introduce highly porous nanocellulose aerogels functionalized with a hydrophobic coating for oil-absorption applications. These aerogels, prepared from renewable cellulose sources, demonstrate selective oil-absorption capabilities and can be recycled or incinerated after use, promoting environmental sustainability. Cataldi et al. [88] delve into the applications of graphene nanoplatelets in composite materials, highlighting their potential in flexible electronics, energy devices, and structural sensing applications. The review discusses progress in utilizing graphene nanoplatelets in biodegradable materials, emphasizing their role in advancing sustainable material solutions.

Table 7 sums up the current status and the future trend of the research carried out on sustainable applied materials.

Table 7. Current status and the research carried out on sustainable applied materials.

Current Status	Future Trend	Domain	Reference
Green and sustainable materials emphasize abundance, low toxicity, and economic affordability	The transition toward a circular economy with enhanced coordination for commercializing sustainable materials	Environmental sustainability, circular economy	Purwasasmita (2017) [16]
NFRPC for engineering applications	Hybridization with synthetic fibers and chemical treatments to enhance performance	Engineering applications	Khalid et al. (2021) [85]
Development of sustainable carbon materials using natural and renewable precursors	Continued use of energy-efficient synthesis processes to reduce greenhouse gas emissions and toxic elements	Renewable energy, environmental science	Titirici et al. (2015) [18]
Use of AM to advance sustainability in materials science	Development of biodegradable and bio-sourced polymers for AM, with an emphasis on recycling and circularity	Aerospace, robotics, healthcare	Sanchez-Rexach et al. (2020) [86]
Highly porous nanocellulose aerogels for oil-absorption applications	Further development of hydrophobic-coated aerogels and their use in oil absorption, with recycling and incineration capabilities	Environmental protection, engineering	Korhonen et al. (2011) [87]
Use of graphene nanoplatelets in composite materials for energy devices and flexible electronics	Continued research into graphene nanoplatelets in biodegradable materials for sustainable applications	Electronics, energy devices, structural sensing	Cataldi et al. (2018) [88]

2.8. Recent Advances in Sustainable Material Design

In recent years, substantial advancements in sustainable material design have emerged, driven by innovative industry approaches. These advancements, encompassing biomimicry, nanotechnology, additive manufacturing, and closed-loop systems, aim to reduce environmental impact while enhancing material performance across diverse applications.

2.8.1. Biomimicry in Material Design

Biomimicry, designing materials inspired by natural processes, has gained significant traction as a sustainable design strategy in recent years. For instance, researchers have developed materials replicating the self-cleaning and water-repelling properties of lotus leaves, offering potential applications for self-cleaning surfaces in architecture and transportation [89]. Biomimetic designs have also driven advancements in lightweight, strong, and durable composites that can replace traditional materials in aerospace and automotive manufacturing [90]. These materials reduce resource usage and enhance durability by emulating biological resilience, ultimately decreasing waste generation [91,92].

2.8.2. Nanotechnology for Enhanced Material Properties

Nanotechnology continues to play a pivotal role in advancing sustainable materials. In 2023, researchers utilized nano-engineering techniques to enhance materials' structural, thermal, and mechanical properties, making them more suitable for extreme applications [93–95]. For example, nanocellulose and graphene-based composites are being employed to improve sustainable materials' strength and thermal stability in sectors such as electronics and renewable energy [96,97]. These nanomaterials, characterized by their biodegradability, lightweight, and high tensile strength, are ideal for solar cells, batteries, and lightweight electronic components. The application of nanotechnology thus promotes sustainability by extending material longevity and performance, reducing the need for resource-intensive replacements [98].

2.8.3. Additive Manufacturing and 3D Printing

Additive manufacturing (AM), particularly 3D printing, has transformed sustainable material production by enabling precise usage and minimal waste. Researchers have explored using biodegradable bioplastics and recycled polymers in 3D printing, producing custom components for construction, healthcare, and consumer goods sectors [99–101]. Recycled PLA (polylactic acid), for example, has been utilized to create modular parts for construction, supporting a circular approach through disassembling and reusing these materials in other projects. Additionally, 3D printing facilitates on-demand production, reducing the need for large inventories and minimizing waste [102].

2.8.4. Closed-Loop Systems for Circularity

Implementing closed-loop systems has become a prominent trend in recent years, particularly in industries focused on sustainability, such as automotive, electronics, and fashion [103,104]. Researchers are developing materials designed for easy disassembly, recycling, or composting at the end of their life cycle, thereby supporting a circular economy [102,105]. In the automotive industry, for instance, recyclable thermoplastics are being engineered for easy disassembly, enabling the reuse of components in new vehicles. Similarly, in the fashion industry, biodegradable synthetic fibers facilitate garment breakdown and reintegration into the supply chain, reducing waste and conserving resources.

2.8.5. Sustainable Composite Materials for Renewable Energy

Innovations in sustainable composites for renewable energy applications have focused on incorporating recycled materials to enhance energy efficiency and sustainability. Researchers have developed composites made from recycled metals and polymers to construct wind turbine blades and solar panel frames, which offer higher durability and reduced weight compared to conventional materials [106]. These advances contribute to more efficient energy generation and reduced resource demand. Furthermore, sustainable battery materials, including recyclable and biodegradable electrolytes, are under active development to improve energy storage systems, further supporting the shift toward renewable energy sources [107,108].

Hence, various innovative approaches have propelled advancements in sustainable material design, including biomimicry, nanotechnology, additive manufacturing, and closed-loop systems. These developments reshape industries from construction and transportation to renewable energy and consumer goods by enhancing material performance, reducing environmental impact, and promoting a circular economy [105,109,110].

As regards the cost implications of adopting sustainable materials, Villagran et al. [111] examine cost-effective phase change materials in solar dryer technologies, highlighting their potential for sustainability and reduced environmental impact. Despite challenges in cost and technical complexity, the work underscores the role of innovation in making such materials economically viable for broader adoption.

Focused on thermal insulation, Ali et al. [112] discuss composite materials as affordable and sustainable options. It evaluates the economic benefits and environmental trade-offs, emphasizing the importance of choosing cost-efficient materials to optimize energy conservation.

The research by Du et al. [113] presents lifecycle cost analyses of lightweight cement mortar integrated with nano-additives. The study balances sustainability and economic feasibility, demonstrating how advanced materials can reduce both environmental and financial costs in construction projects.

Addressing construction and demolition waste, Zhang et al. [114] evaluate its sustainable reuse under a cost–benefit framework. It identifies barriers such as increased initial costs and emphasizes the long-term economic advantages of adopting these practices.

The construction industry significantly contributes to global carbon emissions, yet limited research quantifies the environmental impact of low-carbon materials used as structural members. Ali et al. [115] address the gap by evaluating the life cycle environmental impacts and economic aspects of two novel column types: concrete-filled aluminum alloy tubular (CFAT) and concrete-filled double-skin aluminum alloy tubular (CFDSAT) columns. A traditional concrete-filled steel tubular (CFST) column is also analyzed for comparison. All columns are designed with the same load-carrying capacity to ensure a fair comparison. Replacing the steel tube in CFST with an aluminum alloy tube in CFAT reduces weight by about 17%, and adopting the double-skin technique in CFDSAT leads to a 47% weight reduction. Life Cycle Assessment (LCA) results indicate that CFST and CFAT columns have nearly identical CO_2 emissions, 21% lower than those of the CFDSAT column due to their higher aluminum content. Life cycle cost analysis (LCCA) reveals that the total life cycle costs of the CFAT and CFDSAT columns are approximately 29% and 14% less, respectively, than those of the CFST column. A sensitivity analysis was conducted to assess how variations in data and assumptions affect the life cycle performance outcomes.

Table 8 abstracts the current status and the future trend of the studies conducted on sustainable material design.

Table 8. Current status and the studies conducted on sustainable material design.

Current Status	Future Trend	Domain	Reference
Biomimicry in material design, such as self-cleaning and water-repelling materials inspired by lotus leaves	Development of more biomimetic designs to create lightweight, strong, and durable composites for aerospace and automotive manufacturing	Architecture, transportation, aerospace, automotive	Dai and Chen (2023) [90]
Use of nanotechnology to enhance materials' structural, thermal, and mechanical properties	Continued use of nanotechnology for improving sustainability in electronics and renewable energy, focusing on biodegradability and performance	Electronics, renewable energy	Woo and Oh (2023) [93], Abdelzaher (2023) [94], Hultman (2024) [95]
Additive manufacturing (3D printing) using biodegradable bioplastics and recycled polymers	Advancements in 3D printing for sustainable production of modular parts, with a focus on reducing waste and promoting on-demand production	Construction, healthcare, consumer goods	Andanje et al. (2023) [99],Li, et al. (2024) [100],Bilal et al. (2024) [101]
Focus on closed-loop systems for circularity, including recyclable thermoplastics and biodegradable synthetic fibers	Increased development of materials designed for easy disassembly, recycling, or composting, supporting the circular economy in the automotive and fashion industries	Automotive, fashion, circular economy	Kara et al. (2022) [103],Rosca (2018) [104]
Development of sustainable composite materials for renewable energy, such as wind turbine blades and solar panel frames	Research into recyclable and biodegradable materials for energy storage systems to improve efficiency in renewable energy applications	Renewable energy, energy storage	Ahmed and Maraz (2023) [107], Aguilar Lopez (2024) [108]
Cost-effective phase change materials for solar dryer technologies	Further adoption of phase change materials in sustainable energy applications, focusing on cost reduction and environmental benefits	Renewable energy, thermal insulation	Villagran et al. (2024) [111]
Use of composite materials for thermal insulation	Development of affordable and sustainable composite materials to optimize energy conservation in construction	Construction, energy conservation	Ali et al. (2024) [115]
Evaluation of low-carbon materials used in structural members (CFAT vs. CFST)	Further studies on the environmental and economic impacts of alternative materials like CFAT and CFDSAT columns to reduce carbon emissions	Construction	Ali et al. (2024) [115]
Lifecycle cost analyses of lightweight cement mortar integrated with nano-additives	Continued research into balancing sustainability with economic feasibility in construction, using nano-additives to improve material performance	Construction	Du et al. (2024) [113]
Sustainable reuse of construction and demolition waste	Expanding the use of recycled materials in construction to minimize waste and improve cost-efficiency	Construction	Zhang et al. (2024) [114]

2.9. Literature Overview Review

Through the bibliometric analysis and based on the literature review for sustainable materials, some useful ideas and remarks are formulated for the readers:

- Sustainable materials such as bamboo and FSC-certified wood have a lower carbon footprint than traditional materials due to rapid growth and less energy-intensive extraction and processing processes. Green concrete and other alternative materials to traditional cement also have reduced carbon footprints due to the use of recycled materials and energy-efficient production technologies;
- Bamboo and FSC-certified wood are excellent examples of materials that come from renewable sources. Bamboo is the fastest-growing plant and can be harvested sustainably, while FSC certification guarantees that the wood is sourced from responsibly managed forests;
- Many sustainable materials, such as cellulose fibers for insulation or recycled plastic, are recyclable or biodegradable. This significantly reduces the volume of waste sent to landfills;
- Materials such as treated wood and green concrete are durable and resistant. Properly treated wood can last for decades, and green concrete offers similar durability to traditional concrete but with a reduced environmental impact;

- Green concrete and metal are materials that perform well in extreme conditions, offering resistance to high temperatures, humidity, and UV exposure. Bamboo is resistant to moisture and insects, making it suitable for various applications;
- Treated wood and certain types of cellulose fiber insulation are fire and insect-resistant, providing additional protection in construction;
- The initial cost of sustainable materials can vary. For example, bamboo may be cheaper than traditional wood, while materials such as green concrete may have a higher initial cost due to the advanced technologies required to produce them;
- Sustainable materials such as cellulose fiber insulation and green roofs offer significant long-term savings due to their energy efficiency and durability. These savings can offset the higher initial cost;
- Many governments and organizations offer financial incentives such as subsidies, discounts, tax exemptions, and other forms of financial support for the use of sustainable and energy-efficient materials;
- Many sustainable materials, such as VOC-free water-based paints and cellulose fiber insulation (used in interior design and construction), do not emit toxic substances and are safe for human health;
- The use of local materials, such as locally produced wood and bamboo, contributes to the development of the local economy by creating jobs and supporting local businesses;
- There are many certifications and standards for sustainable materials, such as FSC for wood, LEED (Leadership in Energy and Environmental Design) for sustainable construction, and Cradle to Cradle for recyclable and safe materials for human health.

These literature reviews underscore the growing emphasis on sustainability and eco-friendliness in materials science and engineering. Researchers aim to address pressing environmental challenges and pave the way for a more sustainable future by leveraging renewable resources, developing sustainable synthesis processes, and exploring innovative applications.

3. Systematic Analysis and Review for Published Studies and Research in Sustainable Materials Domain

3.1. General Statements

As mentioned in the paper, sustainable materials research and innovation have significantly increased with the increasing environmental issues of the community and the consideration of sustainable development as an urgent need in the world. Sustainable materials are designed to mitigate the environmental impact and improve resource efficiency. Industries, including construction, packaging, and automation sectors, must consider these. Academics, research scholars, policymakers, and practitioners must examine sustainable materials' evolution, current context, and future trends.

Bibliometric analysis is one of the best methods for mapping the landscape of scientific research. Bibliometrics is a branch of scientometrics that focuses principally on the quantitative study of scientific publications for statistical purposes [116]. These studies offer insight into the composition, movement, and behavior accruing to academic works and assist researchers in determining the influence of works in their discipline, recognizing specialized themes and areas of interest in their field, and understanding how the science areas communicate among themselves.

Few empirical studies have conducted bibliometric analysis of the various facets of sustainable materials. The study by de Sousa [117] using the Scopus database related to sustainable and/or eco-friendly polymers identified key themes, including sustainable materials, mechanical properties, and cellulose. This study further identified future research areas like geo-polymers and natural polymers. This study is limited to the Scopus database and the data related to sustainable and/or eco-friendly polymers.

In addition, Geng et al. [118] conducted bibliometric analysis in the context of sustainable design. This study highlighted the concept of sustainable design for users (SDfUs), which considers the entire life cycle of products from production to consumption. This study found that significant regional differences in research emphasis. Developed countries consider the importance of green building design, whereas developing countries consider end-of-life product design. This study only considers the articles from 1992 to 2019 using the Scopus database. In the same way, Det Udomsap and Hallinger [119] conducted a bibliometric analysis related to sustainable construction using the Scopus database from 2010 to 2020. This study found significant themes, including alternate materials, sustainable construction management, recycling, and social sustainability.

Most of these studies provide valuable insights into sustainable materials. Still, the Scopus database has certain limitations in analyzing data and does not consider the quality of the research contribution. Therefore, it is essential to consider the Web of Science database for the bibliometric analysis that includes quality papers, and analyzing will result in accurate outcomes.

Accordingly, this study bridges this research gap by conducting bibliometric analysis using the Web of Science and extending the scope of publications up to 2023. Accordingly, this study will highlight the latest modifications and trends and illustrate a comprehensive updated view. This study will inform the future directions of the research in sustainable materials and, more importantly, to achieve the objective of sustainable development.

This study conducts bibliometric analysis according to Zupic and Čater [120]. The present analysis considers search criteria including sustainable materials and only review articles published in English. This study excludes non-peer-reviewed sources such as book chapters, dissertations, editorials, and gray literature. This analysis was conducted using the Web of Science database. This database was chosen because of its extensive coverage of the indexed literature. This database is essential for studying citation patterns and research trends [121].

The selection criteria for the bibliometric analysis included publications that focus on sustainable materials, eco-friendly polymers, and related topics within the context of environmental sustainability. The search was limited to articles published between 1999 and 2023 to capture the field's historical evolution and recent advancements. Keywords such as "sustainable materials", "eco-friendly polymers", "biodegradable polymers", "green composites", and "renewable resources" were used to identify relevant publications.

3.2. Inclusion Criteria

The inclusion criteria for the review were as follows:

- Articles have to be published in peer-reviewed journals or presented at recognized conferences;
- Publications must address topics related to sustainable materials, including but not limited to sustainable design, eco-friendly polymers, biodegradable materials, and green composites;
- Only articles written in English were considered;
- Studies must provide comprehensive reviews relevant to the research field.

3.3. Data Analysis

The data analysis involved several stages. First, a comprehensive search was performed in the Web of Science (WoS) databases using predefined keywords and criteria. The retrieved articles were screened for relevance based on their titles, abstracts, and keywords. The articles were then screened to remove duplicates, and the remaining articles were later checked for relevance by going through the full texts of the respective articles.

While analyzing the trends, authors, organizations, and themes in the field, publication counts, citation analysis, and keyword co-occurrence were the main bibliometrics tools used. Specific software such as Biblioshiny 4.0 was used for data visualization and network analysis, giving a complex overview of the field of research. To obtain conclusive findings in the above study questions, the outcomes were summarized to show the trends in sustainable materials research, the current issues, and the future in this field.

3.4. Main Information

In Appendix A, the database from Table A1 consists of 545 documents from 1999 to 2023 published in 299 sources. The annual growth rate of publication was 17.86%, which is an impressive growth that depicts scholarly publications' evolution and dynamic growth over two and half decades. The average age of the document is 3.61 years, and the average citation per document is 51.9, considered the most crucial theme. The system identified 2846 keywords and 1813 author keywords. This database illustrates collaboration among authors that exhibits an average of 4.68 co-authors per document; the international co-authorship percentage is 37.43%. This dataset is vital in helping different scholars understand trends and events in various academic disciplines, and this study will conduct an analysis based on this database.

4. Results and Findings

4.1. Trend Analysis

A trend analysis of publications related to "sustainable materials" publications from 1999 to 2023 is depicted in Table A2. This analysis illustrates an incessant publication in two and half decades. The first two articles published in 1999 were "Photonic crystals in the Optical Regime—Past, present, and future" [122] and "The Reinforcement of Dentures" by Jagger et al. [123]. Then, from 2000 to 2002, there were no publications, and the subsequent fluctuation of publications was around one or two publications per year. However, after 2003, there was a gradual increase in publications with an occasional decrease in specific years. From 2019, there was a significant increase in publications compared with 2018, with 81% growth of publications, and afterward, there was continuous growth of review article publications in the next 4 years. In 2023, it depicts the peak of publications with 155 articles. This trend illustrates the engagement and productivity of academics related to "Sustainable materials" review publications.

4.2. Source Analysis

4.2.1. Bradford's Law

Bradford's law is essential in analyzing core journals of a field of study. Accordingly, all documents are divided into three groups, and the number of documents that belong to journals in each group is identified.

This will identify a large number of publications that fall to a few journals, which are considered core sources that are most influential in the research area. The second group consists of a moderately large number of sources called the middle zone. The third group consists of many journals that publish few publications. This identification is essential to obtain ideas about the distribution of scientific knowledge.

Bradford's law is used in "sustainable materials" research. Zone 1, which is the core zone, consists of 24 journals, including "Polymers", "Materials", and "Construction and Building Materials", which have a higher frequency of publication rate. Zone 2, the middle zone, consists of 96 journals, and Zone 3 consists of 179 journals. These data show the key journals related to "sustainable materials" research in which the findings are disseminated (Table A3).

4.2.2. Source Impact Analysis

The highest-cited journal in this database is "Nature", with 1737 total citations (Table A4). "Progress in Polymer Science" and "ACS Sustainable Chemistry & Engineering" are both third and second in citations demonstrating robust impact, with h-indices of 4 and 5. According to citations, the "Polymers" journal is fourth-ranked, with the highest h-index of 11. Other journals also have different citations, h-index, and m-index, contributing to research development in the "sustainable materials" research field.

4.3. Authors' Analysis

4.3.1. Lotka's Law

Lotka's law is an essential concept in bibliometric analysis that examines the distribution of the scientific productivity of authors [124]. Lotka's law noted that a small number of authors publish many articles, which contributes to a higher percentage of the literature, whereas other authors contribute few papers (Table A5). This is important to identify key authors in the subject field. This depicts inverse square distribution. Most authors (95% of them) publish only one publication. The number of authors increases proportionally as the number of documents decreases. Five authors wrote more than five documents, and only one wrote six. Siengchin S. published six papers related to "sustainable materials."

4.3.2. Authors' Impact Analysis

Williams C.K. was the highest-cited author from the U.K., with 1773 citations per two publications. Romain C. and Zhu Y., the second-highest cited authors from the U.K., have 1737 citations for one publication. Titirici MM has the highest h-index in the top ten cited authors. William C.K., Romain C., and Zhu Y. published "Sustainable polymers from renewable resources", which was the highest-cited article with 1737 citations (Table A6).

4.4. Country Analysis

The United Kingdom has the highest number of citations, with 3643 citations, and scored the second-highest average article citations, with 117.5. Similarly, the USA has the second-highest total citations for 148 articles, the third-highest number of publications, and ranks fourth in average citations. According to the average citations, Saudi Arabia records the highest amount with 138.3, which ranked eighth according to citations (Table A7). This analysis exhibits the third rank according to the total citations obtained by India, with 2171 citations and 192, the highest number of publications. This table illustrates that most cited research is concentrated on developed countries, but different countries contribute to advancing knowledge in "sustainable materials" research.

4.5. Keyword Analysis

This study examines the word frequency of scholarly articles in materials science and sustainability, as depicted in Table 9, revealing several key themes and areas of focus. The most common term is "sustainable materials", which focuses on materials and technologies to lessen the exploitation of natural resources and the adverse impact on the environment and ensure the availability of sustainable resources. This is particularly evident from the higher usage frequency of terms related to sustainability, including "sustainability", "environmental", and "life cycle assessment", which may signify a collective effort within the research context of striving to tackle such ecological issues through advancements in materials and designs.

Furthermore, the evaluation also points out that much emphasis has been placed on particular materials and technologies for sustainable growth. Uses of terms like "cellulose", "nanocellulose", "lignin", and "biopolymers" suggest a lean towards bio-based materials that are derived from renewable resources and are likely to be the replacements of traditional petroleum-based plastics. Furthermore, the use of such terms as "natural fibers", "polysaccharides", and "biochar" indicates a growing trend of using natural materials in various areas, such as the construction and production of water purification equipment. The usage of such descriptor words like "concrete", "compressive strength", and "3D printing" shows the strive to improve the mechanical of sustainable material and manufacturing technology, which is evidence of the interdisciplinary and integrated approach to tackling sustainable problems across numerous sectors.

Table 9. Author keyword frequency analysis.

Keywords	Occurrences
sustainable materials	72
sustainability	48
mechanical properties	22
cellulose	18
adsorption	15
biopolymers	15
nanocellulose	14
sustainable	12
circular economy	11
natural fibers	11
durability	10
environmental impact	10
lignin	10
biocomposites	9
concrete	9
polysaccharides	9
3D printing	8
compressive strength	8
life cycle assessment	8
water treatment	8
biochar	7

4.6. Thematic Analysis

4.6.1. Thematic Map

Figure 1 depicts the thematic analysis of “sustainable materials”. This figure clusters the key terms related to sustainable materials. The thematic map indicates that 10 clusters fall into four quadrants according to the relevance and importance of themes.

Clusters 1, 2, and 3 are motor themes that are highly relevant and highly developing themes. Research scholars need to investigate these themes further. Cluster 1 is labeled as “sustainability”, which includes themes such as “sustainability”, “biopolymers”, “circular economy”, and “environmental impact”. These terms strongly consider environmentally friendly materials, practices, and technology. Secondly, Cluster 2 is labeled as “sustainable materials”, which includes themes such as sustainable materials”, “mechanical properties”, “nanocellulose”, and “natural fibers”. This emphasis on the characteristics of sustainable materials, including strength, durability, and biodegradability. The third cluster is labeled as “cellulose”, which includes themes such as “cellulose”, “lignin”, “biocomposites”, and “self-healing”. This cluster is devoted to the importance of using cellulose-based materials as the critical component in developing and implementing sustainable solutions and the potential uses of the material.

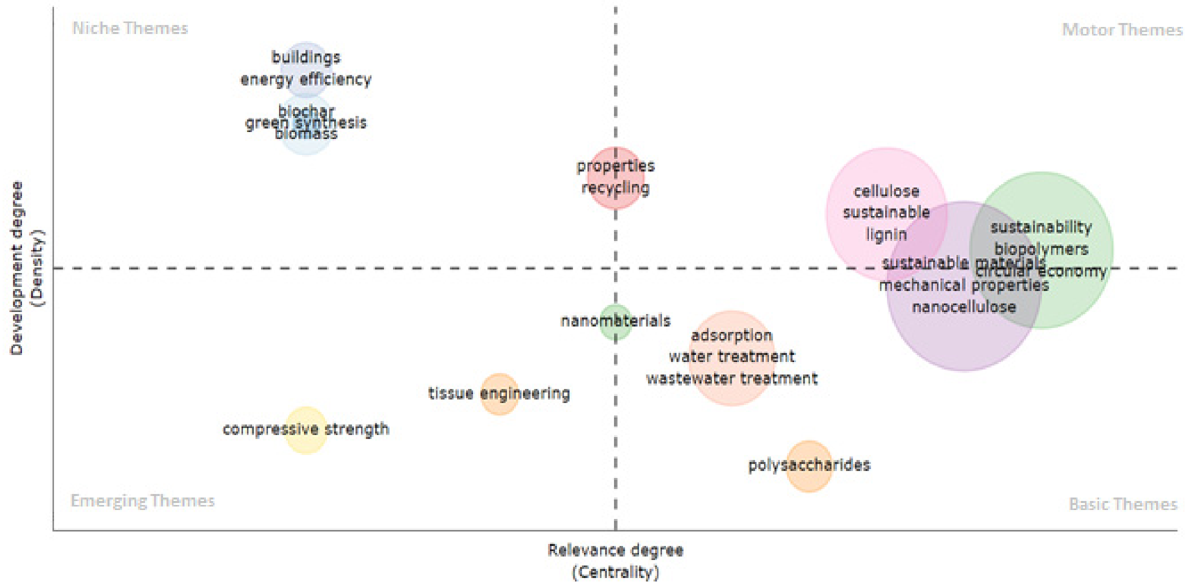

Figure 1. Thematic map.

Clusters 4 and 5 consider emerging themes that are of low relevance and low development. These also need to be considered by research scholars to investigate further. Cluster 4, called "tissue engineering", targets all terms related to tissue engineering, a specialized area of materials science concerned with developing materials designed for functions in biological fields, including tissue regeneration and drug delivery systems. Consequently, Cluster 5, entitled "compressive strength", comprises terms concerned with material properties and performance, similar to those found in the previous clusters, while reflecting a distinct interest in the mechanosensitive attributes of materials, especially their compressive strength.

Cluster 6 is considered a basic theme that is highly relevant and of low development. Research scholars have considered these adequately, and there is no need for further exploration. Cluster 6, marked as "adsorption", contains such terms as "adsorption", "water treatment", and "wastewater treatment", which indicates the major interest in materials and technologies for purification processes and water treatment.

Clusters 7, 8, and 9 are niche themes that are of low relevance and highly developed. Research scholars have considered these not adequately explored and need further exploration. Cluster 7, characterized by the label "buildings", includes terms more linked to building materials and energy in an environmentally sustainable built environment and impulse construction technologies.

Cluster 8 is identified as "biochar", and the keywords used in this cluster include "biochar" and "biomass", indicating that this source largely targets the use of sustainable carbon-based materials in carbon storage and for enhancing soil quality.

Cluster 9, named "green synthesis", includes words related to the synthesis of materials with low environmental impact, which is indicative of the trends to make the synthesis process as eco-friendly as possible.

Cluster 10 is emerging to basic themes. Tagged as "nanomaterials", it contains terms associated with nanotechnology and nanomaterials, pointing to the continuous implementation and innovation of nanoscience and nanotechnology for sustainable uses and advancements.

In general, the proposed thematic maps offer a clear and detailed insight into the significant topics and branches of study within the "sustainable materials" domain, which, thus, could be used for further identification and investigation of specific issues and trends.

4.6.2. Thematic Evolution

The thematic evolution in sustainable materials aims to indicate shifts in the focus of the research area over time to introduce newer trends. The procedure of analyzing the keywords of Scopus and Web of Science indicates several trends and their evolution from the end of the 1990s to 2023 (Figure 2). The overall literature coverage began with introducing the adsorption and water treatment aspects. To start with, enhancements to basic adsorption and water treatment concepts invited much attention to nanomaterial and wastewater treatment processes. Such early themes set the foundation for more specific issues, such as using non-wood materials and Architectural Sustainable Development, which appeared in the early 2000s.

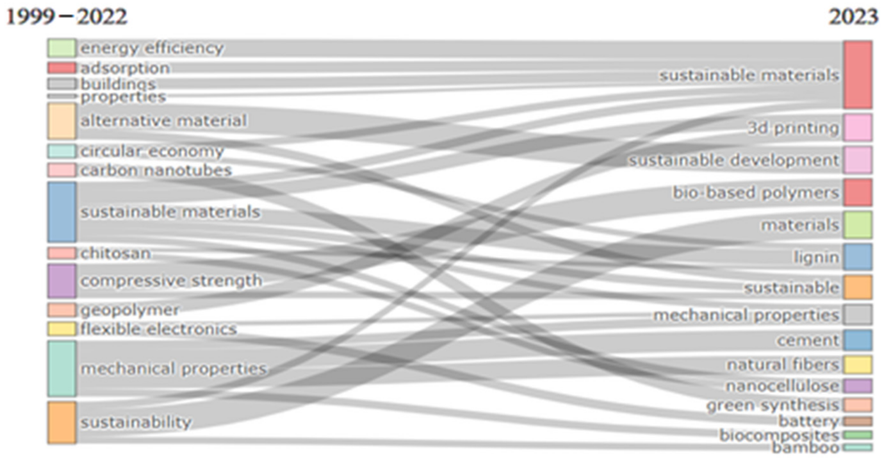

Figure 2. Thematic evolution.

The importance of studying sustainable materials gradually extended to the two areas concerning the actual use of such materials across different sectors. For instance, research on building materials and energy revisited arose to discuss the importance of green content in constructions and their implications for increasing energy efficiency. Analyzing the topic distribution, one can conclude that scientific publications in carbon nanotubes and green synthesis showed an increased interest in further developments of more sophisticated materials and sustainable fabrication techniques.

In recent years, the thematic focus has shifted to more specialized and advanced topics. Notably, the intersection of mechanical properties with biocomposites, natural fibers, and cement indicates a deepening interest in the structural applications of sustainable materials. Terms like 3D printing and Life Cycle Assessment reflect the integration of cutting-edge technologies and holistic environmental evaluations in developing sustainable materials.

The evolution also underscores the increasing relevance of concepts such as circular economy, which ties sustainable materials to broader economic and environmental systems. Linking circular economy themes with lignin, green chemistry, and essential oils demonstrates an interdisciplinary approach that blends materials science with ecological and economic sustainability.

The analysis further highlights the growing importance of biodegradable polymers, green composites, and nanocellulose, which are now central to the discourse on sustainable materials. The prominence of keywords such as biopolymers, additive manufacturing, and self-healing packaging illustrates the innovative directions in which the field is heading. These advancements are crucial for developing materials that meet performance requirements and align with environmental sustainability goals.

4.7. Co-Citation Analysis

Co-citation analysis is a method used to determine the relationship between documents based on the frequency with which they are cited together. This approach helps identify a research field's intellectual structure and uncover key themes and influential works. In this research, we present a co-citation analysis of sustainable materials. These data comprise authors, their clusters, and network analysis coefficients, which include betweenness centrality, closeness centrality, and PageRank coefficients. This information will be employed to diagnose the scholars' co-citation patterns and identify significant clusters in the broader sphere of sustainable materials.

The co-citation analysis underlined four different clusters (Table 10).

Table 10. Co-citation analysis.

Cluster	Label	Authors
Cluster 1	Sustainable Polymers and Green Chemistry	Eperon et al. (2015) [125], Shivani and Poladi (2015) [126], Zhuang et al. (2015) [127], Anastas and Eghbali (2010) [128], Gandini et al. (2016) [129], Zhu et al. (2016) [130]
Cluster 2	Biodegradable Polymers and Natural Fibers	Moon et al. (2011) [131], Laurichesse and Avérous (2014) [132], Upton and Kasko (2016) [133]
Cluster 3	Nanocellulose and Nanocomposites	Klemm et al. (2011) [134], Klemm et al. (2018) [135], Habibi and Sheibani (2010) [136], Habibi (2014) [137], Nechyporchuk et al. (2016) [138]
Cluster 4	Construction Materials	Faruk et al. (2012) [139], Ramamoorthy et al. (2015) [140], Mohammed et al. (2015) [141]

Cluster 1 is named Sustainable Polymers and Green Chemistry. Eperon et al. (2015) [125], Shivani and Poladi (2015) [126], Zhuang et al. (2015) [127], Anastas and Eghbali (2010) [128], and Gandini et al. (2016) [129] are the main authors in this cluster. Zhu et al. (2016) [130] have a high betweenness centrality of 178.72, demonstrating his position as a bridge from one area of research to another within this cluster. Deserving special attention, Gandini et al. (2016) [129] have a high PageRank of 0.0162 and a betweenness centrality equal to 78.36, thus signifying his importance in the "green chemistry" field. More broadly, this cluster underlines the relevance of building green chemistry processes and materials to minimize the environmental impact of industry-related activities.

Cluster 2 is named Biodegradable Polymers and Natural Fibers. Moon et al. (2011) [131], Laurichesse and Avérous (2014) [132], and Upton and Kasko (2016) [133] are the key authors in this cluster. Laurichesse and Avérous (2014) [132] have a high betweenness centrality of 47, demonstrating her position as a bridge from one area of research to another within this cluster. Deserving special attention, Moon et al. (2011) [131] have a high PageRank of 0.0502 and a betweenness centrality equal to 78.36, thus signifying their importance in the "sustainable materials" field. This cluster is focused on techniques and materials that, when discarded, can be processed to leave minimal environmental impact, especially shifting away from synthetic polymers and plastics.

Cluster 3 is named Nanocellulose and Nanocomposites. Klemm et al. (2011) [134], Klemm et al. (2018) [135], Habibi and Sheibani (2010) [136], Habibi (2014) [137], and Nechyporchuk et al. (2016) [138] are the core authors in this cluster. Nechyporchuk et al. (2016) [138] have a high betweenness centrality of 28.8 and a high PageRank of 0.028, demonstrating their position as a bridge from one area of research to another within this cluster. Habibi and Sheibani (2010) [136] and Habibi (2014) [137] also pioneered the theme of nanocellulose in 2010 and 2014, significantly for the principles and utilization of sustainable materials. This cluster outlines the prospect of increasing efficacy and, specifically, reducing the adverse effects of material usage through nanotechnology.

Cluster 4, Sustainable Construction Materials, focuses on alternative materials, recycling, and waste reduction. The central authors were identified as Faruk et al. (2012) [139], Ramamoorthy et al. (2015) [140], and Mohammed et al. (2015) [141]. The four researchers published articles in three journals. Faruk et al. (2012) [139] have the highest betweenness centrality of 427.77 and PageRank of 0.0338, which emphasizes his significant impact on the content related to sustainable construction. This cluster highlights the need to manufacture constructive materials that would be efficient and environmentally mindful, which is essential in one of the most resource-consuming sectors.

4.8. Content Analysis

Zhu et al. [142] introduce a novel class of sustainable materials with enhanced properties. Published in a high-impact journal, it employs advanced experimental techniques and offers groundbreaking insights into eco-friendly materials. Despite its significant contributions, the study may lack a comprehensive life cycle analysis to understand these materials' environmental impact fully. A notable research gap is the need to evaluate these novel materials' long-term sustainability and scalability in industrial applications.

Rhim et al.'s [143] comprehensive review discusses the progress in developing biodegradable polymers and their applications. It provides an extensive overview and systematic categorization of various biodegradable polymers. However, the article offers limited discussion on these materials' economic viability and market adoption. Future studies should focus on biodegradable polymers' cost-effectiveness and real-world performance in commercial products to address this gap.

Titirici et al. [18] focus on the sustainable synthesis of carbon materials from biomass, highlighting innovative methods for converting biomass into high-value carbon materials. While the review critically examines various synthesis routes, discussing their efficiency and sustainability, it may not cover the latest advancements after 2015. Updated reviews incorporating recent technological advancements and their practical applications in industry are needed to fill this gap.

Thakur et al. [144] explore the development of sustainable polymers for various applications, introducing new polymeric materials with potential environmental benefits. Although the study employs a combination of experimental techniques to develop and test the materials, it might lack an in-depth analysis of the environmental lifecycle of the produced polymers. Further investigation is required into these polymers' long-term ecological impacts and lifecycle assessments.

Yan et al. [145] investigate the use of sustainable composites in engineering applications, providing insights into their mechanical properties and potential uses. While the study uses rigorous testing to evaluate the composites' performance under various conditions, it could benefit from a broader range of testing conditions to fully validate the composites' performance. More comprehensive studies are needed to explore these composites' durability and practical applications under various environmental conditions.

Qasem et al. [146] discuss innovative water treatment methods using sustainable materials, introducing novel materials for efficient and eco-friendly water purification. However, the study includes limited field studies to validate laboratory results in real-world settings. Future research should focus on large-scale implementation and long-term effectiveness of these materials in diverse water treatment scenarios.

Stürzel et al. [147] offer an in-depth analysis of the development and applications of sustainable polymers, thoroughly examining advancements and challenges in the field. While the review is a key reference for researchers, it might not fully address the economic aspects of sustainable polymer production. More studies on sustainable polymer technologies' cost–benefit analysis and commercial scalability are needed to fill this gap.

Alcázar-Alay and Meireles [148] explore using sustainable materials in food packaging, highlighting the potential of biopolymers to enhance food packaging sustainability. The study may lack comprehensive testing under various storage and transportation conditions despite its contributions. Further research should investigate the performance and safety of biopolymer packaging in real-world scenarios, including long-term storage studies.

Krauss and De La Rue [122] discuss the application of sustainable materials in quantum electronics, pioneering the integration of sustainable materials in advanced electronic applications. While it remains foundational, it may not cover the latest advancements in quantum electronics and sustainable materials integration. Updated research exploring recent developments and potential future applications in quantum electronics is needed.

Tao et al. [149] present innovative research on advanced sustainable materials with unique properties. They introduce new materials with significant potential for high-performance applications. However, the study could benefit from more comprehensive testing across a wider range of applications. More research should be carried out on the effective utilization of these advanced materials and the testing of the materials in practical experiments and real-life situations.

Below is a critical analysis of the selected articles, which states the following: despite the significant advances in the full-spectrum approach to the design of sustainable materials, several research gaps still need to be addressed.

Potential areas of improvement include understanding the environmental effects in the long run, the business feasibility of new materials, the possibility of implementing new materials at a larger scale, and the performance of the new materials in practical applications. Filling these gaps through a systemized and holistic approach involving multiple academic fields will be essential in enhancing sustainability goals.

Based on the analysis carried out in the present research, in this part of the subsection, responses and implications of the six research fields highlighted in Section 1 are declared.

4.8.1. Impact on the Environment

Most studies, including Zhu et al. (2016) [142] and Thakur et al. (2014) [144], emphasize the eco-friendly nature of sustainable materials but lack a complete lifecycle analysis to evaluate the environmental impact from production to disposal. The following responses are suggested to reduce the economic effects:

- Implement comprehensive lifecycle assessments (LCA). Conduct cradle-to-grave LCAs to capture the carbon footprint, resource consumption, and disposal impacts;
- Integrate biodiversity and ecosystem impact studies. Examine how sourcing these materials affects biodiversity and whether disposal methods are sustainable;
- Introduce renewable source evaluation. Prioritize materials sourced from renewable resources, minimizing the depletion of non-renewable assets.

These responses have the following implications:

- Holistic environmental understanding. Lifecycle analysis provides a complete view of environmental impacts, ensuring that sustainable materials meet environmental standards across their entire lifecycle;
- Support for policy development. Results from LCAs can inform policy recommendations, encouraging regulatory bodies to establish standards for sustainable materials;
- Enhanced brand image for companies. Using materials validated by LCA improves corporate sustainability credentials, appealing to environmentally conscious consumers.

4.8.2. Performance and Durability

Yan et al. (2014) [145] and Tao et al. (2012) [149] highlight the need for comprehensive materials testing in diverse conditions to ensure durability, resilience, and functionality over time. The following responses are suggested to improve performance and durability:

- Standardize durability testing across conditions. Test materials under various stressors such as extreme temperatures, UV exposure, and mechanical wear to validate performance;
- Establish industry-specific standards. Develop benchmarks for durability and resilience based on specific application requirements (e.g., construction, electronics);
- Invest in long-term field studies. Conduct real-world trials to observe material performance in practical, uncontrolled environments over extended periods.

These responses have the stated below implications:

- Enhanced material reliability. Rigorous, standardized testing ensures that materials perform as expected, reducing the likelihood of premature failure or additional maintenance;
- Broadened industry applications. Proven durability across conditions can open up new applications for sustainable materials in industries that demand high performance;
- Higher consumer trust. Materials with demonstrated reliability gain trust from consumers and businesses, promoting wider adoption.

4.8.3. Health and Safety

Alcázar-Alay and Meireles (2015) [148] address some aspects of health and safety but lack comprehensive testing on emissions, indoor air quality, and social impacts such as ethical sourcing. To improve health and safety, the following responses are suggested:

- Conduct toxic emission tests and indoor air quality studies. Analyze emissions to ensure materials do not release harmful chemicals over time, especially in indoor environments;
- Promote ethical sourcing practices. Implement fair labor standards and source materials in ways that support local economies and social equity;
- Introduce Social Sustainability Certifications. Develop certifications recognizing socially and ethically produced materials, allowing consumers to make informed choices.

These responses have mentioned the following implications:

- Enhanced consumer health. Addressing health and safety concerns reassures consumers that sustainable materials contribute to a safe, toxin-free environment;
- Increased ethical transparency. Certifications for social sustainability increase transparency, enabling consumers and companies to support ethical production practices;
- Positive social impact. Supporting local economies and fair labor improves the social sustainability footprint, aligning with corporate social responsibility goals.

This multi-faceted approach to analyzing sustainable material studies and proposing responses creates a balanced framework that comprehensively addresses environmental, economic, durability, and social issues. Implications include the following:

- Interdisciplinary insight. By integrating responses from environmental science, economics, engineering, and social responsibility, the approach ensures sustainable materials meet high standards across multiple dimensions;
- Strategic decision-making for stakeholders. Researchers, policymakers, and businesses benefit from evidence-based insights, enhancing strategic decision-making regarding sustainable material development;
- Accelerated progress toward sustainability goals. Addressing these gaps methodically brings sustainable materials closer to mainstream adoption, advancing broader sustainability objectives.

5. Discussion

The analysis of the current status and future trends of the scientific literature for seven sustainability-related materials categories shows that these categories have a particular distribution among the domains (Table 11). Thus, the weight of sustainability-related materials categories among the 15 domains is as follows: eco-friendly materials (53.33%), sustainable applied materials (46.66%), green materials (40%), sustainable materials (33.33%), alternative materials (26.66%), material recycling and material recovery from complex products (26.66%), and biomaterials (20%).

By using the syntheses from Section 2, we generated a comprehensive image of the main developments and innovations in the sphere of sustainable materials as well as the prospects for the development of research related to this essential subject of sustainable development.

Concerning the analysis of the number of publications and citation frequency of the selected articles on sustainable materials, an increase and steady development have been noted within the last 10 years. The quantitative distribution of the themes from the Web of Science databases for 1999–2023 shows that adsorption and water treatment have been the great pioneers that opened the path for more focused subjects such as biodegradable polymers, nanocellulose, and green composites. This progression speaks to the growing expansion and complexity of understanding sustainable materials.

Table 11. Distribution of the sustainability-related materials categories among the domains.

Domain	Sustainability-Related Materials Categories						
	Sustainable Materials	Green Materials	Biomaterials	Eco-Friendly Materials	Alternative Materials	Material Recycling and Material Recovery from Complex Products	Sustainable Applied Materials
Construction	✓*	✓		✓	✓		✓
Product design		✓	✓	✓		✓	
Energy	✓			✓			✓
Environmental conservation and protection	✓			✓			✓
Electronics		✓	✓				✓
Packaging		✓		✓			
Art, furniture, and interior design				✓	✓		
Medicine			✓				✓
General industries	✓	✓					
Manufacturing					✓	✓	
Clothing				✓			
Education					✓		
Recycling						✓	
Aerospace							✓
Robotics							✓
Plastics industry				✓			
Waste management						✓	
Automotive		✓					
Urban planning	✓						

* The checkmark indicates that the sustainability-related materials category is used in the domain, whereas the empty cell shows that the sustainability-related materials category is not employed in the domain.

Since clusters determine focus areas within the central area of study, they help organize knowledge. Cluster 1 of the critical research areas classifies polymers and green chemistry as crucial for developing eco-friendly chemical procedures. The second cluster consists of biodegradable polymers and natural fibers, for which there are constant initiatives to lessen the utilization of synthetic polymers. As Cluster 3 focuses on nanocellulose and nanocomposites, it also tolerates the concept of nanotechnology to improve the characteristics of materials. Last, Cluster 4 examines the capable and efficient construction of sustainable construction materials where the industry has improved its practices to include eco-friendliness.

This is further elaborated in the co-citation analysis to show the internal connectivity of the research field, revealing the significant authors and the topics in sustainable materials. For instance, scholars such as Zhu Y. and Anastas P. have been acknowledged for their best work in green chemistry and sustainable polymers. The high Betweenness Centrality and Page Rank indicate the strategic position of these authors in bridging the gap between distinct parts of the academic sphere and, more importantly, defining the direction of research within the specialty.

Examining the count of articles published in academic journals, there is a clear pattern of academic productivity over time with an increased incline in recent years. This is evidenced by more papers published in sustainable materials research as research and development companies work to find sustainable solutions to environmental problems. Looking at countries, once again, some of the most prominent contributors include the United States of America, the United Kingdom, India, China, and Germany, among others, which confirms that this subject is a truly international field of research and study.

Still, some of the research gaps are as follows: despite the rising interest in new materials, much of the research lacks sufficient life cycle analyses that describe potential effects over their usage life cycle. Furthermore, there is a need for more applications and case studies to support existing laboratory absorption values, specifically in water treatment and biodegradable polymers. Economics and market uptake of these sustainable materials also present areas of investigation aiming to establish a sound environment for their scaling.

6. Conclusions

The paper focuses, firstly, on a comprehensive discussion of current status and future trends in the scientific literature for seven sustainability-related materials categories, such as sustainable materials, green materials, biomaterials, eco-friendly materials, alternative materials, material recycling and material recovery from complex products, and sustainable applied materials. Secondly, it conducts a bibliometric analysis of 545 studies on sustainable materials that were published in 299 sources between 1999 and 2023 and underlines the challenges and implications with reference to the six research fields earlier stated.

This review of sustainable materials research highlights progress, limitations, and future directions. As sustainable materials transition from foundational research to application-focused studies, recent advancements in biodegradable polymers and nanocellulose demonstrate the field's responsiveness to pressing environmental concerns. Bibliometric analysis has helped identify key themes and influential contributions, providing insights into the field's knowledge base and informing applied research.

6.1. Key Takeaways and Observations

The main takeaways and observations are as follows:

1. Environmental impact and carbon footprint. Sustainable materials like bamboo and FSC-certified wood have significantly lower carbon footprints than traditional materials due to their rapid growth cycles and less energy-intensive extraction processes—innovations such as green concrete use recycled materials and energy-efficient production techniques, reducing environmental impact;
2. Renewability and resource conservation. Materials such as bamboo, FSC-certified wood, and cellulose fiber are renewable resources. Bamboo proliferates and can be sustainably harvested, while FSC certification ensures responsible forestry practices. These materials reduce the strain on non-renewable resources and align with circular economy principles;
3. Recyclability and waste reduction. Many sustainable materials, such as cellulose insulation and recycled plastics, are either recyclable or biodegradable, thus lowering landfill contributions. Recyclable materials like treated wood and green concrete offer durability while ensuring reduced waste and supporting long-term sustainability;
4. Performance in extreme conditions. Sustainable materials such as green concrete, bamboo, and metal composites demonstrate durability and performance under extreme conditions, including resistance to high temperatures, humidity, and UV exposure. These properties make them suitable for applications that require robustness and longevity;
5. Economic considerations and financial incentives. Although the initial costs of sustainable materials can vary—some, like green concrete, are more expensive due to advanced production technologies—the long-term savings from durability and energy efficiency can offset higher initial investments. Additionally, governments and organizations offer financial incentives, such as tax breaks and subsidies, to support the adoption of sustainable materials;
6. Health and safety benefits. Materials such as VOC-free water-based paints and cellulose fiber insulation are safer for human health as they do not emit toxic substances, making them suitable for interior use in construction and design. Sustain-

able materials contribute to healthier living environments and reduced exposure to harmful chemicals;

7. Local economic development. Using locally sourced sustainable materials, such as regional wood or bamboo, boosts local economies, creating jobs and supporting small businesses. This local focus also minimizes transportation-related carbon emissions;
8. Certifications and standards for quality and environmental responsibility. Certifications, such as FSC for wood, LEED for sustainable buildings, and Cradle to Cradle for recyclable materials, ensure quality, safety, and minimal environmental impact. These standards provide benchmarks for sustainable practices across industries.

6.2. Current Limitations and Future Directions

The limitations of the research are detailed below:

- Cost and accessibility. Sustainable materials can have higher initial costs, posing a barrier to widespread adoption. Addressing these costs through production efficiency and scaling technologies will be essential;
- Recycling and disposal challenges. While many sustainable materials are recyclable, complex processes like composite recycling or bio-based material degradation remain challenging and costly;
- Limited large-scale testing. Field testing for new materials is limited, which impacts the understanding of their long-term durability and performance under real-world conditions.

Future research and development directions are described next:

- Lifecycle analyses. Conducting comprehensive lifecycle assessments of sustainable materials to evaluate long-term environmental impact is essential;
- Field testing and cost–benefit analysis. Further large-scale testing and complex cost–benefit assessments will help establish the feasibility of these materials and support their scaling into broader applications;
- Stakeholder engagement. Increased cross-disciplinary collaboration involving scientists, manufacturers, policymakers, and environmental organizations is needed to support sustainable development and adoption of advanced material technologies.

Sustainable materials represent an intersection of environmental responsibility, economic feasibility, and technological innovation. Continued research and development in this field—focused on reducing environmental toxicity, conserving resources, and optimizing energy consumption—will be critical in achieving a harmonious relationship with the ecosystem. Future advancements in composite materials and other innovations promise to create durable, high-performance alternatives that meet the needs of modern industry while reducing ecological footprints.

Analyzing the articles on sustainable materials for critical evaluation develops an understanding of the progress and limitations in the research domain. The transition from basic research to specific areas, such as biodegradable polymers and nanocellulose, that are specific to present environmental issues is exhibited as the field's development. The bibliometric analysis identifies significant themes and the most influential authors in sustainable materials, which provide deep insights into the state of knowledge and directions in the specific academic field and applied research.

In conclusion, sustainable materials are materials with low environmental impact, coming from renewable, recyclable, or natural resources. They are "friendly" materials with the environment. The meaning of their realization and use resides in the following advantages:

- Aims to reduce toxicity on humans and the environment;
- Contributes to the economy of raw materials;
- Aims to reduce pollution due to toxic gas emissions or residues associated with the production and processing of materials;
- Take into account the energy economy;

- They can be reprocessed to obtain other materials.

Using sustainable materials must lead, under the conditions of satisfying human society's need for comfort and progress, to a healthy relationship with the ecosystem. The development of sustainable materials has to be seen as an overall problem related to the entire ecosphere, involving the following:

The development of materials in which the physical, chemical, mechanical, thermal, and/or functional properties are improved and implemented so that they come to the support of man;

- Harmonious coexistence with the ecosphere by minimizing the negative effects produced on the natural environment;
- Optimizing existing technologies and/or applying other "clean technologies" to ensure healthy living conditions in harmony with nature.
- At the same time, sustainable materials must be designed to be "friendly" not only to the environment but also to the people. This double requirement is not always easy to fulfill.

A solution developed in recent years concerns the creation of different categories of composite materials. Composite materials comprise at least two distinct components, offering superior properties to the individual materials. These components include a matrix and a reinforcement, with the matrix usually being polymeric, metallic, or ceramic, and the reinforcement in the form of fibers, particles, or flakes. The properties of composite materials include high strength, light weight, corrosion resistance, durability, and fatigue resistance. They find applications in various industries, including construction, aerospace, renewable energy, healthcare, automotive, sports, recreation, etc.

However, composite materials have challenges, such as high production costs, complex manufacturing processes, and difficulties repairing and recycling them. However, continuous innovations in this field promise to bring new solutions for the development of more sustainable and efficient products and structures in the future.

Several researchers and experts in the field have gained severe ground by proposing innovative materials that reduce the environmental impact and improve resource use efficiency. However, several factors need to be studied to further capitalize on these materials and to reduce some limitations related to the disadvantages initially created by the use of these materials. The main recommendations for improving the new materials in the future are the need for proper life cycle analyses, further large-scale field testing, and complex cost–benefit assessments to ascertain the stability and feasibility of new materials. In addition, stakeholder engagement and cross-disciplinary collaboration would be more important for supporting the environmental sustainability of advanced material technology.

In sum, the progress in sustainable materials has been impressive, and the suggested conclusions will help avoid the perceived gaps, which will be pivotal for the ongoing advancement and deployment of these materials into global sustainable development initiatives.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Main information for the bibliometric analysis.

Timespan	1999–2023
Sources (Journals, Books, etc.)	299
Documents	545
Annual Growth Rate %	17.86
Document Average Age	3.61
Average Citations Per Doc	51.9
References	74,434
DOCUMENT CONTENTS	
Keywords Plus (ID) Author's Keywords (DE)	2846 1813
AUTHORS	
Authors Authors of Single-Authored Docs	2374 21
AUTHORS COLLABORATION	
Single-Authored Docs Co-Authors Per Doc International Co-Authorships %	21 4.68 37.43

Table A2. Publications number evolution.

Year	Articles	Year	Articles	Year	Articles	Year	Articles
1999	3	2006	1	2012	3	2018	16
2000	0	2007	0	2013	6	2019	29
2001	0	2008	1	2014	10	2020	48
2002	0	2009	4	2015	7	2021	100
2003	2	2010	2	2016	16	2022	122
2004	2	2011	4	2017	13	2023	155
2005	1						

Table A3. Bradford's law analysis.

Zone	No. of Journals	No. of Publications
Zone 1	24	183
Zone 2	96	183
Zone 3	179	180

Table A4. Source impact analysis.

Source	h_Index	g_Index	m_Index	TC	NP	PY_Start
Nature	1	1	0.1111	1737	1	2016
Progress In Polymer Science	4	5	0.3333	1476	5	2013
ACS Sustainable Chemistry & Engineering	4	4	0.3636	1283	4	2014
Polymers	11	23	1.5714	952	23	2018

Table A4. *Cont.*

Source	h_Index	g_Index	m_Index	TC	NP	PY_Start
Chemical Society Reviews	2	2	0.2000	919	2	2015
Composites Part B-Engineering	2	2	0.1818	822	2	2014
Carbohydrate Polymers	6	6	0.2857	692	6	2004
Chemical Reviews	5	5	0.5556	657	5	2016
Npj Clean Water	1	1	0.2500	657	1	2021
Advanced Materials	4	4	0.3077	640	4	2012

Table A5. Lotka's law analysis.

Number of Written Documents	Number of Authors	Proportion of Authors
1	2244	0.9452
2	102	0.0430
3	19	0.0080
4	3	0.0013
5	5	0.0021
6	1	0.0004

Table A6. Author impact analysis.

Author	h_Index	g_Index	m_Index	TC	NP	PY_start
Williams CK	2	2	0.2222	1773	2	2016
Romain C	1	1	0.1111	1737	1	2016
Zhu Y	1	1	0.1111	1737	1	2016
Rhim JW	2	2	0.1667	1189	2	2013
Ha CS	1	1	0.0833	1170	1	2013
Park HM	1	1	0.0833	1170	1	2013
Titirici MM	3	3	0.2727	1058	3	2014
Brun N	2	2	0.1818	1041	2	2014
Budarin Vl	2	2	0.1818	1041	2	2014
Clark JH	2	2	0.1818	1041	2	2014

Table A7. Country impact analysis.

Country	TC	Average Article Citations	TP
United Kingdom	3643	117.5	76
USA	3251	63.7	148
India	2171	30.6	192
Germany	1626	101.6	53
China	1550	29.8	170
Malaysia	1474	52.6	113
Korea	1331	110.9	50
Saudi Arabia	1245	138.3	28
Italy	1112	31.8	88
Australia	995	62.2	42

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