ASEAN Journal for Science and Engineering in Materials

Journal homepage: https://ejournal.bumipublikasinusantara.id/index.php/ajsem

Definition and Role of Sustainable Materials in Reaching Global Sustainable Development Goals (SDGs) Completed with Bibliometric Analysis

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ABSTRACT

Sustainable materials are essential in achieving the Sustainable Development Goals (SDGs), particularly in clean energy, water purification, waste reduction, and green infrastructure. This study investigates the role of material innovation in supporting the SDGs using a Systematic Literature Review (SLR) and bibliometric analysis (from Scopus database (2015–2025) using keywords “Sustainable Material,” “Green Material,” and “SDGs”). The findings showed a growing research trend, especially after the COVID-19 pandemic, with significant contributions from chemistry, engineering, and environmental sciences. Materials like nanomaterials, biomaterials, biodegradable polymers, and waste-derived products contribute to SDG 6, 7, 9, 12, and 13. Innovations such as green nanotechnology, bio-based materials, and circular material design show strong potential to address global sustainability challenges. These materials not only support emission reduction and waste valorization but also encourage green job creation and sustainable production. This study highlights interdisciplinary pathways to align material science with sustainable development.

ARTICLE INFO

Article History:
Submitted/Received 17 Mar 2025
First Revised 20 Apr 2025
Accepted 24 Jun 2025
First Available online 30 Jun 2025
Publication Date 01 Mar 2026

Keyword:
Bibliometric,
Covid,
Material design,
Material innovation,
Sustainable development goals,
Sustainable material,
Systematic literature review.

1. INTRODUCTION

Materials are a fundamental element in the development of modern technology and infrastructure, which is the foundation of society's life today (Kalt *et al*., 2021; Chaikittisilp *et al*., 2022). In the context of Sustainable Development Goals (SDGs), material development plays an important role in supporting the achievement of various global goals, such as clean energy (SDG 7), infrastructure and innovation (SDG 9), sustainable consumption and production (SDG 12), and handling climate change (SDG 13) (Fei *et al*., 2021; Lenzen *et al*., 2022; Tiwari, 2023). Innovation in materials science enables the creation of efficient, environmentally friendly, and highly effective technological solutions, such as energy-saving batteries, biomaterials, and recycled materials that support a circular economy (Raabe, 2023; Krauklis *et al*., 2021; Nilimaa, 2023; Jin *et al*., 2023; Mohanty *et al*., 2018; Ahmed & Mohammed, 2024; Martins, 2021; Hussain *et al*., 2024). Therefore, the relationship between materials engineering and achieving the SDGs needs to be studied more deeply as a form of scientific contribution to global sustainability.

Various scientific studies show that the development of advanced materials such as nanomaterials (Khalilov, 2023; Lombardo *et al*., 2020), biomaterials (Lombardo *et al*., 2020; Fenton *et al*., 2018; Huang *et al*., 2021), composite materials, and other functional materials (Thoniyot *et al*., 2015; Dobrzański *et al*., 2011; Darder *et al*., 2007; Perez *et al*., 2013) has made a significant contribution in supporting sustainable development. Innovations such as the use of perovskites and silicon or gallium arsenide (GaAs)-based semiconductors in new generation solar panels have increased the efficiency of solar energy conversion at lower costs, supporting the achievement of SDG 7 (Clean and Affordable Energy) and SDG 13 (Tackling Climate Change) (Pallas *et al*., 2020). In addition, photocatalytic materials based on titanium dioxide (TiO_2) have been proven effective in decomposing organic pollutants through a photodegradation process, offering an environmentally friendly wastewater treatment solution that is relevant to SDG 6 (Clean Water and Sanitation) (Van Thuan *et al*., 2023; Moradeeya *et al*., 2022; Kanan *et al*., 2020). On the other hand, biomaterials and biodegradable polymers such as polyhydroxyalkanoates (PHA), polylactic acid (PLA), and thermoplastic starch (TPS) are emerging as alternatives to conventional plastics, supporting SDG 12 (Responsible Consumption and Production) and SDG 14 (Ocean Ecosystems) through reducing microplastic pollution (Yeo *et al*., 2024; Acharjee *et al*., 2024). In the construction sector, green concrete made from fly ash, slag, and geopolymer is used to reduce the carbon emissions of the cement industry while utilizing industrial waste, contributing to SDG 9 (Infrastructure and Innovation), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Sandanayake *et al*., 2018; Li *et al*., 2023; Komnitsas, 2011). Overall, current literature indicates that materials science and engineering are not only important for technological efficiency but are also key drivers in achieving various SDG targets through a multidisciplinary approach that considers aspects of sustainability, life cycle, bio-compatibility, and affordability.

Although the literature shows rapid progress in the development of sustainable materials, most studies are still sectoral and focus on technical aspects or specific applications towards one or two SDG goals only. For example, many studies address the effectiveness of nanomaterials in water purification or energy conversion efficiency (Santhosh *et al*., 2016; Nasrollahzadeh *et al*., 2021; Villaseñor & Rios, 2018; Peng *et al*., 2016; Zeng *et al*., 2021), but rarely examine how one type of material can have a simultaneous impact on social, economic, and environmental aspects of sustainable development. Apart from that, the integration between life-cycle assessment (LCA), energy efficiency, availability of raw materials, and the potential for replication on an industrial scale has also not been fully discussed in one holistic framework. Thus, approaches that incorporate cross-disciplinary and cross-objective perspectives remain a void that needs to be filled in the current scientific literature.

Most studies have not fully addressed the systemic dimension between materials science and the complexity of interactions between the SDGs goals. For example, the development of bio-based materials not only has an impact on reducing emissions, but also on creating green jobs (SDG 8), increasing access to environmentally friendly technology (SDG 10), and strengthening global partnerships in technological innovation (SDG 17). This kind of perspective is important to avoid silo approaches that hinder systemic transformation towards sustainability. Therefore, a literature review is needed that not only presents a compilation of material types and their applications, but also maps cross-purpose relationships and assesses their implications at a macro level.

This study aims to compile a comprehensive literature review regarding the contribution of materials development to achieving the SDGs, with a focus on interdisciplinary approaches and systemic mapping. This study explores how material innovation, whether sourced from biomass, recycling, or nanotechnology, not only provides ecological benefits but also social and economic benefits. The novelty of this study lies in the cross-sector and cross-objective exploration, as well as the integrative analysis of the extent to which materials science supports the transition towards sustainable production and consumption systems. The results of this literature review can become a conceptual basis for developing science-based research and policy, as well as encouraging cross-sector collaboration in the use of material innovation as a driver of transformation towards sustainable development. This study adds new information regarding SDGs as reported elsewhere (see **Table 1**).

Table 1. Previous studies on SDGs.

No	Title	Reference
1	Safe food treatment technology: The key to realizing the sustainable development goals (SDGs) zero hunger and optimal health	(Rahmah *et al*., 2024)
2	Analysis of student's awareness of sustainable diet in reducing carbon footprint to support sustainable development goals (SDGs) 2030	(Keisyafa *et al*., 2024)
3	Analysis of the application of mediterranean diet patterns on sustainability to support the achievement of sustainable development goals (SDGs): Zero hunger, good health and well beings, responsible consumption, and production	(Nurnabila *et al*., 2023)
4	Efforts to improve sustainable development goals (SDGs) through education on diversification of food using infographic: Animal and vegetable protein	(Awalussillmi *et al*., 2023)
5	Implementation of sustainable development goals (SDGs) no. 12: Responsible production and consumption by optimizing lemon commodities and community empowerment to reduce household waste	(Maulana *et al*., 2023)
6	The influence of environmentally friendly packaging on consumer interest in implementing zero waste in the food industry to meet sustainable development goals (SDGs) needs	(Haq *et al*., 2024)
7	The relationship of vocational education skills in agribusiness processing agricultural products in achieving sustainable development goals (SDGs)	(Gemil *et al*., 2024)
8	Smart learning as transformative impact of technology: A paradigm for accomplishing sustainable development goals (SDGs) in education	(Makinde *et al*., 2024)

Table 1 (continue). Previous studies on SDGs.

No	Title	Reference
9	Techno-economic analysis of production ecobrick from plastic waste to support sustainable development goals (SDGs)	(Syahrudin *et al.*, 2026)
10	Techno-economic analysis of sawdust-based trash cans and their contribution to indonesia's green tourism policy and the sustainable development goals (SDGs)	(Apriliani *et al.*, 2026)
11	Production of wet organic waste ecoenzymes as an alternative solution for environmental conservation supporting sustainable development goals (SDGs): A techno-economic and bibliometric analysis	(Sesrita *et al.*, 2025)
12	Hazard identification, risk assessment, and determining control (HIRADC) for workplace safety in manufacturing industry: A risk-control framework complete with bibliometric literature review analysis to support sustainable development goals (SDGs)	(Henny *et al.*, 2025)
13	Sustainable packaging: Bioplastics as a low-carbon future step for the sustainable development goals (SDGs)	(Basnur *et al.*, 2024)
14	Contributing factors to greenhouse gas emissions in agriculture for supporting sustainable development goals (SDGs): Insights from a systematic literature review completed by computational bibliometric analysis	(Soegoto *et al.*, 2025)
15	Characteristics of jengkol peel (Pithecellobium jiringa) biochar produced at various pyrolysis temperatures for enhanced agricultural waste management and supporting sustainable development goals (SDGs)	(Rahmat *et al.*, 2025)
16	Effect of substrate and water on cultivation of Sumba seaworm (nyale) and experimental practicum design for improving critical and creative thinking skills of prospective science teacher in biology and supporting sustainable development goals (SDGs)	(Kerans *et al.*, 2024)
17	Innovative nanofluid encapsulation in solar stills: Boosting water yield and efficiency under extreme climate supporting sustainable development goals (SDGs)	(Namoussa *et al.*, 2025)
18	Modernization of Submersible Pump Designs for Sustainable Irrigation: A Bibliometric and Experimental Contribution to Sustainable Development Goals (SDGs)	(Glovatskii *et al.*, 2025)
19	Sustainable development goals (SDGs) in engineering education: Definitions, research trends, bibliometric insights, and strategic approaches	(Ragadhita *et al.*, 2026)
20	Integrating multi-stakeholder governance, engineering approaches, and bibliometric literature review insights for sustainable regional road maintenance: Contribution to sustainable development goals (SDGs) 9, 11, and 16	(Yustiarini *et al.*, 2025)
21	Computational engineering of malonate and tetrazole derivatives targeting SARS-CoV-2 main protease: Pharmacokinetics, docking, and molecular dynamics insights to support the sustainable development goals (SDGs), with a bibliometric analysis	(Merzouki *et al.*, 2025)
22	A study on sustainable eggshell-derived hydroxyapatite/CMC membranes: Enhancing flexibility and thermal stability for sustainable development goals (SDGs)	(Waardhani *et al.*, 2025)
23	Towards sustainable wind energy: A systematic review of airfoil and blade technologies over the past 25 years for supporting sustainable development goals (SDGs)	(Krishnan *et al.*, 2024)

Table 1 (continue). Previous studies on SDGs.

No	Title	Reference
24	Assessment of student awareness and application of eco-friendly curriculum and technologies in Indonesian higher education for supporting sustainable development goals (SDGs): A case study on environmental challenges	(Djirong *et al*., 2024)
25	Low-carbon food consumption for solving climate change mitigation: Literature review with bibliometric and simple calculation application for cultivating sustainability consciousness in facing sustainable development goals (SDGs)	(Nurramadhani *et al*., 2024)
26	Sustainable development goals (SDGs) in science education: Definition, literature review, and bibliometric analysis	(Maryanti *et al*., 2022)

2. METHODS

This study employed a Systematic Literature Review (SLR) method combined with bibliometric analysis to obtain a comprehensive understanding of the contribution of material development toward achieving the Sustainable Development Goals (SDGs). The systematic literature review aimed to identify, evaluate, and synthesize relevant research findings systematically and transparently. The SLR process began by formulating research questions, determining inclusion and exclusion criteria, conducting a systematic literature search, selecting articles based on titles, abstracts, and full content, and organizing and synthesizing data from the selected articles. The selection process included only scientific articles published in the Scopus database from 2015 to 2025, focusing on documents discussing sustainable materials and their linkage with the SDGs. The main keywords used in the search included: “Sustainable Material” AND “Sustainable Development Goals” OR “Green Material” OR “Material Innovation” AND “SDGs”. Detailed information regarding bibliometric analysis is reported elsewhere (Rochman *et al*., 2024; Al Husaeni & Nandiyanti, 2022; Al Husaeni & Al Husaeni, 2022).

As a complement to the thematic synthesis from the SLR, bibliometric analysis was carried out to evaluate the scientific structure and research development trends quantitatively. Bibliometric data were obtained in CSV format from Scopus and analyzed using VOSviewer software. Several key indicators were analyzed, including: (i) research developments and trends, namely the number of publications per year on the studied topic to observe the dynamics of research growth; (ii) distribution of documents based on scientific fields, classifying documents according to disciplines (such as engineering, chemistry, environment, energy, and materials science); (iii) number of documents related to the topic by country, showing how many publications were relevant to the research keywords; (iv) network visualization, which enabled visualization of keyword relationships based on co-occurrence (simultaneous appearance in one document), grouped into color-coded clusters, each representing a specific topic or field; and (v) overlay visualization, which was used to show the temporal evolution and emergence of new topics over the 2015–2025 period.

By integrating the SLR and bibliometric approaches, this study produced not only a systematic mapping of the literature but also a strong intellectual map for understanding the scientific contributions and global research directions regarding material innovations aligned with sustainable development goals.

3. RESULTS AND DISCUSSION

3.1. Bibliometric Analysis Results

Figure 1 shows a significant increasing trend in the number of publications discussing the link between sustainable materials and sustainable development goals (SDGs) over the last decade. In 2015, the number of published documents was still relatively low (around 300 documents), reflecting the early stage of academic interest in the integration of materials innovation and global sustainability. Over time, a gradual increase was seen from 2015 to 2020, with the number of documents increasing consistently, indicating growing awareness of the importance of environmentally friendly materials in supporting the SDGs. A sharper increase begins to be seen from 2021 to 2024, where the number of publications increases drastically, reaching more than 3,500 documents in 2024, at the peak of this trend.

This surge is most likely influenced by the increasingly strong global commitment to sustainability after the COVID-19 pandemic, as well as the integration of SDGs in various international research and policy agendas. Initiatives such as the Green Deal, net-zero emissions targets, and the push for the energy transition and circular economy are also encouraging researchers from various disciplines to explore innovative material solutions. Interestingly, in 2025, there will be a slight decrease in the number of documents compared to the previous year. This could be caused by two possibilities: (i) the 2025 data is still not fully indexed (the current year has not been completed), or (ii) there is a stabilization of publication output after the research explosion in previous years.

Figure 2 shows that research on sustainable materials in the context of Sustainable Development Goals (SDGs) has a very multidisciplinary nature. The field of Environmental Science occupies the highest proportion at 14.3%, which indicates that the greatest research focus is on environmental issues, such as climate change mitigation, waste management, water and air pollution, as well as adaptation strategies involving environmentally friendly material innovation. This shows that material-based approaches are widely used as technical solutions to global environmental challenges, which are very relevant to SDG 6 (clean water), SDG 12 (sustainable production-consumption), and SDG 13 (climate change).

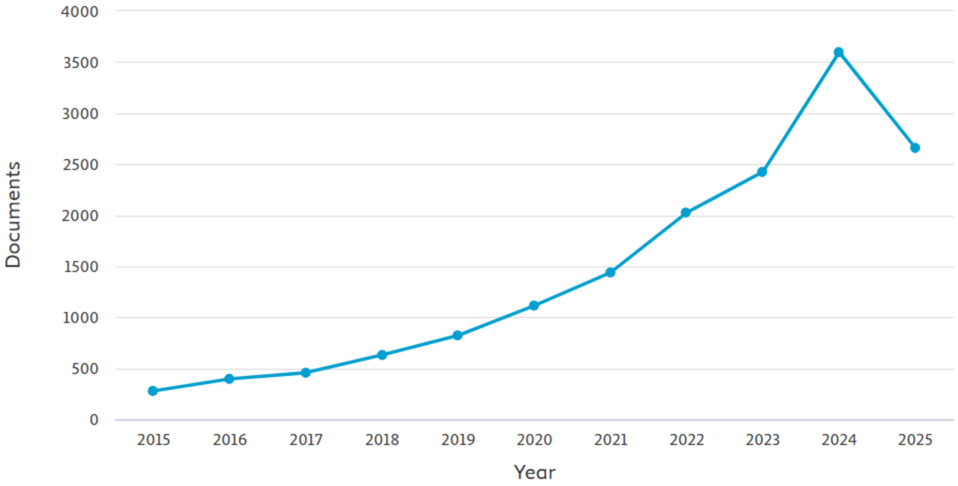

Figure 1. Research trend.

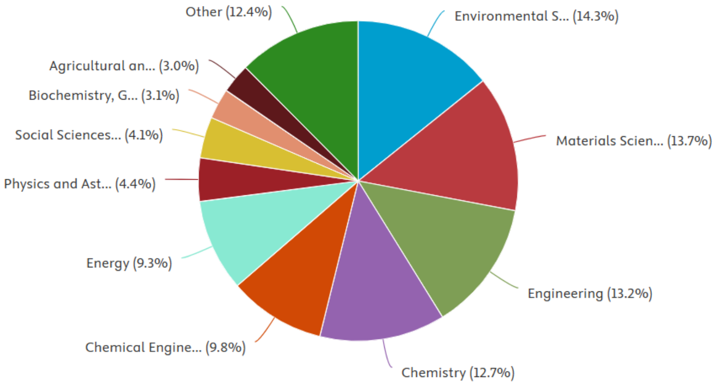

Figure 2. Distribution of documents based on scientific fields that discuss the topic of SDGs in material science.

Furthermore, the fields of Materials Science (13.7%) and Engineering (13.2%) were the next largest contributors, confirming that engineering and materials development, both from fundamental and applied aspects, are the backbone in creating sustainable technology. This includes the development of nanomaterials, biomaterials, composite materials, and industrial waste-based materials used in the energy, infrastructure, transportation, and construction sectors. The fields of Chemistry (12.7%) and Chemical Engineering (9.8%) play a role in the design and synthesis of new materials, such as green catalysts, biodegradable polymers, and efficient chemical production processes with minimal waste, which are closely related to the principles of green chemistry and a circular economy.

Meanwhile, the Energy sector (9.3%) shows the relevance of developing materials in energy storage and conversion, such as lithium-ion batteries, supercapacitors, and perovskite-based solar cells. The field of Physics and Astronomy (4.4%) also contributes to understanding the physical properties and structural characterization of materials at the nano- to atomic-scale, which is important in the development of sensors and low-power smart devices. The contribution from Social Sciences (4.1%) attracts attention because it shows the involvement of social and policy approaches in encouraging the adoption of sustainable material technology in society.

In addition, the fields of Biochemistry, Genetics, and Molecular Biology (3.1%) and Agricultural and Biological Sciences (3.0%) play a role in the development of biomaterials based on living organisms and biological waste, which are used in medical, agricultural, and environmentally friendly packaging applications. Finally, the other category (12.4%) includes contributions from other disciplines such as computer science, education, and public policy, which emphasizes the need for cross-sector and cross-scientific approaches in addressing the complexity of the global challenges faced by the SDGs.

Overall, these data show that the development of sustainable materials is not only a concern in the fields of science and engineering but is also increasingly being approached from a holistic social, economic, and environmental perspective. Therefore, synergy between scientific fields is very necessary to produce material innovations that are not only technically superior but also have a broad positive impact on society and the planet in a sustainable manner.

Figure 3 shows the distribution of the number of documents by country or region that contributed to scientific publications related to sustainable materials and Sustainable Development Goals (SDGs) during the 2015–2025 period. China dominates the number of publications with a total of around 5,000 documents, making it the country with the highest research contribution in this field. This dominance shows China's strong commitment and investment in research and development of sustainable materials technology as part of their national agenda in supporting sustainable development. In second place is India with around 2,200 documents, followed by the United States with around 1,300 documents. These three countries are global research centers that are actively exploring innovative material-based solutions to support the achievement of various SDGs targets, such as renewable energy, waste management, and green construction.

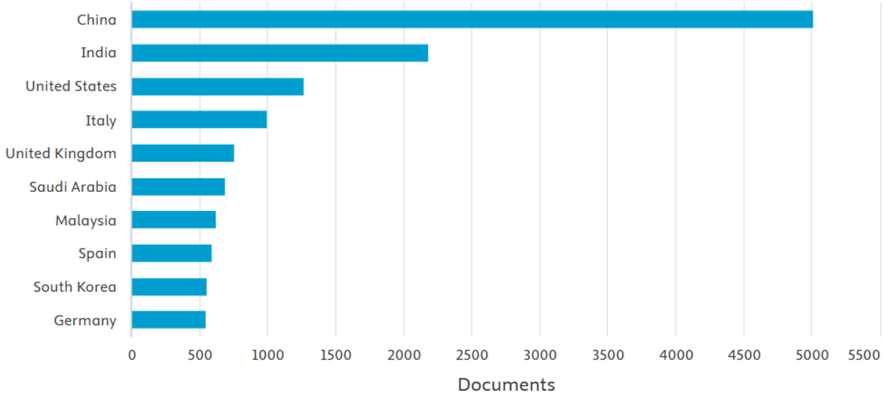

Figure 3. Number of documents related to SDGs in material science by country or region.

Italy and the UK ranked fourth and fifth with around 1,000 and 750 documents, respectively, indicating the significant contribution of European countries to this study. Interestingly, countries from West Asia and Southeast Asia are also included in the top 10 list, such as Saudi Arabia and Malaysia, which each contributed more than 500 documents. This shows the increasing attention and involvement of developing countries in sustainability-oriented research, along with increasing environmental challenges and the need for green technology. Countries such as Spain, South Korea, and Germany also show fairly stable contributions, with publications ranging from 500–700 documents. In general, this data reflects strong global collaboration in the field of sustainable materials science as well as the strategic role of developed and developing countries in advancing research that supports the SDGs agenda across regions.

3.2. Types of Sustainable Material in the Context of SDGs

The development of sustainable materials science is a key element in responding to global challenges outlined in the SDGs. Sustainable materials are not only designed for high efficiency and performance, but also to minimize environmental impact, improve product life cycles, and support the circular economy and green technologies. Innovation in these types of materials allows the creation of real solutions in various sectors such as energy, clean water, health, construction, and waste management.

This section discusses several sustainable materials that are most commonly found in scientific literature and have a significant contribution to achieving the SDGs, namely, nanomaterials, biomaterials, and waste-derived materials. Each type of material has unique characteristics and specific applications that have a broad impact on sustainable development. The discussion in this section describes in detail the definition, nature, technological developments, and relevance of these materials to the relevant SDGs goals.

3.2.1. Nanomaterial

Nanomaterials are one of the most significant innovations in the 21st century. This material has a very small size, ranging from 1 to 100 nanometres, which provides unique properties compared to materials in ordinary sizes. Figure 6 shows some common types of nanostructured materials. Due to their special properties, such as large surface area, high reactivity, and extraordinary optical, magnetic, or mechanical capabilities, nanomaterials are widely used in various sectors, from energy technology, health, and environment, to electronics (García-Quintero & Palencia, 2021).

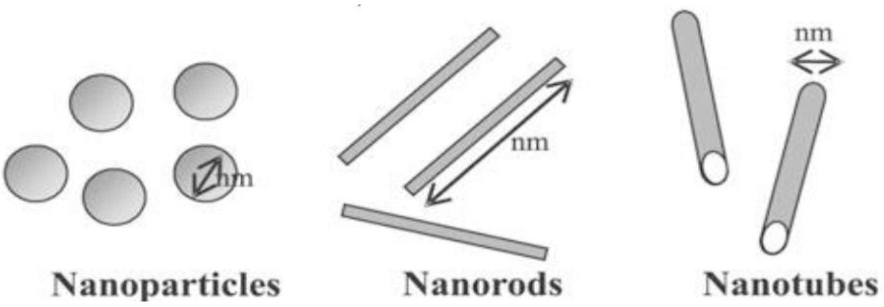

Figure 6. Some common types of nanostructured materials (García-Quintero & Palencia, 2021).

3.2.2.1. Green nano concept

However, as the use of nanomaterials increases, concerns about the environmental and health impacts of their synthesis processes are starting to come into focus. Conventional processes for making nanomaterials often use dangerous chemicals, toxic organic solvents, and produce waste that is difficult to handle. Therefore, a wiser and more responsible approach was born: Green Nanotechnology, or often referred to as Green Nano (García-Quintero & Palencia, 2021).

The Green Nano concept (see **Figure 7**) is a combination of the principles of nanotechnology and green chemistry. This approach aims to produce nanomaterials in a way that is more environmentally friendly, with minimal waste, non-toxic, and energy efficient. These principles are in line with the 12 Principles of Green Chemistry (PGCs) which were first introduced by Paul Anastas and John Warner in 1998 (see https://www.acs.org/green-chemistry-sustainability/principles/12-principles-of-green-chemistry.html). These principles are not just theory, but practical guidelines for chemical synthesis processes (including the manufacture of nanomaterials) that can be carried out with attention to human safety and environmental sustainability.

Several important principles that are often applied in the synthesis of green nanomaterials include:

(i) Waste prevention (Principle 1), where researchers are required to design processes that do not produce hazardous waste.
(ii) Atomic efficiency (Principle 2), i.e., ensuring as many atoms of the starting material as possible are used in the final product (nanoparticles).
(iii) Use of safer solvents (Principle 5) such as water or plant extracts, in place of harmful organic solvents.
(iv) Non-hazardous chemical synthesis (Principle 3), which leads to the use of natural substances from plants, bacteria, or agricultural waste.

Figure 7. Representation of the 12 principles of green chemistry (Anastas & Warner, 1998).

3.2.2.2. Sustainable nanomaterial fabrication through the use of plant extracts

Terms such as "green synthesis of nanomaterials" are increasingly popular because researchers now use many natural materials. The use of plant extracts in the synthesis of nanomaterials has become an increasingly popular approach. This method utilizes secondary metabolite compounds that occur naturally in various parts of plants, such as leaves, fruit, skin, flowers, and roots, which act as reducing agents and stabilizers in the formation of metal nanoparticles. The diversity of active compounds in plants allows variations in the size and type of nanoparticles that can be produced. For example, Hibiscus sabdariffa flower extract is used to synthesize cadmium oxide, while Ziziphus spina-christi produces very small copper nanoparticles. **Table 2** summarizes various types of metal nanoparticles that have been successfully synthesized using plant extracts, indicating the particle sizes and plant parts used.

Table 2. Metallic nanoparticles synthesized with different plant extracts.

Nanomaterial Obtained	**Size (nm)**	**Plant Used**	**Reference**
Cadmium oxide	113	*Hibiscus Sabdariffa* flower extract	(Thovhogi *et al.*, 2016)
Chromium oxide	17–42	*Abutilon indicum (L.)* leaf extract	(Khan *et al.*, 2018)
Copper nanoparticles	5–20	*Ziziphus spina-christi (L.)* fruit extract	(Khani *et al.*, 2018)
Copper oxide	61.48	*Momordica charantia* fruit extract	(Qamar *et al.*, 2020)
Gold	15–25	*Memecylon umbellatum* leaf extract	(Arunachalam *et al.*, 2013)
Silver	15–20	*Memecylon umbellatum* leaf extract	(Arunachalam *et al.*, 2013)
Gold	5.82	*Clerodendrum inerme* leaves extract	(Khan *et al.*, 2020)
Silver	5.54	*Clerodendrum inerme* leaves extract	(Khan *et al.*, 2020)
Gold nanoparticles	10–100	*Nerium oleander* stem bark extract	(Barai *et al.*, 2018)
Gold nanoparticles	5–20	*Gnidia glauca* flower extract	(Ghosh *et al.*, 2012)
Gold nanoparticles	20–140	Rind of watermelon aqueous extract	(Patra & Baek, 2015)
Iron oxide	13.42	*Garcinia mangostana* fruit peel extract	(Yusefi *et al.*, 2021)

Table 2 (continue). Metallic nanoparticles synthesized with different plant extracts.

Nanomaterial Obtained	Size (nm)	Plant Used	Reference
Iron oxide	20–30	*Excoecaria cochinchinensis* extract	(Cai *et al.*, 2019)
Silver nanoparticles	18.2	*Vitex negundo L.* extract	(Zargar *et al.*, 2011)
Silver nanoparticles	37.71–71.99	*Chrysanthemum indicum L.*	(Arokiyaraj *et al.*, 2014)
Silver nanoparticles	21–173	*Conocarpus lancifolius* fruit extract	(Oves *et al.*, 2022)
Silver nanoparticles	25.2	*Nigella sativa* extract	(Alkhalaf *et al.*, 2020)
Silver nanoparticles	45–110	*Brillantaisia patula*, *Crossopteryx febrifuga*, *Senna siamea* extracts	(Kambale *et al.*, 2020)
Silver oxide	50, 60	*Moringa oleifera* gum	(Irfan *et al.*, 2021)
Zinc oxide	52.24	*Cayratia pedata* leaves extract	(Jayachandran *et al.*, 2021)
Zinc oxide	480	*Panax ginseng*, *Acanthopanax senticosus*, *Kalopanax septemlobus*, *Dendropanax morbifera* extracts	(Kaliraj *et al.*, 2019)
Zinc oxide	9–38	*Azadirachta indica* extract	(Madan *et al.*, 2016)

3.2.2.3. Environmentally friendly nanomaterial synthesis method

Several methods that are known to be environmentally friendly and have been widely used in nanomaterial synthesis include: sonochemistry, microwave-assisted synthesis, hydrothermal, solvothermal, and electrochemistry. However, among all these methods, the two most widely used are sonochemical and microwave-assisted methods (Safari & Javadian, 2015; Kumar *et al.*, 2020; Mondal *et al.*, 2020). **Table 3** shows a comparison between sonochemical and microwave methods. The sonochemical method utilizes ultrasonic waves, namely sound waves with a frequency above 20 kHz, which humans cannot hear. These waves produce the phenomenon of acoustic cavitation, namely the formation, growth, and implosive collapse of air bubbles in a liquid. When the bubble collapses, there is a very high local spike in temperature and pressure over a short period of time, causing a drastic increase in the rate of the chemical reaction. This extreme situation allows the formation of nanostructures quickly and efficiently without the need to use dangerous solvents. Sonochemistry is recognized as a fast, green, energy-saving method, and can be used for the synthesis of unusual inorganic nanostructured materials, such as carbonyl compounds (for example: $Fe(CO)_5$, $Co(CO)_3NO$, $Mo(CO)_6$, and $W(CO)_6$). In addition, this method also has the advantage of controlling the size and shape of the nanoparticles (Safari & Javadian, 2015; Jamkhande *et al.*, 2019).

The microwave-assisted synthesis method uses electromagnetic radiation to speed up the reaction process by heating the reaction mixture evenly and quickly (Mondal *et al.*, 2020). This can reduce reaction times significantly and enable more efficient use of energy. The advantages of this method include: shorter reaction time, higher product yield, better product purity, and reaction conditions that are easily optimized (Kumar *et al.*, 2020). Faster reactions also reduce the possibility of undesirable side products forming. Microwave-assisted synthesis has been widely used to produce metal nanoparticles such as silver, gold, zinc oxide, and iron oxide, as well as other nanocomposite materials (Jamkhande *et al.*, 2019).

Table 3. Comparison of sonochemical and microwave methods in nanoparticle synthesis.

Aspect	Sonochemical Method	Microwave-Assisted Synthesis
Working Principle	Ultrasonic waves via acoustic cavitation	Microwave radiation via rapid internal heating
Temperature & Pressure	Extremely high locally due to bubble collapse	Uniform distribution, high energy efficiency
Reaction Time	Fast	Very fast (within minutes)
Solvent Usage	Can use green solvents (e.g., water)	Commonly uses water or alcohol as solvents
Advantages	- Environmentally friendly- Simple procedure- Energy-efficient	- High reproducibility- Time and energy efficient- Produces high-quality products
Disadvantages	Requires specialized ultrasonic equipment	Requires a specific microwave reactor (not a household type)
Examples of Nanoparticles Produced	$Fe(CO)_5$, $Mo(CO)_6$, silver nanoparticles	ZnO, AgNPs, AuNPs, metal nanocomposites

Nanoparticles produced through green synthesis methods offer a wide range of potential applications across fields due to their physicochemical characteristics and high safety (Safari & Javadian, 2015; Kumar *et al.*, 2020). Nanoparticle applications cover various important sectors such as catalysis, medical/biomedical, environmental, water treatment, agriculture, and the food industry (see **Table 4**) (Jamkhande *et al.*, 2019). **Figure 8** shows some nanomaterials that are currently being utilized as building blocks in developing the next generation of sustainable products and technologies in water purification, energy generation, energy conversion and storage, greenhouse gas management and control, materials supply and utilization, and green chemistry and manufacturing (Harish *et al.*, 2022).

Table 4. Applications of green synthetic nanoparticles in the field.

Application Field	Brief Description	Example Materials
Catalysis	Accelerates chemical reactions without being permanently altered	AgNPs, ZnO, TiO_2, Fe_3O_4
Medical/Biomedical	Used as therapeutic agents, drug delivery systems, antibacterial, and anticancer agents	AuNPs, AgNPs, ZnO, CuO
Environmental	Removal of pollutants, emission control, and heavy metal detection	Fe_3O_4, TiO_2, Graphene oxide
Biological	Bioactivity testing, biosensing, and cell labeling	AgNPs, CuNPs, ZnO
Water Treatment	Used as adsorbents or catalysts for purification and heavy metal removal	Fe_3O_4, TiO_2, ZnO
Agriculture	Nutrient/pesticide carriers, plant growth enhancers, pest control	AgNPs, ZnO, CuNPs
Food Industry	Natural preservatives, antimicrobial coatings, and food quality sensors	AgNPs, ZnO, biopolymer nanocomposites
Antimicrobial & Antibacterial	Inhibits pathogenic microbial growth in various applications	AgNPs, CuO, ZnO, TiO_2
Others	Electronics, sensors, magnetic materials, energy storage	Graphene, carbon dots, NiO

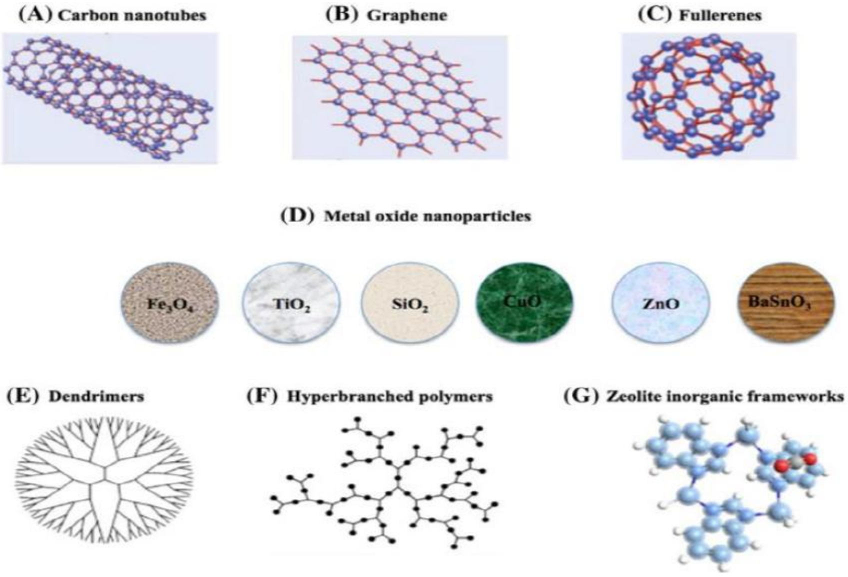

Figure 8. Nanomaterials are used as building blocks in developing sustainable products (Harish *et al*., 2022).

3.2.2.4. Contribution of nanomaterials to SDGs

To illustrate the concrete contribution of Green Nano to the SDGs, **Table 5** presents the relationship of various green nanotechnology applications with relevant sustainable development goals. Each application shows how sustainability principles are translated into scientific practices that have real impacts on society and the environment.

Table 5. The relationship of green nano applications to SDGs.

Green Nano Application	Contribution Description	Relevant SDG
Nanoparticles for Medical Therapy	Safe and biocompatible nanoparticle synthesis for drug delivery, diagnostics, and cancer therapy.	**SDG 3: Good Health and Well-being**
Nanomaterials for Water Purification	Use of nanoparticles such as TiO_2, ZnO, and AgNPs for photocatalysis and filtration of water and wastewater.	**SDG 6: Clean Water and Sanitation**
Nanotechnology in Solar Panels and Energy Storage	Nano-based materials enhance the efficiency of solar cells, supercapacitors, and batteries.	**SDG 7: Affordable and Clean Energy**
Waste Recycling for Nanoparticle Synthesis	Utilizing plant waste as a reducing agent in green nanoparticle synthesis.	**SDG 12: Responsible Consumption and Production**
Low-emission and Eco-friendly Nanoparticle Synthesis	Reduces the use of hazardous solvents and toxic chemicals during production.	**SDG 13: Climate Action**
Use of Local and Biodegradable Materials for Innovation	Developing locally based, sustainable technology solutions using biodegradable resources.	**SDG 9: Industry, Innovation, and Infrastructure**

3.2.2. Biomaterial

Biomaterials are materials specifically designed to interact with biological systems to replace, repair, or enhance the function of tissues and organs in the human body (Amponsah *et al.*, 2025). Biomaterials are classified into two large groups, namely natural biomaterials and synthetic biomaterials. Natural biomaterials (see **Figure 9**) come from biological sources such as proteins (collagen, gelatin, silk), polysaccharides (cellulose, chitosan), as well as de-cellularized tissue such as heart valves or liver. This type of biomaterial has the advantages of high biocompatibility, biodegradability, and an active role in supporting tissue regeneration (Amponsah *et al.*, 2025).

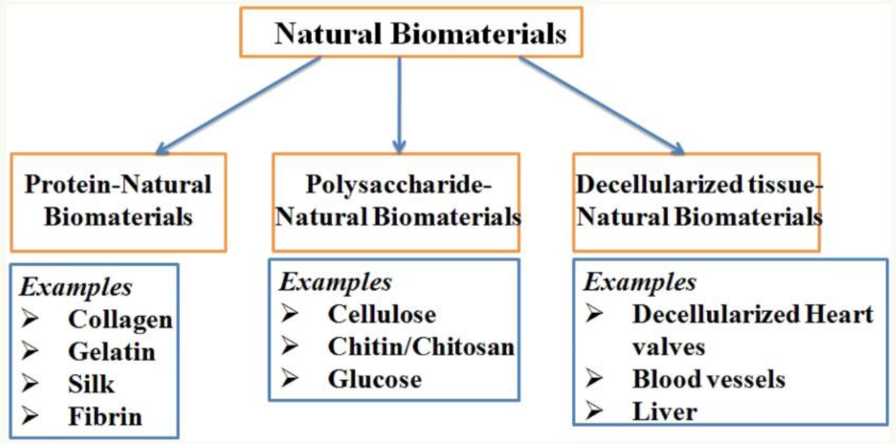

Figure 9. Classification of natural biomaterials (Amponsah *et al.*, 2025).

Meanwhile, synthetic biomaterials (see **Figure 10**) are developed through material engineering; thus, they have mechanical properties and chemical stability that can be adapted to medical needs. This group includes metal biomaterials (titanium, magnesium), ceramics (alumina, bioglass), polymers (thermoset, thermoplastic), as well as composites (a combination of matrix and filler) (Banigo *et al.*, 2019).

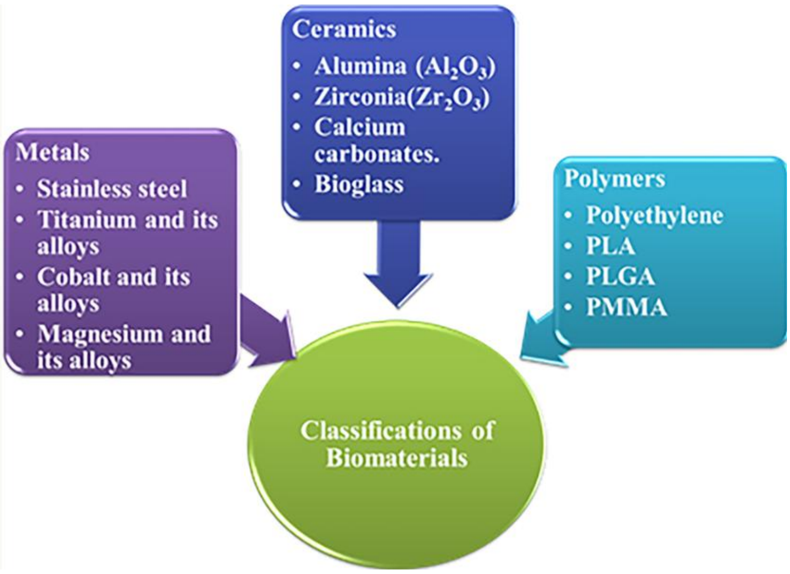

Figure 10. Classification of synthetic biomaterials (Banigo *et al.*, 2019).

3.2.2.1. Metal biomaterial

Metal biomaterials are widely used in the medical world, especially in orthopedic and dental applications, because of their excellent mechanical properties, such as high tensile strength, wear resistance, and resistance to heavy loads. Commonly used types of metal include stainless steel, titanium and its alloys, cobalt and its alloys, and magnesium and its alloys. Titanium is a superior choice because, apart from being strong and light, it also forms a protective oxide layer that prevents corrosion and allows biological integration with body tissue. Magnesium is attractive because of its biodegradable properties, making it a candidate for temporary implants that will dissolve in the body as tissue regenerates. However, the disadvantages of metal biomaterials lie in their tendency to corrosion and relatively low biological reactivity; thus, they often require additional coatings of bioactive materials (Zaman *et al*., 2015).

3.2.2.2. Ceramic biomaterial

Ceramic biomaterials such as alumina (Al_2O_3), zirconia (ZrO_2), bioglass, and calcium carbonate are known for their chemical stability, high hardness, and wear and corrosion resistance, but have the disadvantages of brittleness and low toughness against shock loads. Ceramics are classified into three sub-categories: bioinert, bioresorbable, and bioactive. Bioinert ceramics such as alumina and zirconia do not react chemically with body tissue and are commonly used as structural components in joint and dental implants. Bioresorbable ceramics such as hydroxyapatite (HAp) and tricalcium phosphate (TCP) dissolve slowly in the body and are replaced by natural bone tissue, making them ideal as bone grafts. Meanwhile, bioactive ceramics such as bioglass and glass-ceramics can form chemical bonds with body tissue, trigger the osteointegration process, and accelerate bone regeneration. The main advantage of bioactive ceramics lies in their surface ability to form an apatite layer, which stimulates bone cell growth (Thamaraiselvi & Rajeswari, 2004).

3.2.2.3. Composite

Composite materials are materials formed from a combination of two or more constituent materials through inhomogeneous mixing, where the mechanical properties of each constituent material are different. In general, composite materials are composed of two main components, namely the matrix (binder) and filler (see **Figure 11**). Fillers are usually in the form of fibers or powders, which function to strengthen and improve the mechanical performance of composites. The presence of filler greatly determines the overall strength and stiffness of the composite (Huang *et al*., 2015). When the composite receives a load or stress, the matrix will transmit the load to the filler. The filler then acts as the main barrier until the maximum strength limit is reached. Therefore, the strength of the composite is greatly influenced by the type and form of filler used (Elfakhri *et al*., 2022).

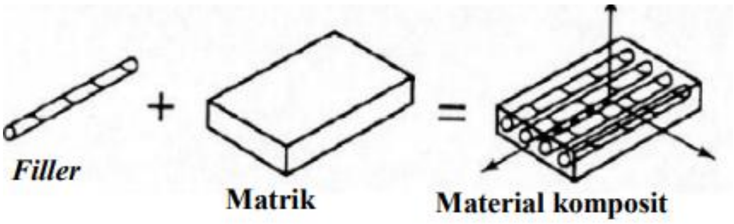

Figure 11. Composite composition (Huang *et al*., 2015).

Based on the form of the filler, composites can be classified into three main types: particle composites, fiber composites, and layered composites, as shown in **Figure 12**. Particle composites use powder as a filler material that is evenly distributed in the matrix. Fiber composites rely on fiber as a reinforcing material and are divided into four types, namely continuous fiber, woven fiber, random fiber, and hybrid composites. Meanwhile, layered composites are composed of two or more layers of different materials combined into a single material unit, with each layer having unique characteristics that contribute to the overall mechanical and structural properties of the composite (Mazitova *et al*., 2022). A summary of composite classification based on filler form is shown in **Table 6**.

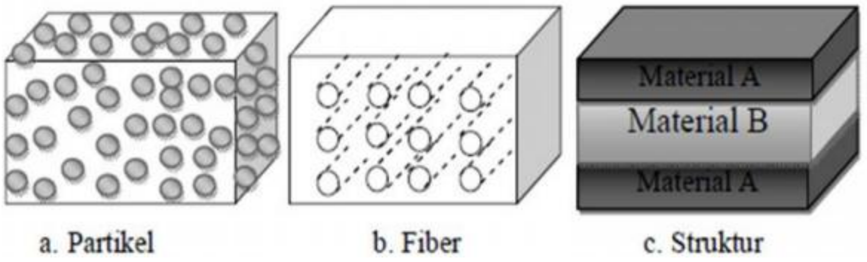

Figure 12. Composite illustration based on reinforcement (Mazitova *et al*., 2022).

The matrix is the main component in the structure of composite materials, which plays an important role in enveloping and protecting the reinforcing or filling material. In a composite system, the matrix functions as a continuous phase that surrounds the dispersed phase, namely fibers or reinforcing particles. The matrix is responsible for distributing external loads to the reinforcement and maintaining the structural stability of the composite. In addition, the matrix protects the fibers from damage due to abrasion between the fibers and from external environmental influences. In conditions where cracks occur, the matrix also functions to absorb strain energy to reduce damage to the fibers. The matrix character is generally soft and ductile. Thus, it is able to form coherent bonds across the fiber surface and is able to withstand deformation before passing it on to the reinforcing material (Mazitova *et al*., 2022).

Table 6. Composite classification based on filler form (Rajak *et al*., 2019).

Type of Composite	Description
Particle-Reinforced Composite	Utilizes powder particles as fillers, evenly distributed within the matrix. Suitable for enhancing stiffness and dimensional stability.
Fiber-Reinforced Composite	Composed of a matrix and fibers as the main reinforcement. The fibers bear loads and improve the material’s strength. This type includes:
– Continuous Fibers	Long, unbroken fibers throughout the composite provide high tensile strength.
– Woven Fibers	Fibers woven into fabric-like structures, offering strength in two directions.
– Random Fibers	Short fibers distributed randomly, suitable for non-directional loading conditions.
– Hybrid Composite	A combination of two or more types of fillers or matrices in a single structure, producing superior combined properties.
Laminated Composite (Laminates)	Consists of two or more layers of different materials, each contributing unique properties to the overall strength, stiffness, or durability.

Matrix materials in composites can be classified into three main groups based on the type of material that makes up the, namely polymer matrix composites, metal matrix composites, and ceramic matrix composites (Sharma *et al*., 2020). Polymer matrix composites generally use thermoset polymers such as epoxy and polyester because they have resistance to high temperatures and chemicals, as well as low viscosity, which allows perfect penetration into the fiber surface (Ramakrishnan *et al*., 2022). Metal matrix composites use metal as a matrix, providing high mechanical strength and resistance to extreme temperatures (Sharma *et al*., 2020). Meanwhile, ceramic matrix composites utilize the heat-resistant and high-h hardness properties of ceramics, suitable for applications with high thermal and mechanical loads (Sharma *et al*., 2020). The choice of this type of matrix must be adjusted to the final needs of the composite, because the matrix character directly influences the mechanical properties, environmental resistance, and long-term performance of the composite material (Ramakrishnan *et al*., 2022). In addition, the composite manufacturing method also determines the final quality of the material, because the manufacturing process will affect the distribution of filler, the quality of the interfacial bond, and the homogeneity of the composite structure (Ramakrishnan *et al*., 2022).

The properties of composite materials are determined by three main factors that interact with each other. First, the forming material has a major influence on the overall intrinsic properties of the composite. The basic characteristics of the constituent materials, such as strength, elasticity, and temperature resistance, will determine the final performance of the composite. Second, the structural arrangement of components, including the shape, orientation, size, and distribution of each component in the structure, makes a significant contribution to the strength, stiffness, and durability of composite materials. The optimal arrangement will increase the effectiveness of load transfer between components and increase the stability of the composite in its use. Third, the interaction between components is an important factor because composites are a combination of different materials, both in shape and properties, resulting in unique combined properties not found in each of the constituent materials individually (Ramakrishnan *et al*., 2022).

3.2.2.4. Polymer

Polymers are large macromolecules formed from repeating units called monomers. The term "polymer" comes from the Greek, namely "poly," which means many, and "mer," which means part. Polymers have long chains and large molecular masses, and if they consist of only a few monomer units, they are called oligomers. Based on the source, polymers are divided into natural polymers, such as natural rubber, cellulose, wool, and silk, and synthetic polymers, such as nylon, plastic, and polyester. Structurally, polymers are divided into three types: straight chain, branched, and three-dimensional or network polymers (see **Figure 13**) (Pillai, 2010; Rebouillat & Pla, 2016). Straight chain polymers have a molecular structure like long, unbranched chains, which tend to be flexible and thermoplastic, examples of which are polyethylene and PVC. Branched polymers have a basic structure that branches from the main chain, thus forming a cross-linked structure. Meanwhile, three-dimensional polymers have chemical bonds in various directions to form a cross-link network, which makes them insoluble and tends to be stiff with a high melting point (Pillai, 2010; Rebouillat & Pla, 2016; Patel & Taufik, 2022).

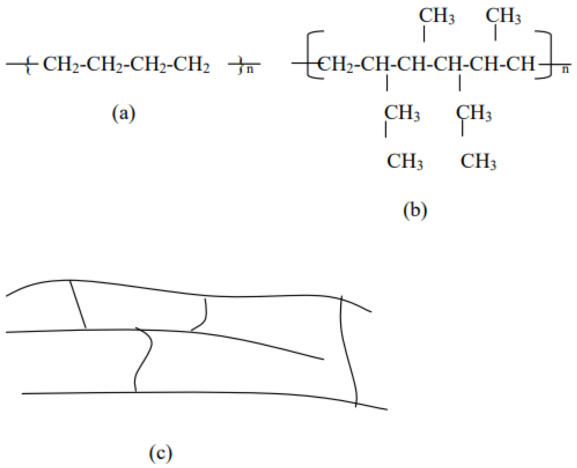

Figure 13. Polymer structure: (a) straight chain; (b) branching, (c) three-dimensional (Patel & Taufik, 2022).

Based on their thermal properties, polymers are divided into two types, namely thermoplastic and thermoset polymers (Pillai, 2010). Thermoplastics soften when heated and harden when cooled, and can be dissolved in certain solvents; for example, polyethylene and polyester. Meanwhile, thermosets have strong cross-links, cannot be remelted or reformed, and are difficult to dissolve, for example, melamine formaldehyde. Polymers are also classified based on their constituent monomers. If it consists of similar monomers, it is called a homopolymer, such as polyethylene and polypropylene. If it consists of two or more types of monomers, it is called a heteropolymer or copolymer, which can be further divided into random, alternating, block and graft copolymers, depending on the arrangement and type of connections between monomers in the polymer chain (see **Figure 14**) (Rebouillat & Pla, 2016). In terms of phase, polymers are categorized into crystalline and amorphous. Crystalline polymers have a regular chain arrangement with a clear melting point. Meanwhile, amorphous polymers have a random arrangement between chains and undergo a glass transition at a certain temperature. In summary, the classification of polymer structures is shown in **Table 7**.

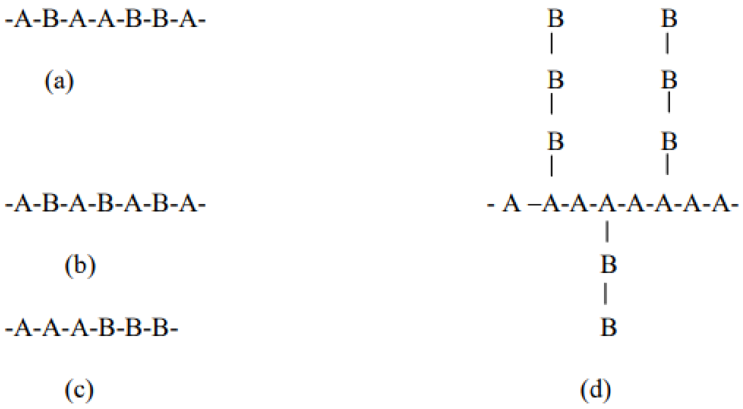

Figure 14. Copolymer structures (a) random, (b) alternating, (c) block, (d) graft, where A and B represent different monomers (Rebouillat & Pla, 2016).

Table 7. Summary of the classification of polymer structures.

Classification	Type	Characteristics	Examples
Source	Natural Polymer	Naturally derived from animals, plants, or minerals	Natural rubber, cellulose, silk
Chain Structure	Synthetic Polymer	Chemically synthesized	Nylon, plastics, polyester
	Linear Chain	Unbranched chains, flexible, soluble	PE (Polyethylene), PVC, PMMA
	Branched Chain	Branches extending from the main chain	Branched polyethylene
	3D Network	Crosslinked in all directions, insoluble, rigid	Diamond, epoxy resin
Thermal Property	Thermoplastic	Softens when heated and hardens when cooled	PE, PP, PVC
	Thermoset	Cannot be remelted, hard, insoluble	Melamine formaldehyde
Monomer Type	Homopolymer	Composed of only one type of monomer	Polyethylene, polypropylene
	Heteropolymer / Copolymer	Composed of two or more different types of monomers	ABS, EVA, PU
Copolymer Type	Random	Monomers arranged randomly	PVC-vinyl acetate
	Alternating	Monomers arranged in alternating sequence	ETFE
	Block	Long blocks of one monomer followed by blocks of another	PS-butadiene
	Graft	Chains of one monomer type grafted onto the backbone of another	ABS, PVAc-chitosan
Phase	Crystalline	Regular chain arrangement, distinct melting point	Nylon, PET
	Amorphous	Irregular chain arrangement, exhibiting glass transition	Polystyrene, PVC

3.2.2.5. Special biomaterials based on nanotechnology

In addition to the four main groups, special materials such as cerium and magnetic nanoparticles (MNPs) have developed rapidly in the field of nanomedicine. Cerium is the most abundant rare earth metal from the lanthanide series and has two main oxidation states, namely Ce^{3+} and Ce^{4+}. Cerium's unique ability to switch between these two oxidation states makes it very useful in a variety of biomedical and industrial applications. In the biomedical field, cerium has shown great potential as a protective agent against cell damage caused by toxicants, pathological damage such as cardiac and brain ischemia, neurological disorders, retinal regeneration, as well as reduction of chronic infections (Priyadarshini & Vijayalakshmi, 2018). Cerium has also been proven to be toxic to cancer cells and can provide protection from radiation. One of the important properties of cerium is its anti-bacterial and antioxidant activity, which comes from its ability to produce Reactive Oxygen Species (ROS). These ROS work by damaging bacterial cell walls and causing cell death. Research also shows that cerium, especially in nanoparticle form (nanocerium), has self-regenerative antioxidant capabilities. This means that cerium can interact with free radicals such as superoxide and hydroxyl as well as hydrogen peroxide to reduce oxidative stress and prevent cell death. This is especially important in the context of diseases associated with oxidative stress that are difficult to treat (Yadav & Singh, 2021).

In nanoparticle form, cerium produces biological effects through the Ce^{3+}/Ce^{4+} redox mechanism that takes place on the particle surface. This mechanism mimics the activity of the enzyme superoxide dismutase (SOD), in which Ce^{3+} ions are oxidized to Ce^{4+} and reduce superoxide to hydrogen peroxide, which can then be converted to molecular oxygen. This process supports cerium's ability to handle oxidative stress and improve cell viability. Apart from that, cerium also shows anti-cancer activity, namely by triggering oxidative stress in cancer cells which causes apoptosis, but still protects normal cells through its antioxidant mechanism. In the endocrine field, cerium has potential as an anti-diabetic agent, especially through its influence on the regulation of insulin secretion. As an antioxidant, cerium is able to capture free radicals and prevent tissue damage, thereby protecting cells from degeneration due to oxidative stress. In the field of tissue engineering, cerium-based scaffolds are very effective in supporting the proliferation and differentiation of mesenchymal cells from bone marrow, which play an important role in bone regeneration and osteointegration. Apart from that, cerium can also be used in drug delivery systems because of its stable nature and ability to interact with target biomolecules specifically. Biomedical applications of cerium are summarized in **Figure 15** (Yadav & Singh, 2021; Priyadarshini *et al*., 2017).

Meanwhile, magnetic nanoparticles based on Fe_3O_4 or γ-Fe_2O_3 are used in cancer therapy via hyperthermia techniques, MRI medical imaging, and targeted drug delivery. The main advantage of MNPs lies in their ability to be modified with polymer or ceramic coatings; thus they can be directed to specific target locations in the body, reducing systemic side effects and increasing therapeutic efficiency (Wu *et al*., 2012).

Magnetic nanoparticles (MNPs), especially those based on iron oxide such as magnetite (Fe_3O_4), are an important component in the field of nanomedicine, a branch of nanotechnology that is developing rapidly in modern medical applications. Its very small size on the nanometer scale gives it the advantage of a high surface area and externally controllable magnetic properties. This makes MNPs very effective in various biomedical applications, such as medical imaging (MRI), cancer therapy, drug delivery systems, and the separation of specific microbes or cells. One of the main applications is hyperthermia therapy, in which MNPs are injected into the tumor site and then heated using a magnetic field to trigger selective death of cancer cells without damaging the surrounding healthy tissue (Gupta *et al*., 2005; Wu *et al*., 2012).

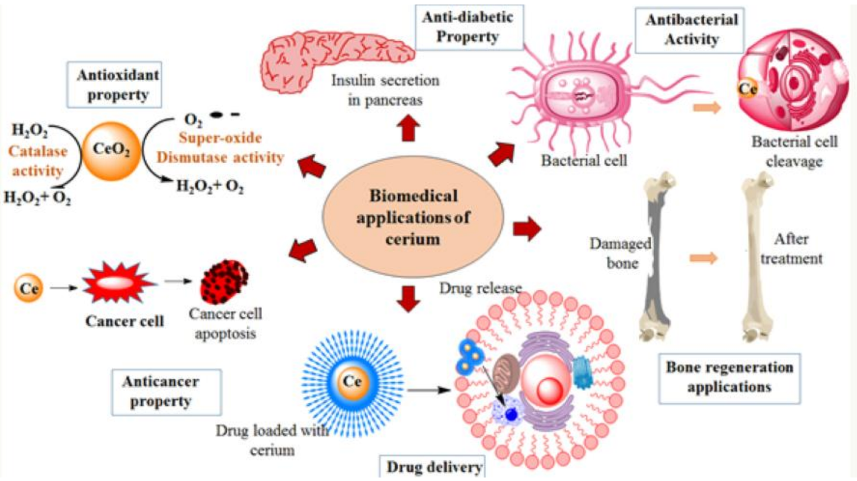

Figure 15. Various biomedical applications of cerium biomaterials (Priyadarshini *et al*., 2017).

Figure 16 describes the various biomedical applications of MNPs in five broad categories. First, in the therapeutic aspect, MNP is used for chemotherapy, gene therapy, and hyperthermia therapy, as well as for direct drug delivery to target cells, which allows for more precise doses and minimal side effects. Second, in the diagnostic field, MNPs are used in MRI, fluorescence imaging, and the use of quantum dots to detect tissue and disease more precisely. Third, in terms of targeting, MNPs are modified with antibodies, proteins or peptides so that they can specifically recognize and attach to target cells or molecules, such as cancer cells. Fourth, in the detection and separation aspect, MNP is able to detect the presence of bacteria and separate them from biological mixtures using a magnetic field, as well as triggering the death of microbes through catalytic reactions. Lastly, general applications of MNPs also include use in biomedical research, tissue regeneration, and treatment of musculoskeletal disorders (Priyadarshini *et al*., 2023).

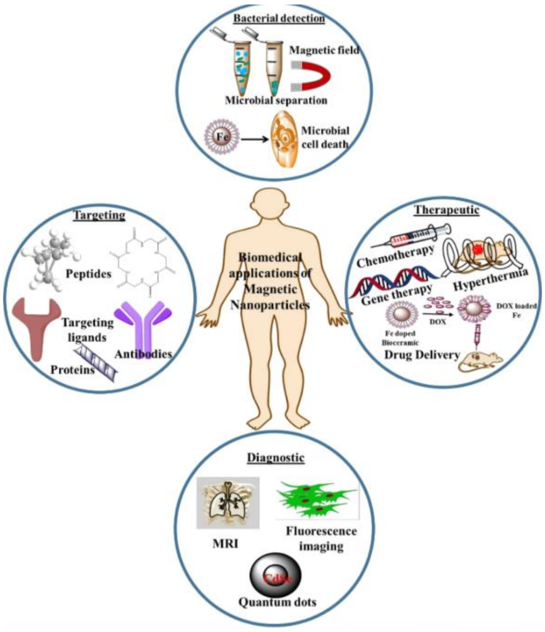

Figure 16. Biomedical applications of biomedical nanoparticles (Priyadarshini *et al*., 2023).

3.2.2.6. Biomaterial properties

The selection of biomaterials is a crucial aspect in the success of medical applications. because biomaterials will interact directly with body tissue and influence the biological responses that arise, such as wound healing, inflammation, and tissue integration. The selected material must have a combination of physical, chemical, mechanical and biological properties that are appropriate to its function and location of use in the body. For example, in surgical implant applications such as bone or joint replacement, biomaterials must be able to withstand sustained mechanical loads without deformation or structural failure. Therefore, metals such as titanium, stainless steel (316L SS), and cobalt-chrome alloy are used because they have high mechanical strength and corrosion resistance. **Figure 17** schematically explains the seven main factors that influence the performance of biomaterials in medical applications (Lemons & Lucas, 1986).

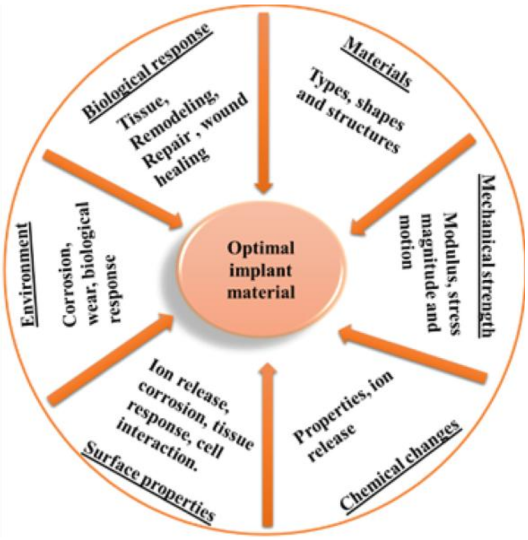

Figure 17. Schematic representation of factors affecting the biomaterials implant (Lemons & Lucas, 1986).

3.2.2.7. Contribution of biomaterials to sdgs

Biomaterials, both natural and synthetic, make a significant contribution to achieving various Sustainable Development Goals (SDGs), especially in the fields of health, industrial innovation, sustainable consumption-production, and environmental protection. First, in the context of SDG 3 (Health and Well-Being), biomaterials play a direct role through the development of biocompatible implants, tissue scaffolds, nanoparticle-based drug delivery systems, and wound healing materials that support tissue regeneration. The use of cerium oxide nanoparticles, for example, provides protection against oxidative damage and has potential as an anti-cancer and anti-inflammatory agent. Meanwhile, magnetic nanoparticles (MNPs) are used in hyperthermia therapy, MRI imaging, and targeted drug delivery systems, all of which improve diagnostic accuracy and therapeutic effectiveness with minimal side effects.

Second, biomaterials support SDG 9 (Industry, Innovation and Infrastructure) through high-tech material engineering that encourages innovation in the health sector and biomedical manufacturing industry. Materials such as metal and ceramic matrix composites, bioglass scaffolds, and special polymers for regenerative applications are examples of how biomaterials support the development of resilient and innovative industries. Third, the contribution of biomaterials to SDG 12 (Responsible Consumption and Production) can be seen from the use of natural raw materials and biological waste such as chitosan from shrimp shells or collagen from livestock waste, which can reduce dependence on petrochemical-based synthetic materials. Biodegradable biomaterials such as magnesium and PLA polymers also reduce long-term medical waste because they dissolve in the body biologically after their job is done.

Fourth, in relation to SDG 13 (Action on Climate Change), biomaterials derived from biomass or organic waste can reduce the carbon footprint of the production process, as well as reduce emissions from the medical disposal process. The use of biomaterials that are efficient and can be produced locally also reduces dependence on carbon-intensive global supply chains. Fifth, for SDG 14 and 15 (Conservation of Marine and Land Ecosystems), biomaterials play a role in supporting environmentally friendly practices by utilizing biological resources sustainably. For example, chitosan or cellulose-based scaffolds from agricultural and marine waste can add value to local resources while protecting marine and forest ecosystems from over-exploitation. In addition, because of their biodegradable nature, biomaterials also contribute to reducing the accumulation of microplastics and toxic materials in nature. Thus, the development and application of biomaterials is not only oriented towards meeting medical needs, but also strengthening the transition towards a green economy and sustainable development that is comprehensive, cross-sectoral, and based on environmentally friendly innovation.

3.2.3. Waste-derived materials

Utilizing waste or waste-derived materials is currently a strategic approach that not only addresses environmental problems caused by food waste, but also produces high-value products that contribute to the circular economy and achieving the SDGs. With rapid population growth, food needs and industrial processing activities also increase, which leads to an increase in the amount of food waste. This waste has great potential to be converted into functional products because of its nutritional content, such as complex carbohydrates, proteins, lipids and bioactive compounds (Raak *et al*., 2017).

The food supply chain produces waste at every stage, from production, storage, processing, distribution, to consumption. Waste can come from plants, such as rice husks, straw, or fruit processing waste, and from animals, such as fishery waste, slaughterhouses, and dairy waste (Raak *et al*., 2017). Conversion of this waste requires appropriate technological strategies and processing systems, thus it can produce biofuels, industrial enzymes, bioactive compounds, nanoparticles, biodegradable plastics, and industrial materials such as collagen and chitosan (Mishra *et al*., 2023).

In plant waste, transformation can be carried out through four main pathways: (i) Extraction produces valuable products such as bioactive compounds, lipids, phenols, nanoparticles, or biofuels such as biodiesel; (ii) Incineration produces ash or construction materials such as hydrogel; (iii) Hydrolysis and fermentation produce bioethanol, biohydrogen, enzymes and bioplastics; (iv) Anaerobic digestion produces energy and organic fertilizer. Meanwhile, animal-based waste has the potential to be processed into collagen, chitosan, protein hydrolyzate, bioactive peptides, and cosmetic products or soil nutrients (Chen *et al*., 2024). **Figure 18** shows how waste from the food supply chain can be transformed into various high-value commercial products through several technology-based processing pathways.

A concrete example, instant noodle waste has been successfully converted into bioethanol with an efficiency of 96.8% through simultaneous fermentation with the microorganism Saccharomyces cerevisiae. Waste cooking oil is also converted into biodiesel using the lipase enzyme, while biohydrogen is produced from empty oil palm bunches or wheat straw using microorganisms such as Enterobacter and Bacillus (Yang *et al*., 2014). On the other hand, fiber-rich lignocellulosic waste such as rice straw, beer dregs, or fruit waste becomes raw material for the production of industrial enzymes such as cellulase, laccase, amylase, and lipase, which are used in various sectors.

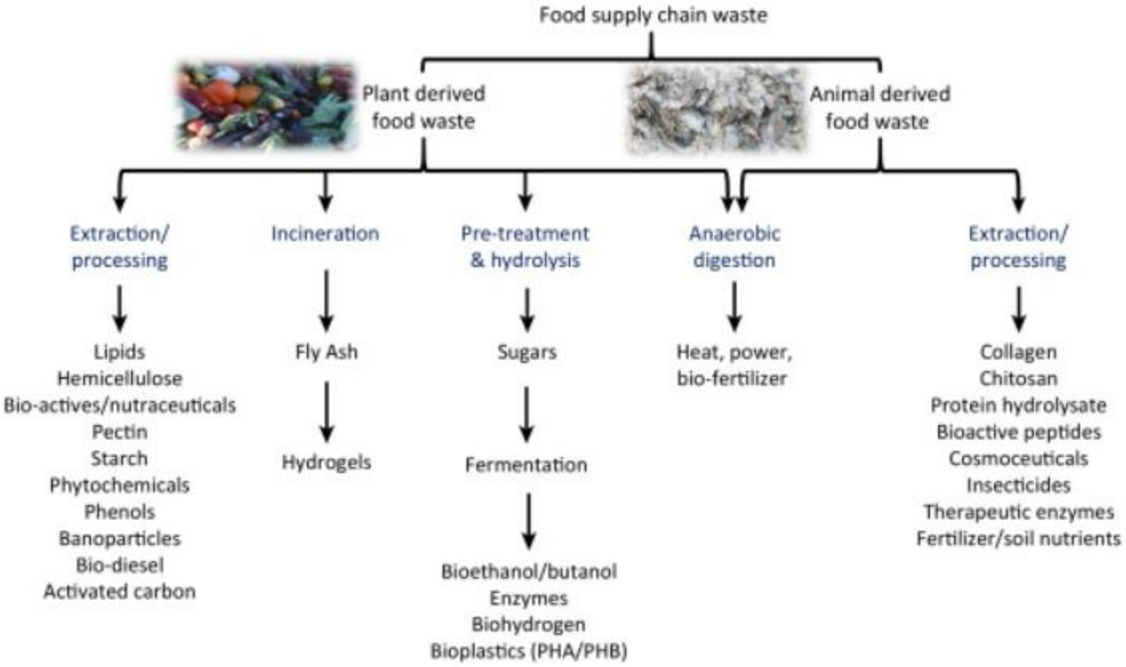

Figure 18. Possible commercial products that can be derived from food supply chain waste (Aït-Kaddour *et al*., 2024).

Food waste, especially lignocellulosic-based organic waste, is currently a potential source for the production of high-value industrial enzymes. The process of producing enzymes from this waste generally begins with the pretreatment stage of lignocellulose, which aims to decompose the complex structure of the material, followed by enzymatic hydrolysis to release its constituent components such as simple sugars. However, in some cases, this enzymatic hydrolysis process can be eliminated if certain microorganisms are used, such as the fungi *Scytalidium thermophilum*, *Melanocarpus sp.*, *Aspergillus sp.*, and *Pleurotus sp.*, which are naturally capable of degrading plant biomass. The types of enzymes most commonly produced from food waste include oxidative enzymes such as cellulase, laccase, amylase, xylanase, phytase and lipase. These enzymes have wide applications in the food, textile, bioenergy and environmental processing industries (Stamatakis, 2010; Ravindran & Jaiswal, 2016).

Food waste, especially from agricultural and fishery products, is now widely used as a source of raw materials to produce bioactive compounds and nutraceuticals, namely compounds with high health benefits. This trend is becoming increasingly popular as awareness of health and sustainability increases, and is even equivalent to using waste for bioenergy production. For example, rice bran, waste from the rice milling industry, is rich in fiber, protein, minerals, vitamins and bioactive compounds such as tocopherols and polyphenols. Consuming rice bran is known to reduce the risk of cancer, improve heart health, and lower cholesterol levels. Studies show that adding 30% rice bran to bread dough can increase antioxidant activity up to five times. In addition, orange peel waste and fruit dregs contain phenols and carotenoids, which are useful for extending the shelf life of food and preventing the formation of unpleasant flavors. Pectin from plant waste is widely used as a thickening agent in candy or as a fat substitute in meat products. Marine product waste such as seaweed, shrimp shells or fish waste produces hydrolyzed protein, chitosan, collagen and natural pigments which are used in the food, pharmaceutical and cosmetic sectors. **Table 8** shows a summary of food waste origins and target molecules for recovery (Cesário *et al*., 2014).

Table 8. Summary of food waste origins and target molecules for recovery (Ravindran *et al.*, 2016).

Waste Origin	Waste Source	High-Value Product
Cereals	Rice bran	Insoluble dietary fiber
	Sesame husk	Insoluble dietary fiber
	Wheat bran	Fructan (prebiotic fiber)
	Oat milling waste	Antioxidants
	Brewer's spent grain	Ferulic acid (antioxidant)
Oil Crops	Olive oil refinery waste	Pectin & phenols
	Winter rapeseed	Phytosterols
	Kalahari melon seed	Phytosterols
	Soy whey waste	Aglycone isoflavones
Fruits & Vegetables	Orange peel	Apocarotenoids, limonene
	Apricot seeds	Protein isolate
	Apple pomace	Polyphenols
	Tomato pomace	Lycopene
	Tomato peel	Carotenoids
Meat & Fishery Waste	Poultry waste	Proteins
	Slaughterhouse waste	Collagen
	Fish waste	Fish protein hydrolysate
	Shrimp & crab shells	Chitosan & carotenoid pigments
Dairy Industry	Cheese whey waste	Lactalbumin (milk protein)

Biodegradable plastics such as Polyhydroxyalkanoates (PHAs) and Poly-3-hydroxybutyrate (PHB) are environmentally friendly alternatives to petroleum-based plastics (Obruca *et al.*, 2015; Cesário *et al.*, 2014). However, the biggest challenge in commercializing this plastic is the high production costs, especially raw material costs. Therefore, food waste and agricultural residues that are abundant and have no economic value have been used as raw materials for PHA/PHB production. Waste such as wheat straw, sugar cane bagasse, wheat waste, palm oil waste and coffee waste have proven to be effectively used as carbon sources by various microorganisms to produce bioplastics. For example, Burkholderia sacchari is able to convert wheat straw hydrolyzate into PHB with an accumulation efficiency of 60% of cell dry weight. Apart from that, spent coffee waste is also a potential raw material. This waste contains around 10% oil which can be converted into PHB by Cupriavidus necator. After the oil is extracted, the solid residue rich in cellulose and hemicellulose is processed into sugar, which is then fermented by Burkholderia cepacia to produce PHB or P(3HBco-3HV) copolymer, thanks to the levulinic acid content in the waste (Cesário *et al.*, 2014). **Table 9** summarizes PHA/PHB producing microorganisms from food waste.

By optimizing waste into high-value materials, we not only reduce the impact of waste on the environment, but also create new resources that support industrial resilience, reduce dependence on fossil raw materials, and accelerate the transition to a sustainable, circular economy. The following is an integrated and comprehensive contribution of waste-derived materials to various SDGs targets:

(i) SDG2: Zero Hunger

First, in the context of SDG 2, the conversion of agricultural and food industry waste into organic fertilizer, biofertilizer and soil enhancer increases land productivity in a sustainable manner. Waste such as agricultural residues, household organic waste, and agro-industrial waste are processed through processes such as anaerobic digestion, producing nutrient-rich biofertilizers. This not only increases crop yields but also reduces farmers' dependence on synthetic chemical fertilizers, while maintaining soil fertility in the long term.

(ii) SDG 3: Good Health and Well-Being
Second, contribution to SDG 3 can be seen from the use of waste into bioactive compounds and nutraceuticals. Products such as polyphenols from apple waste or rice bran act as antioxidants that protect the body from degenerative diseases. Phytosterols from melon seed waste or pectin from olive waste have benefits in lowering cholesterol and maintaining heart health. In fact, animal waste such as shrimp shells and fish waste is processed into chitosan, collagen and functional protein for applications in the fields of pharmaceuticals, cosmetics and wound care, which improves people's health.

(iii) SDG 6: Clean Water and Sanitation
In SDG 6, materials such as chitosan obtained from shrimp shell waste have the ability to act as natural coagulants in water treatment. The use of chitosan can replace synthetic chemicals in the drinking water and wastewater treatment process, increase processing efficiency and maintain the quality of water resources.

(iv) SDG 7: Affordable and Clean Energy
In supporting SDG 7, food and agricultural waste is converted into renewable bioenergy such as bioethanol from instant noodle waste, biodiesel from cooking oil waste, and biohydrogen from empty palm oil bunches. This innovation provides environmentally friendly energy alternatives, reduces dependence on fossil fuels, and accelerates the transition to clean energy.

(v) SDG 8: Decent Work and Economic Growth
On the socio-economic side, the development of waste conversion technology encourages SDG 8 by creating new jobs, especially in the fields of biotechnology, waste processing and bioeconomy-based industries. The development of products such as bioplastics, bioenzymes, nanoparticles and active health ingredients increases the competitiveness of national industry and provides added value to the agricultural and fisheries sectors.

(vi) SDG 9: Industry, Innovation and Infrastructure
Furthermore, contributions to SDG 9 are reflected in the development of high-tech materials from waste, such as nanoparticles from rice husks, biodegradable bioplastics from agricultural residues, as well as hydrogels and fly ash from waste incineration processes. This innovation strengthens sustainable industrial infrastructure, reduces dependence on fossil-based raw materials, and encourages the development of environmentally friendly technologies.

(vii) SDG 12: Responsible Consumption and Production
The implementation of waste-derived materials also supports SDG 12 by encouraging the efficient use of resources and reducing the volume of waste that ends up in final disposal sites (TPA). Processing waste into valuable products reduces carbon footprints, minimizes environmental pollution, and strengthens circular economy principles, where waste is no longer considered a problem but rather a valuable resource.

(viii) SDG 13: Climate Action
Regarding SDG 13, converting waste into biofuels, bioplastics, and other materials with low carbon emissions helps mitigate climate change. By reducing decomposing organic waste that produces greenhouse gases and replacing high-emission fossil-based products, this technology supports the transition to a low-carbon economy and contributes to reducing global emissions.

(ix) SDG 14 dan 15: Life Below Water dan Life on Land

Finally, in the marine and land ecosystem aspects, namely SDG 14 and SDG 15, food and fisheries waste management prevents environmental pollution. The use of biodegradable bioplastics reduces the accumulation of plastic waste in the ocean, while the conversion of organic waste into organic fertilizer improves soil health, prevents land degradation, and protects biodiversity.

Table 9. PHA/PHB producing microorganisms from food waste (Ravindran & Jaiswal, 2016).

Microorganism	Type of Waste	Type of PHA Produced
Bacillus firmus	Rice straw hydrolysate	PHB
Ralstonia eutropha	Sugarcane bagasse	PHB
Halomonas boliviensis	Wheat and potato waste mixture	PHB
Azotobacter beijerinckii	Coconut coir pith waste	PHB
Burkholderia sacchari	Wheat straw hydrolysate	PHB
Mixed culture (activated sludge)	Olive pomace	PHA
Bacillus megaterium	Empty fruit bunch (oil palm waste)	PHB
Saccharophagus degradans	Tequila bagasse waste	PHA
Pseudomonas sp.	Grass	Medium-chain PHA

3.3. Several Examples of Sustainable Material Applications in Various Areas

Materials play an important role in supporting the achievement of the SDGs by strengthening the transition towards a green economy, resource efficiency, and improving the quality of human life sustainably. Material innovation does not just meet the technical needs of an industry, but also drives solutions to global challenges such as the energy crisis, clean water scarcity, environmental degradation, health, and climate change. Various types of materials developed by modern science, including functional materials, waste-based materials, biomass materials, and nanomaterials, have been proven to have a strategic role in supporting various sectors directly related to the SDGs targets.

3.3.1. Materials as energy storage media

The development of biomass-based materials as energy storage components, especially in battery technology, is a strategic step in supporting the transition to a more sustainable, environmentally friendly, and safe energy system. Biomaterials have a number of advantages, such as abundant availability, biodegradable properties, biocompatibility, and the ability to reduce dependence on petroleum-based synthetic materials that have dominated the battery industry.

Currently, various biomaterials (see **Table 10**) such as polysaccharides, lignin, chitosan, collagen, and natural compounds such as polydopamine and flavin have been successfully integrated into various battery components, starting from electrodes, binders, separators, to electrolytes. Polysaccharides obtained from plant biomass and marine waste, such as shrimp shells, are widely used as environmentally friendly binders. Polysaccharide-based binders not only increase the mechanical strength and flexibility of electrodes but also boost ion transport efficiency, without generating synthetic plastic waste as is common in conventional batteries. In addition, polysaccharides such as chitosan can be modified into gel or solid-state electrolytes, which are more stable and reduce the risk of liquid electrolyte leakage (Crespilho *et al.*, 2025).

Lignin, a by-product from the wood industry and agriculture, is an alternative material for separators or electrode coatings that is heat resistant and has high structural strength, thereby increasing battery safety, especially in extreme conditions. Meanwhile, collagen derived from fishery waste is used as an elastic binder that can provide structural strength, making it ideal for flexible batteries and portable electronic devices that require high durability. Polydopamine (PDA), a bio-inspired polymer resulting from the polymerization of dopamine, shows great potential as a multifunctional material. Apart from having strong adhesive properties, PDA is also redox active, acting as a binder, protective layer for electrodes, while increasing the energy storage capacity of the battery. Several studies have shown that PDAs can increase capacity up to 1818 mAh/g in lithium-ion batteries, far exceeding conventional capacities (Crespilho *et al.*, 2025).

On the other hand, flavin, a bioactive compound contained in vitamin B2, also has high redox activity and is used in battery systems, both as electrode material and electrolyte. The use of flavin has been proven to increase battery capacity, stability and lifetime, for example in redox-flow batteries which are able to maintain cycle stability of more than 99% after 100 charges. Not only that, various other biomaterials such as lawsone, hydroxyapatite, humic acid, and nature-inspired inorganic materials such as silica and calcium carbonate, play an important role in improving the structural stability, conductivity and electrochemical efficiency of batteries (Crespilho *et al.*, 2025).

Table 10. Biomaterial as energy storage media application (Crespilho *et al.*, 2025).

Category	Materials	Application
Natural Polymers and Biomolecules	Cellulose, Carrageenan, Chitosan-based materials, Cellulose Acetate, Gelatin-based Hydrogels, Polylactic acid (PLA), Poly(3-Hydroxybutyrate-Co-Hydroxyvalerate) (PHBV), Silk, Recycled Poly(ethylene terephthalate) (PET)-based Materials, Wool	Templates, binders, separators, solid-state electrolytes
Carbon Materials	Sustainable Carbon Materials (e.g., Carbon Nanotubes, Graphene, Bamboo Charcoal)	High conductivity, electrodes
Carbohydrates	Polydopamine, Lawsone, Flavin, Redox compounds (e.g., Ubiquinone, Polyaniline, Ferrocene)	Redox-active materials, electrodes, binders, separators
Recycled and Eco-Friendly Materials	Coffee grounds-derived Activated Carbon, Banana Fiber-Reinforced Composites, Recycled Glass Electrolyte Membranes, Compostable Polymer Blends, Recycled PET-based Materials	Sustainable materials for electrodes, separators, and other battery components
Solvents	Ionic liquids, Deep Eutectic Solvents (DESs), Poly(ionic liquids), Salts, Environmentally Friendly Solvents, Biogels	Electrolytes for LIBs, eco-friendly ionic liquids
Inorganic Materials	Hydroxyapatite, Calcium carbonate, Silica, Zeolites, Metal Organic Frameworks	Stabilizers for electrodes, porous electrodes, separators

3.3.2. Material for environmentally friendly construction and infrastructure

Global demand for infrastructure and construction is increasing sharply due to population growth and economic development. However, the construction sector contributes significantly to energy consumption (36%) and CO2 emissions (39%). This situation creates great pressure on the environment, especially due to dependence on non-renewable natural resources and the minimal adoption of sustainable construction materials or SCMs (Sustainable Construction Materials). SCMs are the key to overcoming the two main challenges of the construction industry, namely the scarcity of natural resources and efforts to reduce carbon emissions in order to realize sustainable development (Chen *et al*., 2024).

SCMs can be classified into two large categories, namely waste materials and renewable natural materials, as shown in Figure 19. Waste that can be utilized includes industrial waste (fly ash, slag, silica fume), agricultural waste (straw, rice husks, plant fibers), construction and building demolition waste (C&D waste), as well as animal wool or compacted soil. Meanwhile, renewable natural materials include bamboo, hempcrete, mycelium, plant-based polyurethane foam, and sheep's wool (Chen *et al*., 2024).

Utilization of SCMs not only reduces dependence on natural raw materials, but also increases energy efficiency and minimizes health impacts. As depicted in the second illustration, the advantages of SCMs include:

(i) Health aspects: Natural materials reduce exposure to toxic materials, improve well-being, and recycled plastic waste minimizes health risks.
(ii) Energy efficiency: Recycling industrial waste reduces energy consumption, while plant and animal fibers improve the thermal insulation of buildings.
(iii) Renewable sources: The use of waste as a cement substitute and technological innovation enable the creation of new environmentally friendly construction materials.

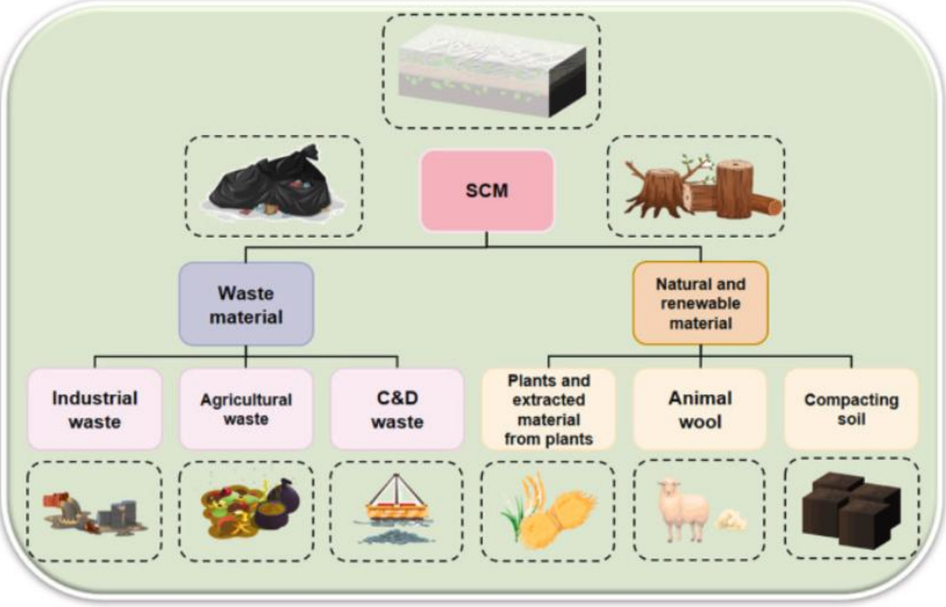

Figure 19. SCM classification (Chen *et al*., 2024).

Examples of applicable SCMs include the use of rice husk ash as a partial replacement for cement, which can increase the compressive strength and durability of concrete as long as it is controlled at optimal proportions (around 5–15%). Industrial waste (such as slag, silica fume, and fly ash) has also been proven to increase the durability of concrete and reduce the carbon footprint. In addition, nanotechnology based on agricultural waste, such as nanoparticles from rice husk ash, sugar cane bagasse, or nanocellulose from plant fibers, has shown great potential in increasing the strength, durability and microstructure of building materials, even to the application of 3D printing for more efficient construction components with minimal waste (Cesário *et al*., 2014). The SCMs' classification table based on source, availability, and main applications is shown in **Table 11**.

Table 11. Classification of SCM based on source, availability and primary application (Li *et al.*, 2022; Cesário *et al.*, 2014).

SCMs Category	Material Type	Availability	Main Applications
Waste-Based Materials	Cork (waste from Quercus suber trees)	Agricultural waste from the Mediterranean	Insulation panels, acoustic panels, green walls
	Straw Bales	Agricultural waste from various regions	Insulation panels, partial replacement for cement
	Recycled Plastic	Municipal, industrial, and construction waste	Composite concrete, eco-friendly bricks
	Precast Concrete	Prefabrication factories	Structural frames, slabs, walls
	Ferrock (iron industry waste)	Industrial waste	Greener alternative to cement
	Timbercrete (sawdust-based material)	Agricultural waste	Architectural elements, fine aggregate substitute
	Terrazzo (epoxy resin composite)	Chemical industry	Flooring, concrete performance enhancer
Natural & Renewable Materials	Bamboo	Fast-growing bamboo plantations	Roof trusses, walls, floors, foundations, scaffolding
	Sheep's Wool	Sheep farming	Insulation, acoustic panels, moisture absorption, cement substitute
	Rammed Earth	Locally sourced compacted soil	Structural building elements
	Hempcrete (hemp plant fibers)	Hemp cultivation	Insulation, acoustic panels
	Plant-Based Polyurethane Foam	Plant extracts	Insulation, acoustic panels
	Mycelium (fungus-based material)	Naturally derived through biological processes	Insulation, acoustic panels

3.3.3. Material for health

Science and technology have played a critical role in advancing healthcare, increasing life expectancy, and reducing mortality through innovative biomedical approaches. One of the most significant developments is the use of biomaterials (see **Table 12**), especially biopolymers, for drug delivery systems, tissue engineering, and regenerative medicine. In recent decades, substantial progress has been made in designing biomaterials that replicate the structure and function of natural tissues. There is growing interest in multifunctional and bioinspired scaffolds with unique physical and chemical properties that enhance tissue regeneration. Polymers, both synthetic and natural, are essential in creating three-dimensional extracellular matrix (ECM) templates to support cell growth and healing. Synthetic polymers offer flexibility in design, allowing fine-tuning of mechanical strength, degradation rates, and immune compatibility. Meanwhile, natural polymers, including collagen, gelatin, hyaluronic acid, alginate, fibrin, and cellulose, provide biocompatibility, biodegradability, and structural similarity to native tissues, making them ideal for medical applications (Baranwal *et al.*, 2022).

Natural biopolymers have been successfully utilized for hard and soft tissue repair, either alone or combined with synthetic components. Their versatility extends to wound healing, vascular grafts, intraocular lenses, artificial organs, drug delivery, dental implants, and more. Biopolymers can be engineered into various forms like hydrogels, membranes, or scaffolds, supporting cell growth, drug release, and structural reinforcement. "Smart" biopolymer hydrogels, which respond to stimuli such as pH, temperature, or electric fields, have also emerged, opening new possibilities in targeted therapies, gene expression control, and bioengineering (Baranwal *et al*., 2022).

In tissue engineering, peptide-based biopolymers, including self-assembling polypeptides and chemically crosslinked gels, provide scaffolds with tailored bioactivity and biodegradability. The synergy between synthetic polymers and biopolymers allows the development of advanced materials capable of modulating cellular behavior and enhancing therapeutic outcomes. Molecular biology and polymer chemistry advancements enable precise control over biopolymer structures, making them highly adaptable for medical applications (Baranwal *et al*., 2022).

Table 12. Medical application of biopolymers (Baranwal *et al*., 2022).

Biopolymer	Medical Applications
Collagen	Tissue culture coating, simple gels for cell culture
Alginate	Regenerative medicine, tissue engineering
Hyaluronic Acid	Joint lubrication, skin/corneal wound healing
Fibrin	Blood clotting, wound healing, surgical sealants
Silk Fibroin	Regenerative medicine, wound healing, tissue bioengineering
Agarose	Skeletal tissue regeneration, cell encapsulation (kidney, fibroblasts)
Carrageenan	Skeletal tissue regeneration, cell delivery systems
Fibronectin	Wound healing, cardiac repair, bone regeneration
PHAs (Polyhydroxyalkanoates)	Drug delivery, bone tissue regeneration
Elastin	Soft-tissue reconstruction, orthopedic implants, cell encapsulation
Keratin	Corneal tissue engineering, skin regeneration
Starch	Bone/cartilage regeneration, spinal cord injury treatment

3.3.4. Material for water treatment and environment

Environmental pollution has become one of the most pressing global challenges, driven by increasing contamination of air, water, and soil from industrial activities, agriculture, urbanization, and other human actions. Pollutants such as particulate matter, heavy metals, pesticides, fertilizers, oil spills, toxic gases, and organic waste present complex and harmful mixtures that are difficult to remediate using conventional technologies. To address this, scientists have increasingly turned to nanotechnology for developing advanced, efficient, and targeted environmental remediation strategies. **Figure 20** shows environmental remediation techniques that are broadly categorized into five key approaches (Guerra *et al*., 2018).

Nanomaterials, due to their nanoscale size and large surface-to-volume ratio, exhibit enhanced reactivity, tunable surface chemistry, and the ability to be functionalized for specific pollutant capture. Compared to bulk materials, nanomaterials allow precise control over properties like size, morphology, porosity, and chemical composition, enhancing their selectivity, efficiency, and stability for pollutant remediation. Hybrid or composite nanomaterials, combining different components (e.g., nanoparticles with supporting scaffolds), further improve performance by integrating the desirable properties of each material, such as enhanced stability and target-specific pollutant interaction (Guerra *et al*., 2018).

However, while nanotechnology presents promising solutions, challenges remain regarding environmental safety and long-term stability. Materials used for remediation must themselves be non-toxic, preferably biodegradable, and capable of safe decomposition after use to avoid secondary pollution. Furthermore, the design of nanomaterials for environmental applications must consider target specificity, cost-effectiveness, ease of synthesis, recyclability, and potential for regeneration (Guerra *et al*., 2018).

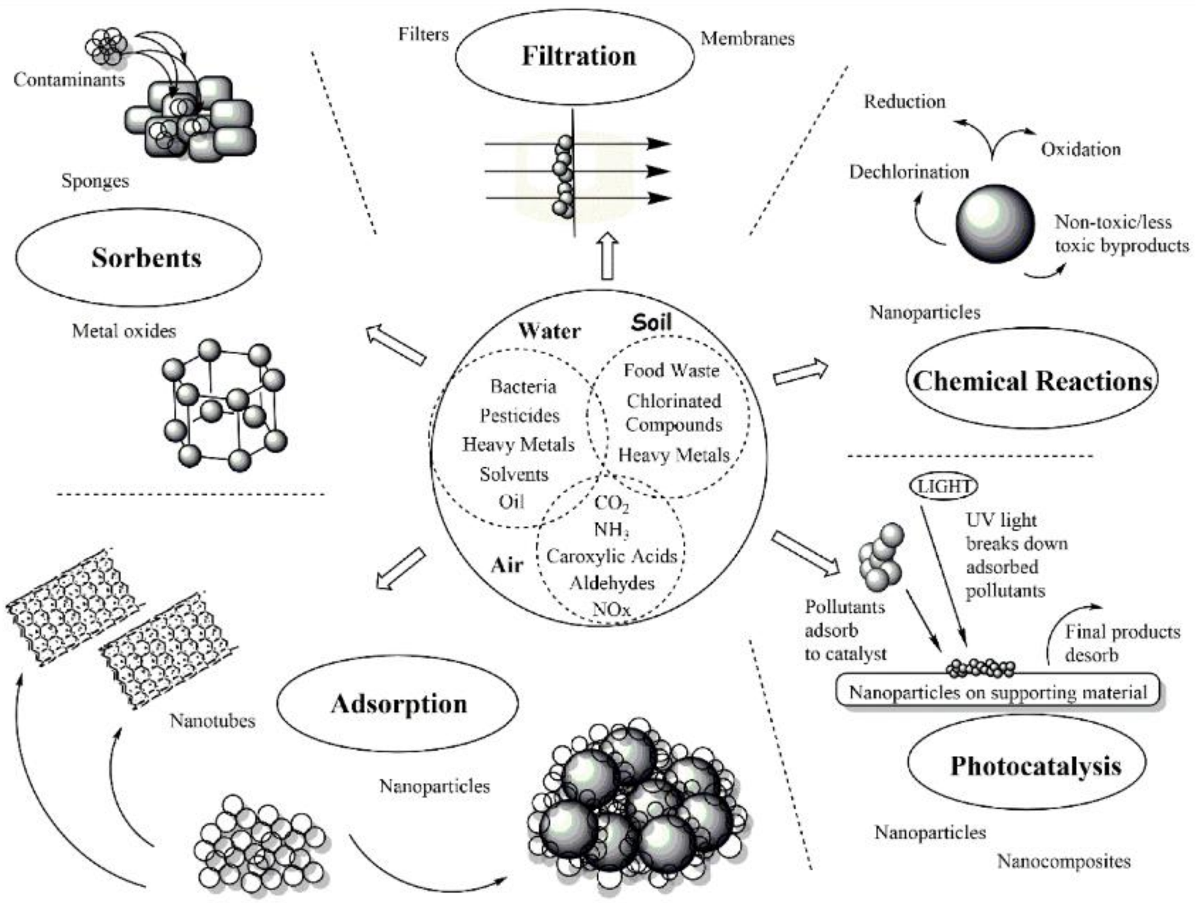

Figure 20. Environmental remediation approaches (Guerra *et al*., 2018).

3.4. Responsible Material Management: The Relationship of Chemistry, Material Stewardship, and Sustainability

The concept of the relationship between chemistry, material stewardship (responsible material management), and sustainable development is visualized systematically through two key diagrams that show the contribution of chemistry to sustainability. **Figure 21** represents the "layers of the onion" concept in which chemistry is placed at the innermost core, providing the molecular and material basis for global sustainability (Whalen *et al*., 2022). In **Figure 21**, efforts to achieve sustainability are built in stages, starting from the scientific basis of chemistry itself, to the material stewardship mission, then strengthened by global frameworks such as SDGs, Planetary Boundaries, and Human Security, continued by various chemical movements and orientations, up to analytical tools and cross-disciplinary strategies in the outermost circle (Matlin *et al*., 2025).

At its core, chemistry plays an important role as a provider of knowledge and materials innovation, which underlies almost all aspects of sustainable development. The main mission of chemistry in the current era is to ensure the transformation, use and conservation of the earth's material resources in accordance with the principles of sustainability, which not only considers the availability of materials, but also their impact on the planet's physical and biological systems. Material stewardship in this case is not just about recycling or production efficiency, but includes holistic efforts to maximize the useful life of materials, understand the limited stock of elements on earth, and innovate science-based products and processes to reduce environmental and social impacts (Matlin *et al*., 2025).

Frameworks such as the SDGs play an important role in concretely directing chemistry's contribution to sustainability. The SDGs contain global targets such as climate action, pollution reduction, clean energy transition, water, food and health management, all of which require material innovation and chemical solutions that are safe, efficient and sustainable. In addition, the concept of Planetary Boundaries clarifies the safe limits of the earth system that must not be exceeded. Chemistry plays a role in monitoring indicators such as concentrations of hazardous chemicals, carbon emissions, or biogeochemical cycles that affect the stability of global ecosystems (Matlin *et al*., 2025).

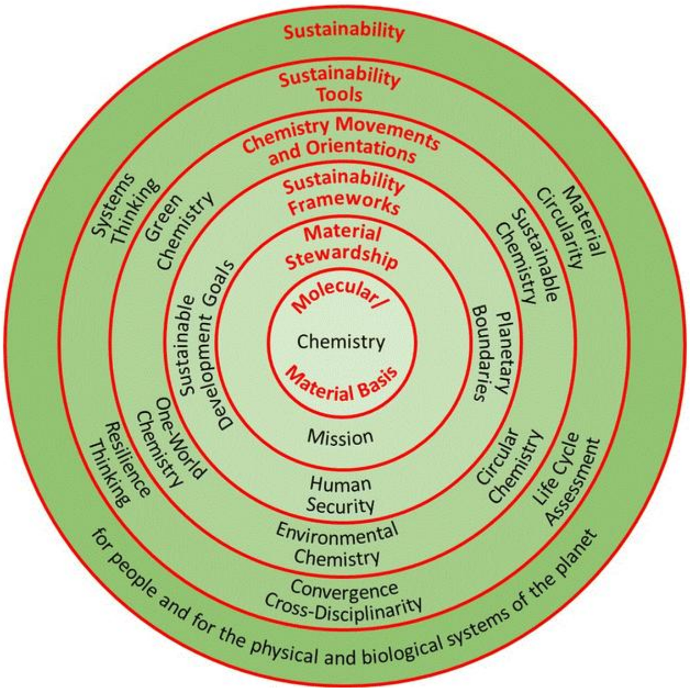

Figure 21. Chemistry's contributions to sustainability, grounded in its molecular/material basis and mediated by a material stewardship mission, frameworks, chemistry movements and orientations, and tools (Matlin *et al*., 2025).

Figure 22 deepens the understanding of stewardship by mapping three fundamental elements: Care (care/responsibility), Knowledge (knowledge/understanding), and Agency (capacity/ability). It is in the intersection area of these three elements that stewards take real action, namely actions based on ethics, motivation and knowledge that are directed at managing material resources responsibly. Chemistry plays a central role here, because in addition to providing scientific understanding of the behavior of material systems and their impacts, chemistry also builds new technologies, processes and materials that enable effective stewardship. Furthermore, in the Care dimension, chemistry is required to take responsibility for maintaining the availability of material resources, for example through designing materials that are more durable, efficient production processes, and reducing dependence on critical or rare materials. In the Knowledge dimension, the role of chemistry is very strong in understanding the impact of materials on the environment through analytical tools such as Life Cycle Assessment (LCA), systems analysis, and chemical pollution monitoring. On the Agency side, various movements such as Green Chemistry, Sustainable Chemistry, Circular Chemistry, and the One-World Chemistry approach build practical capacity, both at the individual, industry and global system levels to implement material stewardship in real terms (Mathevet *et al*., 2018).

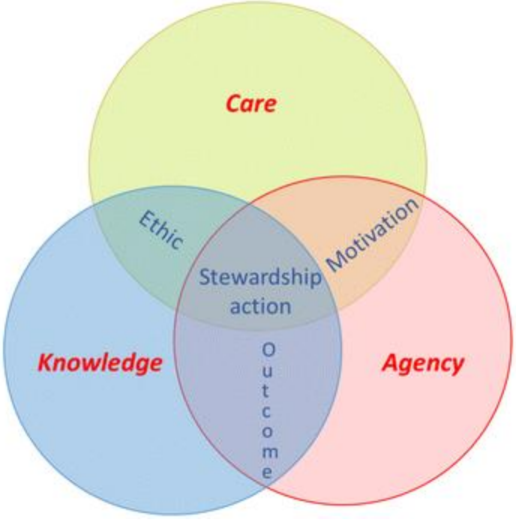

Figure 22. Meanings and domains of stewardship guiding chemistry's role in material stewardship reproduced (Matlin *et al*., 2025).

Supporting tools such as Material Circularity, LCA, Systems Thinking, and cross-disciplinary collaboration are the technical foundation in driving the transformation of industry and society towards a more efficient, safe and sustainable direction. However, it is important to realize that material circularity or recycling alone does not automatically produce sustainability if it is not accompanied by reduced consumption, impact management throughout the supply chain, and product design that considers environmental degradation and safety. In conclusion, the integration model between chemistry, material stewardship, and sustainability underlines that sustainable development is not just a matter of policy or technology, but involves ethical responsibility, strong scientific knowledge, and practical abilities to realize change. The role of chemistry as an applied science is vital for understanding Earth's material systems, designing innovative solutions, and guiding global society to stay within safe planetary limits while meeting current and future human needs (Guinée *et al*., 2022; Espinosa *et al*., 2022).

3.5. Progress and Indicator for the Sustainable Development Goals

Materials in the context of achieving the Sustainable Development Goals or SDGs must be the main instrument that prioritizes handling climate change, financial sector reform, the transition to affordable and clean energy, as well as the application of the concept of material circularity which encourages sustainable economic growth. Climate change is the most pressing challenge that threatens the balance of the earth system. The production and consumption of materials such as building materials, metals, plastics, and technological components contributes significantly to greenhouse gas emissions, environmental degradation, and overexploitation of natural resources. Therefore, innovation in the materials sector is a priority to support the low-carbon transition. This includes the development of energy efficient materials, biomass-based materials, environmentally friendly nanomaterials, as well as carbon capture technology that can strengthen the resilience of ecosystems, infrastructure and public health (Tiwari, 2023).

Apart from technical aspects, financial sector reform is very necessary so that the entire process of production, distribution, use and recycling of materials is in line with sustainability principles. The 2023 SDGs report emphasizes six financial reform priorities, namely investment that supports sustainable development, strengthening sustainability indicators, developing a transparent financial system, integrating national planning with the SDGs, strong supervision and regulation, and innovation in international cooperation. Material management must be the focus of green investment and sustainable finance, because the availability and distribution of low-carbon technology materials will determine the acceleration of the clean energy transition and the achievement of other SDGs targets (Mahmood *et al*., 2024).

Another priority that must be emphasized is the development of clean and affordable energy. This energy transition relies heavily on the availability of innovative materials such as silicon, rare earth metals, graphene, recycled materials for solar panels, wind turbines, high-capacity batteries and energy storage technology components. Without efficient, strong and environmentally friendly materials, the costs of renewable energy technology are difficult to reduce, thus access to clean and affordable energy is uneven, especially in developing countries. Therefore, material innovation must be directed at increasing efficiency, reducing costs, and expanding global society's access to low-carbon energy, while strengthening energy security in various regions (Islam *et al*., 2025).

Apart from that, the application of the concept of materials circularity is a key element in supporting inclusive and sustainable economic growth. Material circularity is not just limited to recycling, but also includes more durable product designs, minimal waste production processes, recovery of critical elements from e-waste, and reduced dependence on new resources. By implementing a circular economy in the materials sector, resource efficiency, waste reduction, green job opportunities will be created and the supply of raw materials for future industry and technology will be increased. However, material circularity must be complemented by environmental impact evaluation throughout the product life cycle through approaches such as life cycle assessment in order to truly contribute to sustainability (Reuter *et al*., 2019).

By integrating these four priorities, namely controlling climate change, financial reform, clean energy transition, and material circularity, the global material system can be a catalyst in realizing sustainable development, green economic growth, and increasing the welfare of the world's people without compromising the balance of the ecosystem and the planet's resources.

4. CONCLUSION

The results of this study show that sustainable material innovation has a very important role in realizing the Sustainable Development Goals (SDGs) targets. The development of nanomaterials, biomaterials, biodegradable polymers and waste-based materials has been proven to not only increase technological efficiency, but also have a broad positive impact on the environment, health and economy. Through the Green Nanotechnology approach, the use of waste for bioenergy and bioplastics, as well as the use of biomaterials for health, this innovation makes a real contribution to answering global challenges such as the availability of clean water (SDG 6), affordable energy (SDG 7), industrial innovation (SDG 9), sustainable consumption-production (SDG 12), and action on climate change (SDG 13).

Furthermore, responsible material management is key in supporting the achievement of the SDGs. Materials are no longer just industrial needs, but concrete solutions to big problems such as the energy crisis, pollution, limited natural resources, and improving the quality of human life. Innovations such as biomass-based materials for energy storage, environmentally friendly construction components, polymer materials for health, and nanomaterials for water treatment, show that sustainability principles such as resource efficiency, waste minimization, ecosystem resilience, and the transition to clean energy must be the basis for the development of future materials.

Progress in this field cannot be separated from the role of strong innovation management, cross-sector synergy, and policy support that is in line with the circular economy. Especially in developing countries, the success of sustainable materials strategies relies heavily on local creativity and innovation. The material circularity concept helps optimize resource use, extend product life cycles, and create environmentally friendly jobs. On the other hand, chemistry plays a central role as a scientific foundation in providing appropriate technology and solutions that are in line with ethics and sustainability. When materials innovation is supported by climate action, financial transformation, and a commitment to clean and inclusive energy, sustainable materials can become a key driver of green growth, ecological balance, and a fairer, healthier future for all.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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