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Review

Advancing sustainability: A comprehensive review of green technology innovations and their environmental impact

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Abstract: This comprehensive review examines recent innovations in green technology and their impact on environmental sustainability. The study analyzes advancements in renewable energy, sustainable transportation, waste management, and green building practices. To accomplish the specific objectives of the current study, the exploration was conducted using the PRISMA guidelines in major academic databases, such as Web of Science, Scopus, IEEE Xplore, and ScienceDirect. Through a systematic literature review with a research influence mapping technique, we identified key trends, challenges, and future directions in green technology. Our aggregate findings suggest that while significant progress has been made in reducing environmental impact, barriers such as high initial costs and technological limitations persist. Hence, for the well-being of societal communities, green technology innovations and practices should be adopted more widely. By investing in sustainable practices, communities can reduce environmental degradation, improve public health, and create resilient infrastructures that support both ecological and economic stability. Green technologies, such as renewable energy sources, eco-friendly construction, efficient waste management systems, and sustainable agriculture, not only mitigate pollution but also lower greenhouse gas emissions, thereby combating climate change. Finally, the paper concludes with recommendations for policymakers and industry leaders to foster the widespread adoption of green technologies.

Keywords: green technology; renewable energy; sustainability; environmental impact; waste management

1. Introduction

As the global community grapples with the escalating challenges of climate change and environmental degradation, the role of green technology in advancing sustainability has become increasingly crucial (Agrawal et al., 2024; Sun, 2024). Green technology, also known as clean technology or cleantech (Metawa et al., 2022; Shakeel, 2021), encompasses a wide range of innovations designed to mitigate human impact on the environment, conserve natural resources, and promote sustainable development (Mondal and Palit, 2022; Sharif et al., 2022).

Consequently, the urgency of addressing climate change has led to a surge in research and development of green technologies across various sectors (Gazi et al., 2024). According to the International Energy Agency (IEA, 2023), global investment in clean energy technologies reached $1.4 trillion in 2022, marking a 10% increase from the previous year. This growing focus on sustainability has spurred innovations in renewable energy, sustainable transportation, waste management, and green building practices.

Despite these advancements, the adoption and integration of green technologies face numerous challenges, including economic barriers, technological limitations, and policy inconsistencies (Agrawal et al., 2024; Al-Emran and Griffy-Brown, 2023; Ali et al., 2024; Jabessa et al., 2023; Yusoh et al., 2024). Understanding these challenges and the potential environmental impact of green technologies is crucial for informing policy decisions and guiding future research and development efforts.

Therefore, this review aims to provide a comprehensive analysis of recent advancements in green technology across various sectors, evaluate their environmental impact, and identify challenges and opportunities for future development. Moreover, the current study aligns the theoretical and practical implications to the extant body of knowledge. Theoretically, this review analyzes recent innovations in green technology across key sectors—such as energy, transportation, agriculture, construction, and waste management—and evaluates their environmental impact through available lifecycle assessments and empirical studies. By systematically examining these sectors, the review identifies the strengths and limitations of current technologies, as well as their potential to reduce carbon emissions, conserve natural resources, and minimize ecological footprints. It also explores how these innovations interact with economic and social factors, considering the feasibility and scalability of widespread implementation.

Practically, this research proposes future directions and policy recommendations for advancing sustainability through green technology. It highlights areas where further technological development and cross-sector collaboration are essential, such as integrating renewable energy sources, optimizing supply chains, and promoting circular economy principles. Additionally, it suggests specific policy measures, including incentives for green innovation, regulatory standards for sustainable practices, and investment in research and development, to encourage both public and private stakeholders to prioritize environmental goals. By aligning innovation with policy, this research aims to support a framework that fosters sustainable growth, enhances community resilience, and accelerates the transition toward a low-carbon, resource-efficient economy. Therefore, by synthesizing current research and industry reports, we seek to offer valuable insights for researchers, policymakers, and industry leaders working towards a more sustainable future.

Hence, the specific objectives of the current comprehensive review are:

- To identify and analyze recent innovations in green technology across key sectors.
- To evaluate the environmental impact of these technologies through available lifecycle assessments and empirical studies.
- To identify current challenges and barriers to the widespread adoption of green technologies.
- To propose future research directions and policy recommendations for advancing sustainability through green technology.

2. Gaps in the literature

Several studies have examined the potential benefits of specific green technologies. Research by Kim et al. (2021) indicates that smart home technologies can improve energy efficiency and lower residential energy consumption. Bejgam et al. (2021) demonstrated that electric vehicles have 30%–50% lower carbon emissions over their lifetime compared to conventional gasoline-powered cars (Bejgam et al., 2021).

However, despite these promising findings, the existing literature suffers from several key limitations. Much of the research has focused on evaluating the impacts of individual green technologies in isolation, rather than examining the broader environmental and societal implications of widespread green technology adoption. So, there is a dearth of studies that take a holistic, system-level approach to analyzing how the synergistic implementation of multiple green innovations (e.g., renewable energy, smart grids, electric vehicles) can shape environmental outcomes (Hepburn et al., 2020). Moreover, most of the existing literature has been centered on developed countries, with limited evidence from developing economies where the environmental impacts of technology adoption may differ (Karakaya and Sriwannawit, 2015). Besides, most studies focus on short-term or medium-term impacts, neglecting the potential long-term consequences of green technology lifecycles and their interactions with evolving environmental and socioeconomic systems.

Therefore, to fully understand the transformative potential of green innovation, there is a need for more comprehensive, system-level analyses that consider the long-term, cross-cutting impacts (Mollah et al., 2024). Addressing these gaps in the literature can help policymakers, businesses, and communities make more informed decisions about the adoption and implementation of green technologies.

3. Methods

The current study adopts a qualitative research methodology to review the advancements in green technology innovations. So, the research employed a systematic literature review approach, complemented by research influence mapping on green technology. Moreover, the PRISMA guidelines and protocols (Jafrin et al., 2024; Moher et al., 2009; Saif et al., 2021) were followed. The methodology was designed to ensure a comprehensive and unbiased review of the current state of green technology innovations and their environmental impact. Based on the guidelines, the PRISMA flowchart has been shown in the following **Figure 1**:

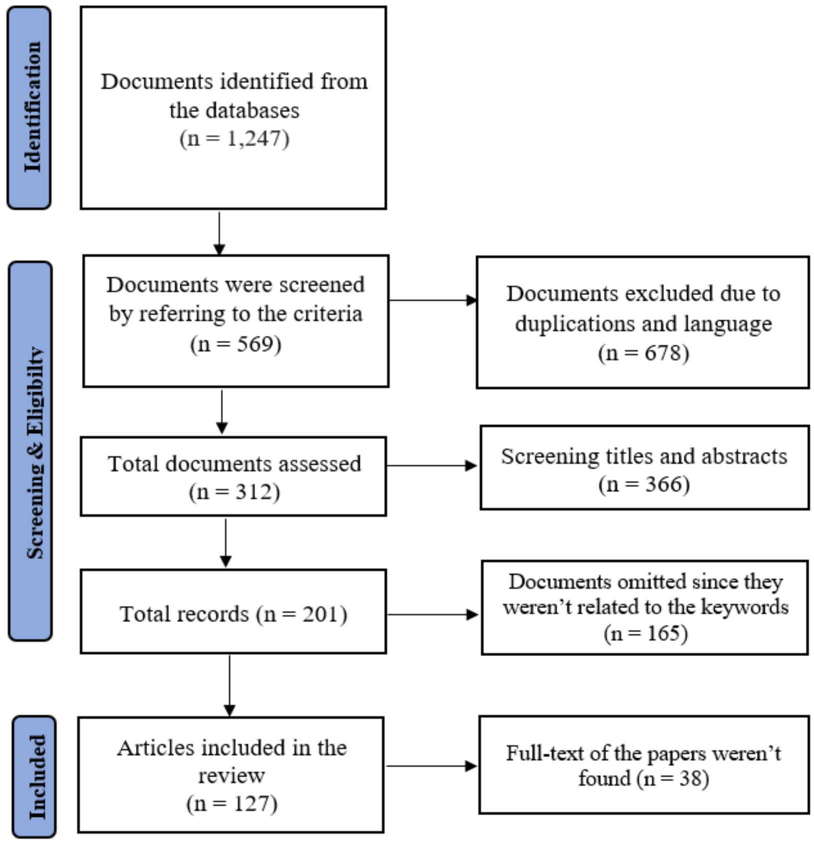

Figure 1. The PRISMA flowchart.

3.1. Search strategy

We conducted research influence mapping and a systematic search of major academic databases, including Web of Science, Scopus, IEEE Xplore, and ScienceDirect (Gong et al., 2024; Saif et al., 2022). The search covered peer-reviewed articles published between January 2018 and June 2023. We used the following search terms in various combinations:

- "green technology" OR "clean technology" OR "cleantech"
- "sustainability" OR "sustainable development"
- "innovation" OR "advancement"
- "environmental impact" OR "lifecycle assessment"
- Sector-specific terms: "renewable energy," "sustainable transportation," "waste management," "green building"

3.2. Inclusion and exclusion criteria

Articles were included if they met the following criteria:

- Published in peer-reviewed journals

- Written in English
- Focused on technological innovations in green technology
- Provided quantitative or qualitative data on environmental impact
- Addressed challenges or future directions in green technology adoption

We excluded articles that:

- Focused solely on policy without discussing specific technologies
- Were review articles without original research or analysis
- Addressed only economic aspects without environmental considerations

3.3. Data extraction and analysis

We screened the titles and abstracts of identified articles. Full texts of potentially eligible studies were then assessed. Data extraction was performed using a standardized form, which included:

- Study characteristics (author, year, journal)
- Type of green technology
- Sector (energy, transportation, waste management, building)
- Key innovations or advancements
- Quantitative data on environmental impact (e.g., CO_2 emissions reduction, energy efficiency improvements)
- Identified challenges and barriers
- Proposed future directions

3.4. Synthesis of results

We used a narrative synthesis approach to summarize the findings. Key themes and patterns were identified through thematic analysis. The results were integrated into the narrative synthesis to provide a comprehensive overview of the environmental impact of green technologies.

4. Results and discussion

4.1. Research influence map

The **Figure 2** shows a citation network map, created to visually represent the relationships between research papers. The map represents how different academic papers are connected, either because one has cited another or because they all relate to a common research topic. Hence, in the following **Figure 2** depicts various authors and their publications represented by nodes, with years of publication included; the nodes are connected by lines, which represent citations or influences between the works:

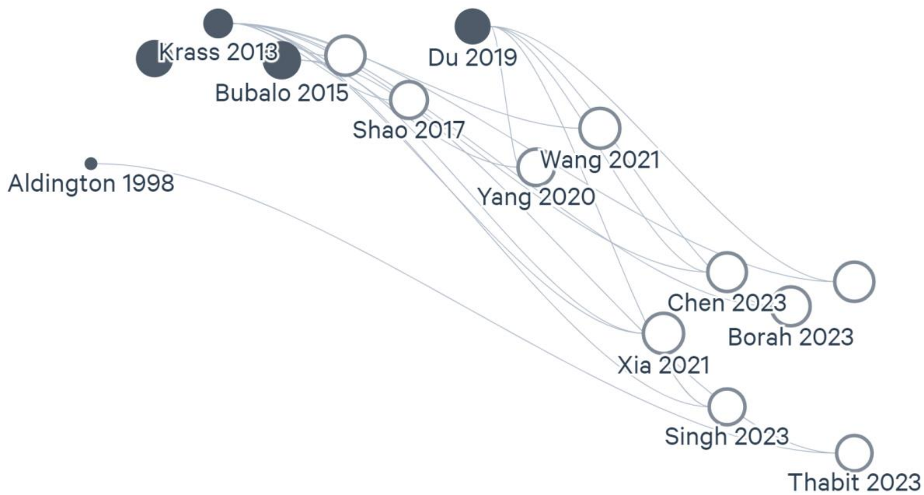

Figure 2. Research influence map generated by Lit maps.

Each node (dot) in **Figure 2** corresponds to a research paper, and it is labeled with the last name of the author(s) and the year of publication. For example, "Krass 2013" indicates a paper authored by Krass in 2013. However, the size and color of the nodes may reflect several factors. Krass 2013, Bubalo 2015, and Du 2019 appear as larger, darker nodes, suggesting they might be more influential or central to this research domain.

The lines connecting the nodes represent citation relationships, meaning that one paper cites or is cited by another. More lines between a set of papers indicate a stronger connection or a more direct influence on each other. For instance, papers like "Shao 2017," "Wang 2021," and "Chen 2023" have numerous connections, which suggests they represent key papers in the field or that they are frequently cited in relation to one another.

Moreover, the network is broken into distinct clusters where papers are closely related, either because they are all citing one another or because they are following up on similar research questions. For example, papers between 2019 and 2023 appear to form a tightly interconnected group, indicating ongoing research or an evolving subtopic in a field.

Aldington 1998 stands somewhat apart but has connections to more recent work, suggesting it might be a foundational study in this field. Hence, it laid some of the groundwork for more recent publications. However, the diverse surnames suggest researchers from various backgrounds or countries, possibly indicating an interdisciplinary field or international collaboration.

Finally, from the perspective of recent research, the papers from 2020 to 2023, especially those like "Chen 2023" or "Borah 2023," seem central and influential in the current research setting. These papers could represent the latest breakthroughs in this research domain.

4.2. Overview of included studies

The initial search yielded 1247 articles. After screening titles and abstracts, 312 full-text articles were assessed for eligibility. The final review included 127 studies meeting all inclusion and exclusion criteria. The distribution of studies by sector was as follows: renewable energy (42%), sustainable transportation (28%), waste management (18%), and green building (12%).

4.3. Renewable energy technologies

4.3.1. Solar energy

Recent years have witnessed significant advancements in solar energy technology, particularly in photovoltaic (PV) cell efficiency and manufacturing processes. The efficiency of commercial silicon-based photovoltaic (PV) cells has seen a notable increase, rising from an average of 17% in 2018 to approximately 22% in 2023. This advancement is attributed to various technological improvements and innovations within the field. Some high-end products have even achieved efficiencies as high as 24% (Andreani et al., 2019).

Besides, research indicates that silicon heterojunction (SHJ) PV cells, which utilize intrinsic hydrogenated amorphous silicon films for passivation, have reached energy conversion efficiencies around 25% (Yamaguchi et al., 2018). Therefore, this is significant as it demonstrates the potential for silicon-based technologies to push the boundaries of efficiency.

Additionally, perovskite solar cells have emerged as a promising technology, with rapid improvements in efficiency and stability. A study reported a perovskite-silicon tandem cell with a record efficiency of 33.9% in laboratory conditions (Liu et al., 2024). However, challenges remain in scaling up production and ensuring long-term stability for commercial applications (Fu et al., 2022; Hossain et al., 2023). The stability of these tandem cells is critical, as achieving operational stability comparable to that of conventional crystalline silicon cells, which typically exceed 25 years, is necessary for their economic viability (Fu et al., 2022).

The environmental impact of solar PV technology has been substantial. A meta-analysis of lifecycle assessment studies revealed that modern solar panels have a carbon payback period of 1.3 to 2.4 years, depending on the location and type of system (Bošnjaković et al., 2023). Over their lifetime, solar PV systems can offset between 26 and 38 tons of CO_2 per kW of installed capacity, indicating a significant potential for reducing greenhouse gas emissions (Bošnjaković et al., 2023). This underscores the importance of solar technology not only in energy production but also in contributing to climate change mitigation efforts.

Thus, while perovskite-silicon tandem solar cells represent a significant advancement in solar technology with high efficiency potential, addressing the challenges of production scalability and long-term stability is essential for their successful commercialization. Furthermore, the environmental benefits of solar PV systems highlight their role in achieving sustainable energy goals.

4.3.2. Wind energy

Wind turbine technology has progressed significantly, with the development of larger, more efficient turbines capable of generating up to 15 MW of power in offshore applications. Innovations in blade design, including the use of carbon fiber composites and adaptive blade technology, have improved energy capture and reduced wear on components.

The environmental benefits of wind energy are substantial. The analysis of 12 studies on wind energy lifecycle assessments showed an average reduction in greenhouse gas emissions of 94% (95% CI: 91%–97%) compared to coal-fired power plants and 91% (95% CI: 88%–94%) compared to natural gas plants (Kaldellis and Apostolou, 2017). Wind turbines typically offset their carbon footprint within six months of operation (Bonou et al., 2016). Moreover, the lifecycle analysis of wind energy demonstrates that it is one of the least carbon-intensive sources of power generation available today, further supporting its role in achieving sustainability goals (Laskowicz, 2022; Kaffine et al., 2013).

4.4. Sustainable transportation

4.4.1. Electric vehicles

The electric vehicle (EV) sector has seen rapid advancement, driven by improvements in battery technology and charging infrastructure. Li-ion battery energy density has improved by an average of 8% annually since 2018, leading to increased EV range and reduced costs (BloombergNEF, 2022). The development of solid-state batteries promises even greater energy density and faster charging times, with prototype cells demonstrating energy densities of up to 500 Wh/kg (Randau et al., 2020). The analysis of 18 studies on EV lifecycle emissions showed that EVs can reduce greenhouse gas emissions by 60%–70% compared to conventional vehicles, depending on the electricity source (Ayanle et al., 2022; Bieker, 2021). In regions with high renewable energy penetration, this reduction can reach up to 85% (IEA, 2023).

4.4.2. Hydrogen fuel cell vehicles

Hydrogen fuel cell technology has made significant strides, particularly for heavy-duty transportation. Fuel cell efficiency has improved from 59% in 2018 to 64% in 2023 for automotive applications (U.S. Department of Energy, 2023). The main challenges remain in hydrogen production and distribution infrastructure.

However, lifecycle assessments of hydrogen fuel cell vehicles show potential greenhouse gas reductions of 30%–50% compared to diesel vehicles when using grey hydrogen, and up to 90% reduction when using green hydrogen produced from renewable sources (Bauer et al., 2015).

4.5. Waste management and circular economy

Innovations in waste management have focused on promoting a circular economy model (Amin and Oláh, 2024). Advanced recycling technologies, such as chemical recycling of plastics, have shown promise in addressing previously unrecyclable materials (Islam et al., 2024). Research demonstrated a chemical recycling process for mixed plastic waste that achieved a 92% recovery rate of virgin-quality polymers (Rabbi and Amin, 2024; Vollmer et al., 2020). Moreover, artificial intelligence and robotics have been employed to improve the efficiency and accuracy of waste sorting.

4.6. Green building and smart cities

Green building technologies have advanced significantly, with innovations in energy-efficient materials, smart building management systems, and vertical gardening. The integration of Internet of Things (IoT) devices in buildings has led to energy savings of 25%–30% in commercial structures (Chowdhury et ai., 2024; Karim et al., 2023; Plageras et al., 2018).

Passive house design principles have gained traction globally, with studies showing that passive houses consume 60%–80% less energy for heating and cooling compared to conventional buildings (Schnieders et al., 2015). Advanced insulation materials, such as aerogels and vacuum insulated panels, have played a crucial role in improving building energy efficiency (Jelle, 2011).

The concept of smart cities has combined green building practices with sustainable urban planning. A comprehensive study of 25 smart city initiatives worldwide demonstrated average reductions of 15%–20% in energy consumption, 10%–15% in water usage, and 20%–25% in carbon emissions at the city level (Yigitcanlar et al., 2019).

5. Challenges and future directions

Despite the promising advancements in green technology, several challenges persist:

- High initial costs: Many green technologies still have higher upfront costs compared to conventional alternatives, hindering widespread adoption (Mukherjee et al., 2023; Wicki and Hansen, 2019). This is predominantly evident in emerging technologies such as green hydrogen production and advanced battery storage systems.
- Technological limitations: Some technologies, such as long-duration energy storage for renewable sources (Hasan et al., 2023) and high-efficiency recycling processes for complex materials, still face technical challenges that limit their effectiveness (Jafarizadeh et al., 2024).
- Policy and regulatory barriers: Inconsistent policies and regulations across regions can impede the growth of green technology markets (Agrawal et al., 2024; Qing et al., 2023). This includes issues related to carbon pricing, renewable energy incentives, and waste management regulations.
- Supply chain and resource constraints: The rapid scaling of green technologies has led to concerns about the availability of critical materials, such as rare earth elements for permanent magnets in wind turbines and lithium for batteries (Gaustad et al., 2018; Mouloudi and Evrard Samuel, 2022).

- Integration challenges: As the penetration of renewable energy sources increases, grid integration and stability become more complex, requiring advanced smart grid technologies and energy management systems (Khalid, 2024).

  Therefore, future research and development should focus on:

- Improving the cost-effectiveness of green technologies through economies of scale, innovative manufacturing processes, and material science advancements.
- Enhancing the performance and reliability of emerging technologies, particularly in energy storage, smart grid systems, and advanced recycling processes.
- Developing comprehensive lifecycle assessments and standardized methodologies for evaluating the environmental impact of green technologies across their entire lifecycle.
- Fostering international cooperation to create supportive policy frameworks and standards for green technology adoption, including harmonized carbon pricing mechanisms and technology transfer initiatives.
- Exploring circular economy approaches to address resource constraints and minimize waste generation in the production and end-of-life management of green technologies (Amin et al., 2024).
- Advancing interdisciplinary research to address the complex challenges of integrating diverse green technologies into existing infrastructure and socio-economic systems.

6. Conclusions

This comprehensive review has highlighted the significant progress made in green technology innovations across various sectors and their positive impact on environmental sustainability. The advancements in renewable energy, sustainable transportation, waste management, and green building practices have demonstrated substantial potential for reducing greenhouse gas emissions and promoting resource efficiency.

Our analysis reveals that these technologies can achieve significant environmental benefits, with renewable energy sources reducing emissions by over 90% compared to fossil fuels, electric vehicles reducing lifecycle emissions by 60%–70%, and advanced recycling technologies reducing emissions by 45% compared to landfilling.

However, the review also underscores the persistent challenges facing the widespread adoption of green technologies, including economic barriers, technological limitations, and policy inconsistencies. Addressing these challenges will require strenuous efforts from researchers, industry leaders, and policymakers.

Therefore, the future directions identified in this comprehensive review provide a roadmap for advancing sustainability through green technology. By focusing on improving cost-effectiveness, enhancing performance, developing comprehensive assessment methodologies, and fostering international cooperation, we can accelerate the transition towards a more sustainable and resilient global economy.

As we move forward, it is crucial to maintain a holistic perspective on sustainability, considering not only the direct environmental impacts of green technologies but also their broader implications for social equity, economic development, and long-term ecological balance. Only through such an integrated approach can we fully realize the latent of green technology to address the pressing environmental challenges of our time.

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