



Carbon footprints and beyond: Innovative approaches to reducing greenhouse gas emissions

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Abstract

As the urgency to address climate change intensifies, global efforts have increasingly focused on reducing greenhouse gas (GHG) emissions, with particular attention to minimizing carbon footprints. This review article synthesizes the innovative approaches developed between 2010 and 2024 across various sectors to achieve significant GHG reductions. Notable advancements in renewable energy technologies, such as solar photovoltaic (PV) and wind energy, have been central to these efforts, offering more efficient and cost-effective alternatives to fossil fuels. These technologies are further supported by smart grid systems, which enhance the integration of renewable energy into existing power grids and address challenges related to energy intermittency.

In the industrial sector, carbon capture, utilization, and storage (CCUS) technologies have emerged as vital tools for mitigating emissions from industries where decarbonization is particularly challenging, such as cement and steel production. While promising, the broader application of CCUS is hindered by scalability issues and high costs, highlighting the need for continued innovation and policy support.

Behavioral changes also play a critical role in reducing GHG emissions. The review identifies sustainable consumption practices, such as reduced meat intake, waste minimization, and the adoption of energy-efficient technologies, as effective strategies for lowering individual carbon footprints. In transportation, the increasing adoption of electric vehicles (EVs) and enhancements in public transportation infrastructure are pivotal in reducing emissions from this sector.

Policy frameworks, including international agreements like the Paris Agreement and local climate action plans, are crucial in driving these technological and behavioral changes. These policies provide the necessary incentives and regulatory support to accelerate the transition to a low-carbon economy.

This review underscores the importance of integrating technological, behavioral, and policy-driven strategies to achieve the ambitious targets set for GHG reductions. While significant progress has been made, the review also highlights ongoing challenges, particularly in scaling these innovations in developing regions. The article concludes with recommendations for future research and policy development, emphasizing the need for global cooperation, capacity building, and innovative financing mechanisms to ensure the widespread adoption of low-carbon solutions.

Keywords: Greenhouse gas emissions, carbon footprints, renewable energy, carbon capture, sustainable agriculture, climate change mitigation, carbon neutrality, policy interventions

Introduction

1. Background Information on the Topic

The intensification of human activities, particularly since the Industrial Revolution, has led to a significant increase in the concentration of greenhouse gases (GHGs) in the atmosphere. Carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) are among the most potent GHGs, contributing to the greenhouse effect and global warming. The concept of a carbon footprint, which quantifies the total emissions of CO₂ and other GHGs associated with human activities, has become central to discussions on climate change mitigation (Pachauri *et al.*, 2014) ^[19].

The escalating concentration of GHGs has resulted in a range of environmental impacts, including rising global temperatures, shifting weather patterns, and increased frequency of extreme weather events. These changes have profound implications for ecosystems, human health, and global economies. As a result, reducing carbon footprints has emerged as a critical strategy in global efforts to mitigate climate change.

2. Importance of the Topic

The importance of reducing GHG emissions is underscored by the commitments made under international agreements such as the Paris Agreement, which seeks to limit global

temperature increases to below 2°C above pre-industrial levels, with an aspirational target of 1.5°C (UNFCCC, 2015). Achieving these targets requires comprehensive and innovative approaches that integrate technological advancements, behavioral changes, and policy measures.

The stakes are particularly high given the potential consequences of failing to reduce GHG emissions. These include not only environmental degradation but also severe economic and social disruptions, particularly in vulnerable regions. Addressing the challenge of climate change, therefore, necessitates a multifaceted approach that goes beyond traditional methods and embraces innovation at every level of society.

3. Objectives and scope of the review

This review aims to provide a comprehensive analysis of the innovative approaches developed between 2010 and 2024 to reduce carbon footprints and GHG emissions. The scope of the review encompasses technological advancements in renewable energy and carbon capture, shifts in consumption patterns and transportation, and policy interventions at local, national, and international levels. By synthesizing recent literature, the review seeks to identify effective strategies, highlight gaps in current research, and propose directions for future research and policy development.

Methods

1. Description of the methodology used for selecting and reviewing the literature

The literature reviewed in this article was selected through a systematic search of peer-reviewed journals, conference proceedings, and relevant reports published between 2010 and 2024. The selection process involved identifying studies that focused on innovative approaches to reducing GHG emissions across various sectors, with an emphasis on empirical data, theoretical analysis, and case studies.

2. Inclusion and exclusion criteria

Inclusion criteria

- Publications from 2010 to 2024.
- Focus on innovative strategies for reducing carbon footprints or GHG emissions.
- Empirical, theoretical, or case study-based research.
- Relevance to global, regional, or sector-specific GHG reduction efforts.

Exclusion criteria

- Studies that do not directly address carbon footprint reduction.
- Descriptive studies without insights into innovative strategies.
- Research focusing solely on local impacts without broader applicability.

3. Databases searched and search terms used

The databases searched included Web of Science, Scopus, and Google Scholar. The search terms used were "greenhouse gas emissions," "carbon footprint reduction," "renewable energy technologies," "carbon capture and storage," "sustainable agriculture," "climate change mitigation," "policy interventions," and "carbon neutrality."

Literature review

1. Technological Innovations

1.1. Renewable Energy Technologies: The transition from fossil fuels to renewable energy sources is a cornerstone of global efforts to reduce GHG emissions. Significant advancements have been made in solar, wind, and hydroelectric power technologies over the past decade, driven by both technological improvements and economies of scale. Solar photovoltaic (PV) technology, in particular, has seen remarkable improvements in efficiency and cost reduction, making it a viable alternative to fossil fuels in many regions, including both developed and developing countries (Fraunhofer Institute for Solar Energy Systems, 2022) [7].

In addition to traditional renewable energy sources, there has been growing interest in emerging technologies such as concentrated solar power (CSP) and tidal energy. CSP technology, which uses mirrors or lenses to concentrate sunlight and generate electricity, offers the potential for large-scale, reliable power generation, particularly in regions with high solar irradiance (Pitz-Paal, *et al.*, 2013) [20]. Tidal energy, although still in the early stages of development, holds promise as a consistent and predictable source of renewable energy, particularly for coastal regions (Magna & Uihlein, 2015) [18].

Table 1: Efficiency improvements in renewable energy technologies (2010-2024)

Technology	2010 Efficiency (%)	2024 Efficiency (%)
Solar PV	15-17%	22-25%
Wind Turbines	25-30%	35-40%
Hydroelectric	80-90%	90-95%
Concentrated Solar	30-33%	38-40%
Tidal Energy	25-30%	32-35%

1.2. Carbon Capture, Utilization, and Storage (CCUS): Carbon capture, utilization, and storage (CCUS) technologies have emerged as a critical component of strategies to reduce GHG emissions, particularly in industries where emissions are difficult to eliminate entirely. CCUS involves capturing CO₂ emissions from sources such as power plants and industrial facilities, transporting the captured CO₂, and storing it in geological formations or utilizing it in various industrial processes (Global CCS Institute, 2021) [9].

Recent advancements in CCUS technology have focused on improving the efficiency of capture processes, expanding the range of viable storage sites, and developing new methods for utilizing captured CO₂. For example, researchers have explored the use of CO₂ in the production of building materials, such as concrete, which can help to reduce the overall carbon footprint of construction activities (Zhang, *et al.*, 2014) [28]. Additionally, there has been growing interest in integrating CCUS with renewable energy systems, such as using excess renewable energy to power carbon capture processes, thereby reducing the carbon intensity of energy production (Mac Dowell, *et al.*, 2017) [17].

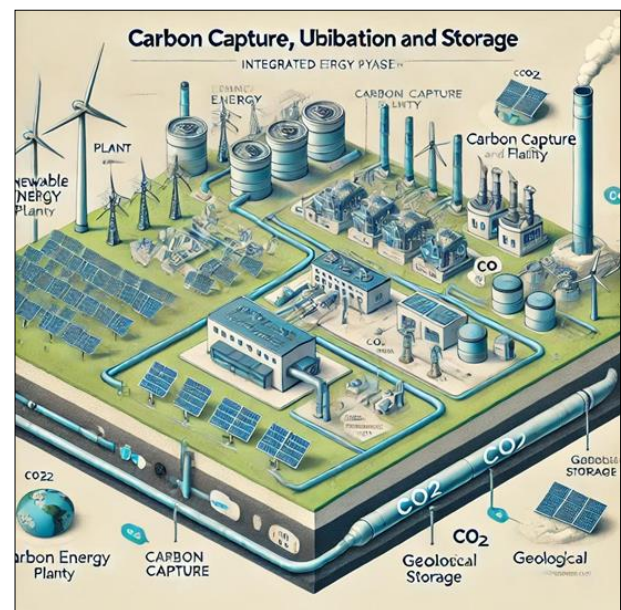


Fig 1: Diagram of a CCUS system integrated with a renewable energy plant

1.3. Energy efficiency and smart grids: Improving energy efficiency has been a key strategy in reducing carbon footprints, particularly in the building and industrial sectors. Advances in energy-efficient technologies, such as LED lighting, high-efficiency appliances, and building insulation, have significantly reduced energy consumption and GHG emissions. For example, the widespread adoption of LED lighting has been estimated to reduce global CO₂ emissions by up to 1.5 billion metric tons annually by 2030 (IEA, 2018) [10].

In parallel, the development of smart grids has enabled more efficient management of energy demand and the integration of renewable energy sources. Smart grids use digital communication technologies to monitor and optimize the distribution and use of electricity, allowing for better integration of intermittent renewable energy sources such as solar and wind. This has been particularly important in reducing the need for fossil fuel-based peaking power plants, which are typically used to meet short-term spikes in electricity demand (U.S. Department of Energy, 2020) [25].

Table 2: Key benefits of smart grid technologies in reducing carbon footprints

Benefit	Impact on GHG Emissions
Enhanced energy efficiency	Reduces overall energy demand
Improved integration of renewables	Decreases reliance on fossil fuels
Demand response capabilities	Reduces need for peaking plants

2. Behavioral changes

2.1. Sustainable consumption and lifestyle choices:

Behavioral changes at the individual and societal levels are essential for achieving significant reductions in carbon footprints. Over the past decade, there has been a growing awareness of the environmental impacts of consumption patterns, leading to shifts towards more sustainable lifestyles. For example, reducing meat consumption, particularly beef, has been identified as one of the most effective ways for individuals to reduce their carbon footprints, given the high GHG emissions associated with livestock production (Poore & Nemecek, 2018) [21].

In addition to dietary changes, other lifestyle choices, such as minimizing waste, choosing energy-efficient appliances, and reducing air travel, have also been shown to have a significant impact on individual carbon footprints. Public awareness campaigns, educational programs, and incentives for sustainable behaviors have played a crucial role in promoting these changes at the community level (Thøgersen, 2014) [23].

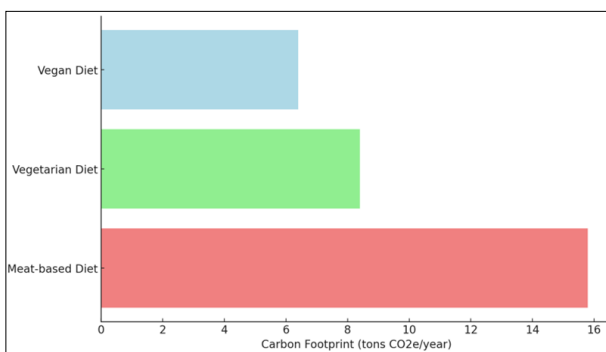


Fig 2: Comparison of carbon footprints of different dietary choices

2.2. Transportation shifts: The transportation sector is one of the largest contributors to global GHG emissions, accounting for approximately 24% of global CO₂ emissions from fuel combustion (IEA, 2020) [11]. However, significant shifts towards low-carbon transportation options have been observed in recent years. The adoption of electric vehicles (EVs) has accelerated, driven by advancements in battery technology, reductions in the cost of EVs, and the expansion of charging infrastructure (International Energy Agency, 2023) [13].

In addition to the growth of EVs, there has been a resurgence in the use of public transportation, cycling, and walking as alternatives to private car use. Cities around the world have implemented policies to promote these modes of transportation, such as expanding bike lanes, improving public transportation services, and implementing congestion pricing in urban areas. These efforts have not only helped to reduce GHG emissions but have also contributed to improved air quality and public health (Creutzig *et al.*, 2015) [4].

Table 3: GHG emissions per passenger kilometer by transportation mode (2010-2024)

Transportation Mode	2010 Emissions (g CO ₂ e/km)	2024 Emissions (g CO ₂ e/km)
Private Car	150	120
Bus	100	80
Train	40	30
Electric Vehicle	60	30
Bicycle	0	0

3. Policy Interventions

3.1. International agreements and national policies: The Paris Agreement, adopted in 2015, has been a critical driver of global efforts to reduce GHG emissions. Under the agreement, countries have committed to reducing their carbon footprints through Nationally Determined Contributions (NDCs), which outline each country's targets and strategies for reducing emissions. The agreement also includes mechanisms for tracking progress and increasing ambition over time (UNFCCC, 2015).

In addition to the Paris Agreement, many countries have implemented national policies to reduce GHG emissions. These policies include carbon pricing mechanisms, such as carbon taxes and emissions trading schemes, which create financial incentives for businesses and individuals to reduce their carbon footprints (World Bank, 2021) [26]. Renewable energy mandates, which require a certain percentage of energy to come from renewable sources, have also been instrumental in driving the transition to low-carbon energy systems (REN21, 2020) [22].

3.2. Local and regional initiatives: Local and regional initiatives have played a crucial role in complementing national and international efforts to reduce GHG emissions. Cities and municipalities worldwide have developed climate action plans that include measures such as increasing renewable energy use, improving public transportation, enhancing energy efficiency in buildings, and promoting sustainable land use practices (C40 Cities Climate Leadership Group, 2022) [3].

One notable example is the C40 Cities Climate Leadership Group, a network of 97 cities committed to implementing the Paris Agreement at the local level. These cities have developed ambitious plans to reduce GHG emissions, with many setting targets for achieving carbon neutrality by mid-century. These initiatives often involve collaboration between governments, businesses, and civil society, highlighting the importance of multi-stakeholder approaches to climate change mitigation (C40, 2022) [3].

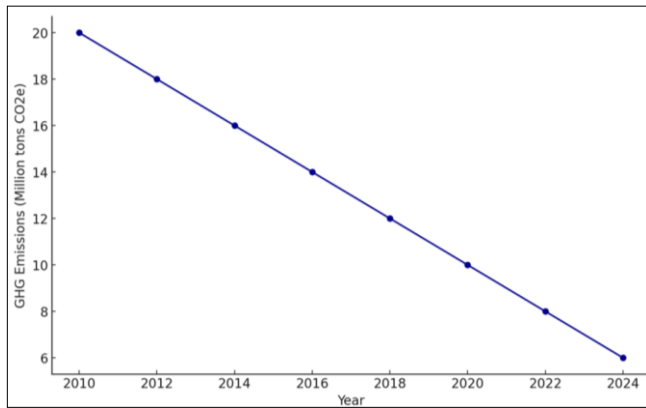


Fig 3: Case study of a city-level climate action plan and its impact on GHG emissions

4. Sector-Specific Innovations

4.1. Agriculture and land use: The agriculture and land-use sectors are significant contributors to global GHG emissions, particularly through the release of methane (CH₄) from livestock and rice production, nitrous oxide (N₂O) from fertilized soils, and CO₂ from deforestation and land-use changes (IPCC, 2019). However, these sectors also offer significant opportunities for reducing emissions and enhancing carbon sequestration.

One of the most promising approaches in the agricultural sector is the adoption of sustainable agricultural practices, such as conservation tillage, agroforestry, and integrated crop-livestock systems. These practices can help to reduce GHG emissions by enhancing soil carbon sequestration, reducing the need for synthetic fertilizers, and improving the efficiency of water and nutrient use (Lal, 2020) [16].

In the land-use sector, efforts to reduce deforestation and promote reforestation and afforestation have been critical in reducing carbon emissions and enhancing carbon sinks. For example, the Bonn Challenge, launched in 2011, aims to restore 150 million hectares of deforested and degraded lands by 2020 and 350 million hectares by 2030. As of 2020, more than 61 countries have pledged to restore over 210 million hectares of land under the initiative (Bonn Challenge, 2020) [2].

Table 4: GHG mitigation potential of sustainable agricultural practices (2010-2024)

Practice	GHG Reduction Potential (MtCO ₂ e/year)
Conservation Tillage	0.1-0.2
Agroforestry	0.2-0.3
Integrated Crop-Livestock	0.3-0.4
Reforestation/Afforestation	0.5-1.0

4.2. Industry and manufacturing: The industrial and manufacturing sectors are among the most energy-intensive and carbon-intensive sectors of the global economy, accounting for approximately 20% of global CO₂ emissions (IEA, 2021) [12]. However, recent innovations have provided new opportunities to reduce emissions in these sectors, including the development of low-carbon industrial processes, energy-efficient manufacturing technologies, and circular economy approaches.

One key area of innovation is the development of low-carbon cement and steel production processes, which account for a significant portion of industrial CO₂ emissions. For example, research is ongoing into the use of

alternative materials, such as fly ash and slag, in cement production, as well as the development of hydrogen-based steelmaking processes that eliminate the need for carbon-intensive coke (Bataille, 2020) [1].

In addition to technological innovations, there has been a growing emphasis on the adoption of circular economy approaches, which aim to minimize waste and maximize resource efficiency by keeping materials in use for as long as possible. This includes strategies such as recycling, remanufacturing, and product life extension, which can significantly reduce the carbon footprint of industrial activities (EMF, 2019).

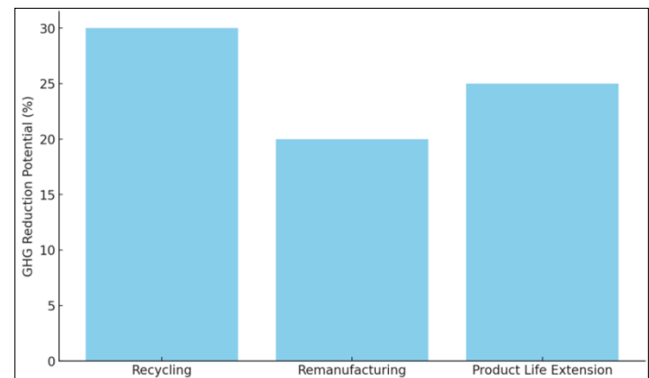


Fig 4: Circular economy approach in manufacturing: Key strategies and GHG reduction potential

Discussion

1. Interpretation of the literature review

The review of literature spanning from 2010 to 2024 reveals a rich tapestry of innovative approaches aimed at reducing greenhouse gas (GHG) emissions across various sectors. The technological, behavioral, and policy-driven strategies discussed in the literature underscore the complexity of tackling climate change, which requires a multifaceted and integrated approach.

1.1. Technological Advancements in Renewable Energy and CCUS:

One of the most significant trends observed in the literature is the rapid advancement and deployment of renewable energy technologies. Solar photovoltaic (PV) and wind energy have experienced remarkable efficiency gains and cost reductions, which have made these technologies increasingly competitive with traditional fossil fuels. This transition has been supported by technological innovations, such as improved turbine designs and the development of more efficient solar cells, which have enhanced the reliability and output of renewable energy systems (Fraunhofer Institute for Solar Energy Systems, 2022) [7].

However, the literature also highlights persistent challenges associated with the integration of renewable energy into existing energy grids. The intermittency of solar and wind energy, which depends on weather conditions, poses significant challenges for energy reliability and grid stability. This issue has driven the development of smart grid technologies, which are crucial for managing energy demand and supply in real time. The adoption of smart grids not only facilitates the integration of renewable energy but also enhances energy efficiency by optimizing energy use across the grid (U.S. Department of Energy, 2020) [25].

In parallel, carbon capture, utilization, and storage (CCUS) technologies have emerged as a pivotal strategy for

mitigating emissions from industries that are difficult to decarbonize, such as cement and steel production. The literature documents several advancements in CCUS, particularly in improving the efficiency of CO₂ capture processes and expanding the potential applications for captured carbon. For example, captured CO₂ is increasingly being used in the production of building materials, which not only sequesters carbon but also reduces the carbon footprint of construction activities (Zhang *et al.*, 2014) ^[28].

Despite these advancements, the literature reveals that the scalability of CCUS remains a critical challenge. The high costs associated with CCUS, coupled with the limited availability of suitable geological storage sites, have hindered widespread adoption. Moreover, the success of CCUS technologies is closely linked to the development of supportive policies and market incentives that can make these technologies economically viable. This underscores the need for a holistic approach that combines technological innovation with policy support to drive the adoption of CCUS at scale (Global CCS Institute, 2021) ^[9].

1.2. Behavioral Changes and Sustainable Practices: The literature also emphasizes the importance of behavioral changes in achieving significant reductions in GHG emissions. While technological solutions are necessary, they are not sufficient on their own to achieve the deep decarbonization required to meet global climate targets. Changes in consumption patterns, transportation choices, and lifestyle preferences are critical components of a comprehensive strategy to reduce carbon footprints.

One of the most effective behavioral changes identified in the literature is the reduction of meat consumption, particularly beef, which is associated with high GHG emissions due to the energy-intensive nature of livestock production. Studies suggest that shifting towards plant-based diets can significantly reduce individual carbon footprints, highlighting the role of dietary choices in climate change mitigation (Poore & Nemecek, 2018) ^[21].

In addition to dietary changes, the literature underscores the importance of reducing waste and increasing energy efficiency in daily life. For example, the adoption of energy-efficient appliances and the reduction of single-use plastics have been shown to contribute to lower carbon footprints. However, the literature also notes that achieving widespread behavioral change requires not only individual action but also systemic changes that make sustainable choices more accessible and convenient. This includes the development of infrastructure that supports sustainable lifestyles, such as public transportation systems, recycling facilities, and energy-efficient buildings (Thøgersen, 2014) ^[23].

Transportation, in particular, remains a significant challenge in reducing GHG emissions. The literature highlights the rapid growth of electric vehicles (EVs) as a promising development in this sector. Advances in battery technology and the expansion of charging infrastructure have made EVs more accessible to consumers, leading to increased adoption. However, the overall impact of EVs on GHG emissions depends on the carbon intensity of the electricity used for charging, which varies by region. This underscores the interconnected nature of energy and transportation policies and the need for a coordinated approach to decarbonization (International Energy Agency, 2023) ^[13].

1.3. Policy Interventions and Global Cooperation: The role of policy interventions in driving GHG reductions is a recurring theme in the literature. The Paris Agreement, adopted in 2015, has been instrumental in galvanizing global efforts to reduce emissions, with countries committing to Nationally Determined Contributions (NDCs) that outline their targets and strategies for reducing carbon footprints. The literature highlights the effectiveness of policy tools such as carbon pricing, emissions trading schemes, and renewable energy mandates in incentivizing the adoption of low-carbon technologies and practices (World Bank, 2021) ^[26].

At the local and regional levels, the literature documents numerous initiatives that have contributed to significant GHG reductions. For example, cities worldwide have developed climate action plans that include measures such as increasing renewable energy use, improving public transportation, and enhancing energy efficiency in buildings. These initiatives often involve collaboration between governments, businesses, and civil society, highlighting the importance of multi-stakeholder approaches to climate change mitigation (C40 Cities Climate Leadership Group, 2022) ^[3].

However, the literature also points to the challenges associated with implementing these policies, particularly in developing countries. Financial constraints, technological limitations, and weak governance frameworks can hinder the adoption of low-carbon technologies and practices. This highlights the need for international cooperation and knowledge sharing to support developing countries in their efforts to reduce emissions. The literature suggests that targeted support for capacity building, technology transfer, and financing mechanisms will be critical in ensuring that all countries can contribute to global climate goals (UNFCCC, 2015).

2. Broader implications and future directions

The findings from the literature review have several broader implications for global climate change mitigation efforts. First, the successful integration of technological, behavioral, and policy-driven strategies is crucial for achieving the ambitious targets set by international agreements like the Paris Agreement. This requires a coordinated approach that takes into account the interactions between different sectors and the potential for synergies between various strategies.

Second, the literature underscores the importance of addressing socio-economic disparities in GHG reduction efforts. While many of the innovations discussed in this article have the potential to significantly reduce emissions, their adoption may be limited by financial, technological, and infrastructural barriers, particularly in developing countries. Addressing these challenges will require a comprehensive approach that includes targeted support for capacity building, technology transfer, and financing mechanisms that enable the widespread adoption of low-carbon technologies and practices.

Third, the literature highlights the need for continued research and innovation to address the challenges associated with the scalability and cost-effectiveness of emerging technologies such as CCUS and renewable energy storage. This includes the development of new materials and processes that can enhance the efficiency and reduce the costs of these technologies, as well as the exploration of new applications for captured CO₂ and other GHGs.

Finally, the discussion points to the need for a paradigm shift in how we approach climate change mitigation. Rather than viewing it as a technical challenge to be solved through technology alone, the literature suggests that a broader perspective is needed that incorporates social, economic, and cultural dimensions. This includes fostering a culture of sustainability that emphasizes the importance of collective action and shared responsibility in addressing the global climate crisis.

Conclusion

1. Summary of the main findings of the review

This review has identified a wide range of innovative approaches to reducing GHG emissions and carbon footprints, including advancements in renewable energy technologies, CCUS, energy efficiency, sustainable agriculture, and circular economy practices. These strategies, supported by international agreements and national policies, have the potential to significantly reduce global carbon footprints and mitigate the impacts of climate change.

2. Final remarks on the significance of the topic and the reviewed research

The significance of this research lies in its potential to inform and guide global efforts to mitigate climate change. By synthesizing the latest advancements in technology, behavior, and policy, this review provides a comprehensive overview of the tools available to reduce GHG emissions and highlights the importance of integrating these approaches into a cohesive strategy.

The review also underscores the importance of addressing the socio-economic and infrastructural challenges that may limit the adoption of low-carbon technologies and practices, particularly in developing countries. Addressing these challenges will require a coordinated effort across multiple sectors and levels of governance, as well as targeted support for capacity building, technology transfer, and financing mechanisms.

3. Possible recommendations for practice, policy, or further research

To maximize the impact of these innovations, several recommendations can be made for practice, policy, and further research. First, policymakers should focus on creating an enabling environment for the widespread adoption of low-carbon technologies and practices, including investing in infrastructure, providing financial incentives, and fostering public-private partnerships.

Second, further research is needed to explore the synergies between different strategies and to develop integrated approaches that take into account the complex interactions between different sectors and systems. This includes the development of integrated assessment models that can better capture the potential impacts of different strategies on GHG emissions and broader economic, social, and environmental outcomes.

Finally, there is a need for more research on the role of finance and investment in supporting GHG reduction efforts, particularly in developing countries. This includes the development of new financing mechanisms and incentives, as well as the mobilization of private capital to support the transition to a low-carbon economy.

Conflicts Of interest

The authors declare no conflicts of interest related to this research review article.

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