Review Article

A Perspective on Carbon Footprints and Carbon Reduction in Various Sectors

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Abstract
The escalating threat of climate change, driven largely by anthropogenic greenhouse gas emissions, has intensified global attention on carbon footprint analysis and reduction strategies. This review presents a multidisciplinary analysis of the sources, types and sector-specific impacts of greenhouse gas emissions, focusing on energy, transportation, industrial business, agriculture, buildings and waste management. It explores the evolving concept of the carbon footprint and evaluates strategies for its reduction through technological innovations, behavioral change and policy mechanisms. Emphasis is placed on emerging solutions such as clean energy systems, low carbon infrastructure, carbon capture and storage and circular economy practices. By integrating multidisciplinary insights, the paper identifies challenges, opportunities and future directions for achieving substantial carbon mitigation and supporting the transition toward low carbon and climate resilient systems.

Keywords: Carbon footprint, Carbon reduction, Circular economy, Climate mitigation, Greenhouse gas emissions

1 Introduction

Carbon footprint refers to the cumulative greenhouse gas (GHG) emissions resulting from human activities, both direct and indirect, typically measured in terms of carbon dioxide equivalents (CO_2-eq). These emissions contribute significantly to global warming and climate change.

Global climate changes cause significant challenges to sustainable development that are mainly attributed to greenhouse gas emissions by human activities. International frameworks such as the Paris Agreement and UN Sustainable Development Goals (UN SDGs) highlight the evolution to a low-carbon economy, with the circular economy as a prime strategy to attain this goal [1], [2]. In response, worldwide governments have executed policies intended to decrease emissions and proper utilization of available resources. For example, the European Green Deal targets industrial emissions from various metal processing and production industries, whereas North America supports improvements in plastic recycling technologies. Efforts to mitigate climate change are also reshaping industries and governance, leading to substantial investments in decarbonizing energy production [3], [4]. However, these efforts alone are insufficient to meet global climate targets, as greenhouse gas emissions continue to rise. One of the major challenges is carbon leakage, where emissions are outsourced to other countries, particularly in developed regions [5]. A comprehensive approach to reducing carbon footprints must consider both production and consumption-based emissions. Carbon footprint assessments, particularly from a consumption perspective, are essential for understanding mitigation trends. Shifting the consumption patterns is crucial for mitigating climate change. According to the Intergovernmental Panel on Climate Change (IPCC), changes in individual behavior, lifestyle choices and cultural norms can significantly influence energy demand and the level of greenhouse gas emissions, thereby offering considerable potential for mitigation. Building on this, strategies such as moderating consumption levels, embracing the sharing economy, and encouraging sustainable behaviors offer significant potential for reducing emissions. The European Union, through key policy frameworks like the "Roadmap for a Low Carbon Economy in 2050" and the "Transport White Paper", emphasizes the critical role of behavioral transformation in achieving climate goals in a cost-effective manner. Consequently, shifting daily habits and consumption decisions becomes indispensable in the fight against global climate change [6]–[8]. Furthermore, the conversion of natural land for rapid urban expansion can exacerbate carbon emissions, primarily due to increased energy demands associated with human settlement and industrial activities [9], [10].

2 Types of Greenhouse Gas Emissions

The huge release of greenhouse gases (GHG) like carbon dioxide and methane from various sources in the environment is causing global climatic variations. Human and societal activities, particularly those related to energy consumption, land use and resource exploitation, significantly influence the dynamic interactions between radiatively active trace gases and the Earth's climate system. These effects are further amplified or modulated by natural feedback mechanisms within the biosphere and atmosphere, making the overall relationship between anthropogenic actions and climate outcomes highly complex [11]. The main contributors to greenhouse gas emissions are industrialized sectors and urban centers. As rural areas undergo urbanization and adopt modern agricultural practices, their emission levels are also on the rise [12]. Within the energy system, coal-fired power generation remains the dominant source of emissions, often concentrated in a few highly polluting facilities that persist due to political and economic resistance to their decommissioning. In contrast, emissions from the building and transportation sectors are more diffuse, involving numerous actors and deeply intertwined with infrastructure, urban planning and everyday behaviors, thus posing both technological and societal challenges to effective mitigation [13]. Consequently, both industrialization and urbanization, whether directly through energy production and manufacturing or indirectly through land use changes and infrastructure development, contribute to carbon emissions, as explored in the following sections.

2.1 *Direct carbon emissions*

The direct carbon emissions are closely related to the in-house and building emissions, like residential electrical utilization and domestic utility of petroleum, coal, and propane gases [14]. More than 5 million barrels of oil are consumed daily by the worldwide airline industry, which is one of the direct carbon emissions from the aviation sector. Between 2 and 2.5 percent of all anthropogenic CO_2 emissions come from civil aircraft [15]. The global construction industry's direct CO_2 emissions predominantly stem from four major energy sources: gasoline, diesel, other petroleum products (OTHPETRO) and light fuel oil (LFO). In developing countries, the construction sector accounts for a larger share of both direct and indirect CO_2 emissions compared to more economically advanced nations, due to rapid urban expansion, less efficient technologies, and limited regulatory enforcement. For instance, the construction industry in Turkey exhibits one of the highest carbon emission intensities globally, reflecting the significant environmental impact associated with its building practices and energy consumption patterns [16]. From a tourist standpoint, three-quarters of direct tourism carbon emissions came from transportation, with lodging and food services coming in second (12.45%) and retail in third (12.10%) [17]. Additionally, infrastructures contribute to human-caused direct greenhouse gas emissions across the whole socio-metabolic environment. Emissions originate not only during the operational use of infrastructure such as buildings and transportation systems, but also during earlier stages, including the extraction, manufacturing and processing of raw materials for construction. Furthermore, although to a lesser extent, emissions persist through end-of-life processes like demolition and waste management [18]. When assessing the overall environmental footprint, economies of scale in direct emissions can lead to nearly double the output [19]. According to Ahmad *et. al.,* [20], in India's six largest cities, electricity consumption is the dominant source of greenhouse gas emissions, accounting for approximately 78%, followed by cooking fuels at 14% and gasoline combustion at 7%. Urbanization-induced transformations in land use and land cover are widely recognized as significant contributors to emissions, responsible for more than 30% of anthropogenic CO_2 outputs. Moreover, the conversion of natural landscapes into agricultural or built environments directly undermines the carbon sequestration capacity of terrestrial ecosystems, further exacerbating the climate impact [21].

2.2 *Indirect and other carbon emissions*

Indirect carbon emissions associated with household consumption arise throughout the entire life cycle of goods and services. These emissions are generated at various stages, including raw material extraction, manufacturing, transportation, marketing and across all contributing industrial sectors [22]. Similarly, in the tourism sector, carbon emissions extend beyond direct travel-related energy use. Tourism also relies heavily on inputs from other industries, making its indirect emissions substantial, it is estimated to contribute between 50% and 60% of the sector's total carbon footprint [17]. Since 2007, China has emerged as the world's biggest source of primary energy consumption and carbon emissions. About 80% of the country's energy consumption comes from indirect energy usage from intermediary inputs, highlighting the significant potential for indirect emissions across various sectors [23]. A typical example of such emissions can be seen in electric vehicle use, where the greenhouse gases are not emitted at the point of vehicle operation, but rather during the electricity generation process at power plants. These emissions fall under the category of indirect emissions, as they originate from activities not directly controlled by the end user [24]–[26].

Globally, transport, accommodation, and food represent the top three contributors to indirect household carbon emissions (IHCEs), accounting for 20%, 19%, and 17% respectively. Between 2007 and 2017, the proportion of IHCEs from the cultural, education, entertainment and medical sectors increased steadily, from 10.87% to 20.56% [27]. Indirect emissions are often tied to overlooked segments of a product or service's life cycle. These include emissions from infrastructure and capital goods used to extract raw materials, process and transport them, manufacture the final product, deliver it to consumers, maintain it over its useful life and eventually manage its disposal. Life cycle assessment (LCA) thus offers the most comprehensive approach to evaluating greenhouse gas emissions linked to goods and services [28]–[30].

According to Ma *et. al.,* [31], as the income gap narrows in rural areas, residents experience increased purchasing power. This socioeconomic shift leads to higher consumption of goods and services, which, in turn, raises the per capita indirect carbon emissions from rural households.

3 Carbon Footprints

Figure 1 shows the carbon footprints in various sectors such as energy production and transformation, buildings, petroleum refining, waste management, road and non-road transportation, land use transformation and forestry, industry and agriculture. Among these, energy-intensive industries such as steel, cement, basic chemicals, aluminum, glass and pulp are notable contributors to greenhouse gas emissions. These sectors rely heavily on high-temperature processes and fossil fuel-based energy, making them major sources of carbon output within the industrial category. For example, steel manufacturing uses coke, a well-known coal-derived fuel, which generates high emissions. Likewise, cement and concrete production generate large amounts of CO_2 due to calcination and energy-intensive processes. Furthermore, the chemical industry emits significant greenhouse gases from fossil fuel-based feedstocks like ethylene and ammonia, while the textile and paper industries consume large amounts of energy and generate waste [32], [33].

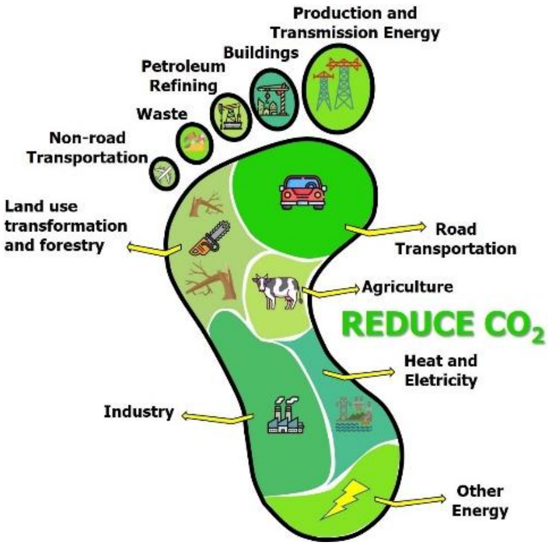

Figure 1: Carbon footprints in various sectors.

Another major contributor to carbon emissions is the electricity sector. The use of fossil fuels to generate electricity accounts for more than 40% of all energy-related CO_2 emissions, as coal, oil and natural gas dominate the energy production. Importantly, all power-producing technologies release greenhouse gases at some point during their life cycle, adversely affecting both humans and the ecosystem [34]. Coal-fired power plants have the highest emissions among energy sources while natural gas power plants emit less than coal but still contribute significantly. Additionally, oil-based power generation generally used in remote areas and for backup power, also contributes to substantial emissions.

Similarly, the agricultural sector, which is the backbone of the economy of many emerging and developing countries contributes approximately 12% of global anthropogenic greenhouse gas emissions [35]. This is mainly through methane (CH_4) and nitrous oxide (N_2O), both of which possess a much higher global warming potential than CO_2. Although released in smaller amounts, CH_4 has a warming effect approximately 21 times that of CO_2, while N_2O is about 310 times more potent [36]. Specifically, livestock farming contributes to methane emissions through digestion and anaerobic decomposition in flooded fields leads to methane generation. Meanwhile, the application of nitrogen-based fertilizers leads to the release of nitrous oxide. Additionally, deforestation to clear land for agriculture not only contributes to direct emissions but also diminishes natural carbon sinks, further intensifying atmospheric greenhouse gas concentrations [37].

In addition to agriculture, the transportation sector is responsible for around 15–20% of global CO_2 emissions annually [38]. The increasing demand for personal vehicles, freight transport and urbanization exacerbates the emissions. Among the various transportation modes, light-duty vehicles like passenger cars and vans contribute significantly, producing around 15% of the EU's CO_2 emissions [39], followed by trucks, freight transport and public transport. Moreover, non-road transportation, including aviation, shipping and rail transport, also contributes to emissions. For example, aviation alone accounts for nearly 2–3% of global emissions. In 2022, aviation-related emissions rose to nearly 800 million tonnes of CO_2, representing around 80% of the levels recorded prior to the COVID-19 pandemic [40]. In addition, the shipping industry, which predominantly relies on fossil fuels such as marine gas oil and heavy fuel oil, emits a range of harmful gases, including CO_2, CH_4 and N_2O. Notably, ships also release sulfur oxides (SOx), which, while not directly contributing to climate change, present serious threats to environmental quality and human health [41].

Beyond these large sectors, other energy-related activities such as cooking, small-scale power generation and industrial heating also contribute to carbon footprints. Cooking with open fires or inefficient stoves, often fueled by wood, coal or charcoal emits significant amounts of climate-warming pollutants. Incomplete combustion during these processes leads to the release of short-lived climate pollutants such as black carbon and methane, along with other greenhouse gases, including carbon monoxide (CO) and CO_2, all of which contribute to atmospheric warming and air quality degradation. [42].

Land use change plays a significant role in influencing carbon emissions, as it directly impacts the amount of carbon stored in soil and vegetation [43]. Activities such as deforestation, urban expansion and intensive agricultural practices can lead to the release of large quantities of greenhouse gases, particularly CO_2, thereby accelerating global warming and climate change [44]–[47]. The Intergovernmental Panel on Climate Change (IPCC) estimates that land use change, including deforestation, accounts for roughly 12% of total global greenhouse gas emissions. However, due to the complexity of tracking and quantifying emissions from land use dynamics, the actual contribution could be even higher than current estimates suggest [48], [49].

Another major contributor to greenhouse gases is the buildings and construction sector, which accounts for approximately 37% of global emissions [50]. This is largely due to the carbon-intensive nature of producing and utilizing construction materials such as steel, aluminum and cement. While mitigation efforts in this sector have historically emphasized reducing operational emissions associated with lighting, heating and cooling, there is growing recognition of the need to address embodied emissions embedded in materials and construction processes.

Moreover, the extraction and transportation of fossil fuels contribute substantially to greenhouse gas emissions and air pollution, even before combustion occurs. Fossil fuel activities release harmful pollutants during drilling, processing, and transport stages. A 2017 study published in Environmental Health Perspectives reported that nearly 17.6 million people in the United States are regularly exposed to hazardous air pollutants emitted by oil and gas extraction sites, as well as associated infrastructure. The expansion of hydraulic fracturing, or fracking, has worsened these environmental impacts, despite increasing evidence of its adverse health effects. Mining operations also generate toxic airborne particulate matter, posing risks to miners and surrounding communities. Practices like strip mining, especially in ecologically sensitive regions such as Canada's boreal forest, can also disturb vast carbon reserves stored in vegetation and soil, leading to significant releases of CO_2 and undermining natural carbon sinks [51].

The oil refining industry is another major contributor to greenhouse gas emissions, ranking as the third-largest stationary source globally and responsible for approximately 5% of energy-sector GHG emissions in 2019 [52]. From 2010 to 2018, emissions from this sector rose by 24% [53]. Refining crude oil involves multiple energy-intensive processes, including distillation, catalytic cracking, coking, reforming and other various post-treatment steps. These operations demand significant thermal energy, leading to considerable CO_2 emissions. Key emission sources within refineries include fuel combustion for heating distillation columns and reactors, steam generation, the incineration of petroleum coke, and the reforming of hydrocarbons [54].

The accumulation of waste in landfills and dumpsites also often results in the release of harmful pollutants, impacting both environmental and human health. The decomposition of organic waste leads to the release of volatile organic compounds (VOCs) along with hazardous gases such as benzene and toluene. Moreover, methane emissions from landfills further exacerbate climate change, posing additional risks such as explosions and fires in high concentrations [55]. Consequently, reducing the carbon footprint across these diverse sectors is critical for effective climate change mitigation and for advancing toward long-term global sustainability objectives.

4 Ways to Reduce Carbon Footprints

Figure 2 illustrates twelve strategies for reducing carbon footprints across various aspects of daily life. One key approach is lowering the consumption of meat and dairy products, as livestock farming is a major contributor to greenhouse gas emissions associated with climate change. Reducing red meat intake can help curb the demand for intensive animal farming, which is often linked to deforestation and ecosystem degradation [56]. Shifting towards plant-based diets also contributes significantly to emission reductions, as plant-derived foods typically generate much lower carbon emissions than their animal-based counterparts. Additionally, choosing locally sourced and seasonal produce reduces the need for long distance transportation, thereby minimizing emissions associated with food logistics. Minimizing food waste is another critical measure, as organic waste in landfills emits methane, a greenhouse gas far more potent than CO_2. An effective approach to managing unavoidable food scraps is composting, which allows organic material to decompose aerobically, thereby minimizing methane release. In addition, composting returns nutrients to the soil and decreases dependency on synthetic fertilizers. Other best practices include saving water, planting more trees and more usage of green energy.

Figure 2: Reduction of carbon footprints.

The fashion industry, particularly the fast fashion segment, is a significant contributor to environmental degradation due to its emphasis on rapid production, frequent style changes and low-cost materials. This model results in overproduction and overconsumption, leading to large volumes of textile waste and widespread pollution [57]. The environmental footprint of fast fashion encompasses the use of toxic dyes, substantial water consumption, and carbon-intensive manufacturing processes. With an estimated 85% of textiles being discarded annually, largely ending up in landfills or being incinerated, sustainable fashion practices are essential for reducing this burden. Choosing second-hand or upcycled garments, donating unwanted clothing and utilizing reusable or recycled shopping bags are effective strategies to curb textile waste, conserve resources and reduce the sector's overall carbon footprint [58].

Additionally, improving energy efficiency in household practices can contribute meaningfully to emissions reduction. For instance, washing machines consume considerable energy, especially during hot water cycles. By running only full loads and using lower water temperatures, households can substantially decrease electricity consumption. These adjustments not only lower utility costs but also reduce indirect CO_2 emissions associated with energy production, particularly in regions where electricity is generated from fossil fuels. Such behavioral shifts, though small at the individual level, can collectively have a substantial environmental impact when widely adopted.

Moreover, the utilization of renewable energy sources within households is a fundamental step toward reducing carbon footprints. Renewable energy, such as solar, wind or hydroelectric power, generates electricity with minimal greenhouse gas emissions, thereby offering a cleaner and more sustainable energy supply. Transitioning to energy-efficient appliances, particularly those with certified product ratings, can further lower household electricity consumption by optimizing energy usage without compromising performance. The adoption of smart technologies such as smart thermostats represents another impactful measure. These devices enhance energy efficiency by automatically adjusting indoor temperatures based on occupancy patterns and external weather conditions, thus reducing unnecessary heating or cooling and conserving energy over time. Similarly, replacing conventional incandescent or halogen light bulbs with LED alternatives is a simple yet effective strategy; LEDs consume up to 90% less energy and have a significantly longer lifespan, which contributes to both cost savings and emission reductions [59]. Shifting to rechargeable batteries offers a more environmentally responsible alternative to single-use variants, as it reduces hazardous waste and the resource demands of repeated manufacturing.

Recycling plays a pivotal role in emission reduction strategies. By properly sorting and recycling materials such as paper, plastic, glass and metal, households can help reduce the demand for virgin resources, thus cutting emissions associated with material extraction, processing and waste disposal. Studies estimate that increased global recycling efforts could lead to a 25% reduction in carbon emissions by 2050 [56]. Using reusable shopping bags reduces the amount of waste in landfills and decreases carbon emissions from plastic production. Choosing products with recyclable packaging reduces resource consumption and energy required for manufacturing and disposal. These practices further cut down the waste and reduce the greenhouse gas emissions related to the fabrication of newer packaging materials.

Transportation choices also exert a substantial influence on personal carbon footprints. Reducing reliance on air travel is one of the most effective ways to cut individual emissions, as aviation is a high-impact sector in terms of GHG output. Opting for public transit, ride-sharing, biking or walking provides lower-emission alternatives that also alleviate urban congestion [60]. Additionally, the adoption of electric or hydrogen-powered vehicles presents a cleaner option for personal mobility, particularly when charged with renewable energy sources.

Finally, engaging in tree-planting and reforestation efforts supports long-term climate goals by enhancing carbon sequestration. Trees absorb CO_2 from the atmosphere, acting as natural carbon sinks and contributing to ecosystem restoration [61], [62]. Altogether, these interconnected practices represent a cohesive and holistic framework for reducing carbon footprints at the household level and advancing broader climate resilience.

5 Conclusions

Carbon emissions are generated through diverse processes across multiple sectors, highlighting the need for a more focused approach to managing and reducing carbon footprints. Addressing these emissions requires not only heightened awareness but also the strategic application of technological innovations aimed at minimizing carbon outputs in both direct and indirect forms. Governments play a pivotal role in this effort by enacting regulatory frameworks, setting emission standards, and promoting energy conservation through policy interventions and fiscal incentives.

Future research should prioritize the development and implementation of advanced emission reduction strategies, including innovations in energy-efficient systems, clean manufacturing technologies, and low-carbon infrastructure. Equally important is the exploration of policy mechanisms that support the widespread adoption of green technologies and incentivize sustainable industrial practices. In addition, integrating circular economy principles such as resource efficiency, product reuse and waste recycling offers significant potential for reducing emissions across production and consumption cycles. Research into these practices can help identify scalable models for decarbonizing supply chains and minimizing environmental impacts. Furthermore, advancing carbon capture, utilization and storage technologies represents a critical avenue for mitigating greenhouse gas emissions from high-emission sectors. Continued investment in and research on these technologies will support the growth of environmentally responsible enterprises and reinforce global efforts to combat climate change. Since carbon credit has developed into a potentially profitable industrial business, researchers ought to concentrate on it.

Author Contributions

All authors contributed equally to this manuscript. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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