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Assessing the Carbon Footprint of Plastics: From Polymer Synthesis to Environmental Pollution

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ARTICLE INFO

Received: October 08, 2025
Revised: December 05, 2025
Accepted: December 29, 2025
Published: February 01, 2026



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Abstract: Throughout their existence, plastics, which are now omnipresent in contemporary life, have been a substantial contributor to the destruction of the environment and the release of carbon. This article aims to investigate the carbon footprint of plastics, beginning with their foundation in polymers derived from petrochemicals and ending with their disposal as pollutants. The manufacturing of plastics requires a significant amount of energy. It depends on fossil fuels, which emit significant amounts of carbon dioxide and other greenhouse gases. In addition, the environmental effect of plastics is further exacerbated by their lifespan, which includes shipping, consumption, and disposal of the material. This article highlights the urgent need for sustainable alternatives and better waste management techniques to offset plastic pollution's mounting environmental difficulties and carbon emissions.

Keywords: Climate change; Plastic carbon footprint; Plastic pollution; Emission factor; Petrochemicals.

1. Introduction

Plastics are pervasive in contemporary culture. The essential ingredients that produce the things we use daily have beneficial qualities that we often overlook. Exceptional durability, lightweight, strength, and adaptable physical qualities are crucial for manufacturing, transportation, product efficacy, and lifespan. Plastics enhance sustainability when used in energy-efficient goods and are inherently energy-efficient materials, requiring less energy for production than alternatives. Nonetheless, durability presents a dual challenge with plastics. that its usage transforms into persistence when reaching the end of life. Consequently, the pressing task of plastic waste management necessitates a judicious equilibrium between plastics' advantageous and perhaps indispensable qualities and the avoidance of damage. Plastics are omnipresent in contemporary culture. The essential ingredients that produce the things of daily use have beneficial qualities that we often overlook. Exceptional durability, lightweight, strength, and adaptable physical qualities are crucial for manufacturing, transportation, product performance, and lifetime. Plastics enhance sustainability when used in energy-efficient goods and are inherently energy-efficient materials, requiring less energy for production than alternatives [1]. Nonetheless, durability presents a dual challenge with plastics.

And in application transforms into persistence upon reaching the end of life. Consequently, the pressing task of plastic waste management necessitates a judicious equilibrium between plastics' advantageous, rather vital characteristics and the avoidance of damage [2]. The carbon footprint measures the climate effect and denotes the total carbon emissions released into the atmosphere directly from producing a substance or product. The carbon footprint of a typical Western consumer varies between 10 and 20 ton of carbon per year, primarily due to activities such as heating, transportation, cooling, lighting, food production, and recreation. Two primary causes often influence the carbon footprints linked to non-energy, materials-related consumer demands. Worldwide, our infrastructures need about nine billion ton of steel, reinforced concrete, clay, brick, and glass, leading to a carbon footprint of building materials of almost one ton of carbon per inhabitant each year. The demand for electricity and heat related to non-energy items in households generates a carbon footprint of around one ton per person annually. The average carbon footprint per human is three to four tons annually, with consumer goods, especially plastics, being a substantial and increasing factor [3].

1.1. Background and Significance

Last century, plastics become vital to modern life. Their durability, low bulk, and versatility make them advantageous, with hundreds of millions of tons produced annually. The scientific community is increasingly concerned about plastics' environmental impacts, but microplastics that have already entered the ecosystem have received the most excellent attention. Plastic pollution's visual impact, entanglement and ingestion by higher animals, and degradation into toxic and persistent microparticles and nano plastics are concerns. However, plastics have environmental costs throughout their life cycle. Raw material extraction, polymer synthesis, product production, disassembly, disposal, and end-of-life processing all have environmental costs. Last century, plastics become vital to modern life. They are valued for their strength, lightweight, and versatility, with hundreds of millions of tons produced annually. Researchers worry about plastics' environmental impact, especially microplastics that have penetrated the ecosystem. Concerns include plastic pollution's visual impact, animal entanglement and ingestion, and possible degradation into toxic microparticles and nano plastics [4, 5]. However, plastics have environmental consequences throughout their life cycle. Raw material extraction, polymer synthesis, product production, disassembly, disposal, and end-of-life processing all have environmental costs [6]. A prevalent way to quantify environmental costs is the measurement of greenhouse gas emissions in a CO₂-equivalent footprint, calculated based on the mass or energy used in producing or treating a product. This metric is often used to assess the carbon efficiency of goods and processes. It has become the foundation for advocating expanded producer responsibility, with a low-carbon circular economy seen as a critical objective for future international socioeconomic frameworks. Numerous publications exist about the carbon footprint of polymers and plastics; however, most of the material is complex and sometimes misleading to non-experts. Consequently, this study aims to provide a comprehensive and comprehensible analysis of the pertinent facts [7].

1.2. Scope and Objectives

Recent estimates indicate that worldwide plastic manufacturing has resulted in a cumulative total of 8,300 Mt of plastic material, culminating in 6,300 Mt of plastic product trash. This indicates that 12% of all plastic ever produced, over 1 trillion kilograms, has entered the environment, contributing to a substantial ecological burden due to plastic trash's durability and the persistent input of macro and microplastics. Without adequate remediation methods, the detrimental effects of these trends are expected to intensify significantly. Consequently, evaluating the environmental impact of existing plastic manufacturing methods is essential to guide initiatives for enhancing plastic circularity [8].

This uncertainty is anticipated to increase as society recognizes the need to convert the petrochemical and plastics industry into a net-zero-carbon sector over the next 30 to 40 years. The potential of new polymer additives to facilitate the creation of easily degradable plastic goods while maintaining mechanical integrity is a compelling research opportunity [9].

2. Understanding Plastics and Polymers

Moldable and sculptable, traditional plastics are made of synthetic polymers or resins. While synthetic polymers are the most common source of plastics, polymers may also be found in nature. Plant cell walls, which include cellulose, are composed of glucose polymers. Linen and cotton are examples of cellulose-based materials. Proteins found in animal and insect products include silk and wool. Polymers are created by linking similar monomers to create a macromolecule. What makes a polymer unique is the kind and order of the monomers that make it up. A small amount of monomer in the finished plastic will not have much impact since the monomer sequence is destroyed when millions of polymer chains are added [10]. Composition and molecular weight affect polymer characteristics. Most plastics employ synthetic polymers from coal, natural gas, and crude petrochemical feedstocks. Renewable biomass may be used to make bio-based polymers from plant sugars or oils. Bio-based polymers are currently a minor part of the worldwide market and have struggled to compete economically with petroleum-based polymers, although continuous research into sustainable methods and novel materials is ongoing. Attributing macroscopic polymer characteristics and microstructures to their products has justified various contributions [11].

2.1. Definition and Types of Plastics

Plastics are diverse substances with unique properties that facilitate many applications. Their molecular structures are similar due to their petrochemical origins. The Greek origin of "plastic" is "plassein" meaning "to mould". Plastics consist of macromolecules and may include plasticizers and other compounds. Polymers are often referred to as plastics. The term is also colloquially used to refer to appositional natural polymers such as fish scales and bones. Although prevalent in the environment, plastic often denotes synthetic polymers rather than naturally occurring macromolecules in discussing the environmental consequences of plastic production and disposal [12]. Plastics may be classified as synthetic, hybrid, organic, or inorganic, with petroleum-derived synthetic organic polymers being the predominant kind. Diverse materials yield various polymers. These include petroleum and thermoplastic; reusable items such as water bottles, containers, and storage boxes; recyclable materials; and single-use products—manufactured once, used, and then disposed. A multitude of PET-based shopping bags, food containers, bottles, straws, receptacles, cups, utensils, balloons, and party decorations are classified as single-use plastics. Regardless of the fundamental substance, all plastics exhibit same longevity, chemical stability, and resistance to oils and fats [13].

2.2. Chemical Structure of Polymers

The chemical structure significantly influences material qualities, including cleanliness, toxicological risks, and biological efficacy. The polymer manufacturing method involves the synthesis of molecular precursors that are reacted to elongate chains known as polymers. The choice of monomers affects the overall properties of the polymer, including the connectivity, structure, and characteristics such as crystallinity and micro-phase separation of the synthesized polymer chain. They may assist in optimizing specific responses and system variables, including phase segregation, surface activity, and discrepancies in multi-material properties [14]. Monomers and functional group type and position affect polymer performance and environmental effect. Green monomers have been extensively designed for this purpose. Plant components provide photosynthesis-produced carbon, hydrogen, and oxygen.

OHP compounds lack the oxygen group, which is significant in materials and chemistry. PCL and PLA components fix this. The body may use the oxygen in its ester functional groups via typical metabolic processes. Byproduct benefits include PCL's less crystalline, softer texture, and more straightforward processing. Bioactive glasses can boost PLA activity, but their flexibility in manufacturing allows for the biodegradable polymer application. Biodegradable OHPs may enhance medical device design, surgical partner care, and patient outcomes [15].

3. Carbon Footprint Basics

A carbon footprint gives an individual or institution a straightforward measure of greenhouse gas emissions. When applied to a consumer product, the notion is less obvious, with several options that make evaluating and trusting data challenging. This chapter discusses the core concepts for consumers and industry regarding their carbon footprints, plastics' consequences, and ways to reduce them. A person, organization, event, or product's "carbon footprint" is their direct and indirect greenhouse gas emissions, including carbon dioxide and methane [16].

3.1. What is a Carbon Footprint?

A comprehensive definition of carbon footprint is needed to understand plastic carbon footprints from polymer manufacture to land and ocean contamination. A carbon footprint is the total quantity of CO₂, CH₄, and N₂O generated directly and indirectly to support human activities as CO₂ equivalents. The carbon footprint of polymers for plastics in the petrochemical industry accounts for greenhouse gases emitted during production, processing, transportation, storage, use, and disposal to determine the potential loss or release of greenhouse gases to the environment. Based on ten tons/year production estimates, the cradle-to-grave carbon footprint for a typical petrochemical polymer produced from crude oil processing is assessed for distribution by land, sea, and air worldwide before disposal [17].

3.2. Methods of Calculating Carbon Footprint

Various methodologies have been established to assess the effects of materials and processes, focusing on air quality, climate change, and other issues, as researchers formulated recommendations for monitoring and mitigating emissions. The carbon footprint is a fundamental entry point for examining extensive economic and environmental concerns since economic costs often correspond with greenhouse gas emissions; nevertheless, further comprehensive information may be necessary. The fundamental inquiries for several procedures are analogous and need comprehensive, high-quality, and information-rich databases. This encompasses process data, energy demands, the kind, source, and transportation used for non-generating energy [18]. Life cycle modeling is a prevalent method, supported by computers and data models that aggregate and organize information from many sources. These models often describe processes and may be organized in tables to monitor the origins of the intended effects. Life cycle models often account for direct/indirect effects, given the complexity of operations that may intertwine actions and effects. For instance, polymers synthesized from atmospheric carbon dioxide, such as polyurethanes produced from CO₂, possess a standard mixed categorization. A system often has many objectives, options, uncertainties, and unquantified factors. The region may include transfers of energy, commodities, trash, and information. The geographical and temporal parameters of a system may be extensive, be excessive of many direct/indirect effects [19].

4. Life Cycle Assessment (LCA)

4.1. Concept and Importance

Based on similar volume or mass comparisons of emissions, a product's carbon footprint is its total CO₂ equivalent, including all greenhouse gases, from feedstock extraction to disposal. Plastics' environmental carbon footprint comes from lost items or components that enter an uncontrolled loop owing to improper disposal. These losses taint the environment through the unavoidable and grotesque display of litter, and fundamental elements air, rainwater, passive sunlight, superficial mechanical agents, and the growth of flora and fauna in the presence of plastic waste contribute to the reporting and quantifiable increase in the carbon footprint of plastics during their conversion into pollution. Based on similar volume or mass comparisons of emissions, a product's carbon footprint is its total CO₂ equivalent, including all greenhouse gases, from feedstock extraction to disposal. Plastics' environmental carbon footprint comes from lost items or components that enter an uncontrolled loop owing to improper disposal. Unavoidable and grotesque litter taints the environment, and fundamental elements air, rainwater, passive sunlight, superficial mechanical agents, and the growth of flora and fauna in the presence of plastic waste significantly contribute, both in reporting and in direct, quantifiable terms, to the carbon footprint of plastics as they convert into pollution [20].

4.2. Case studies

Packaging case studies demonstrated that biodegradable materials increase carbon footprint in significant impact areas. This is because biodegradation has increased. PET rigid containers are preferable to PLA ones. A regenerated PLA scenario would reduce carbon emissions by nearly 75%. Advanced life cycle assessment continuous process simulation may replace lab-scale techniques. One example is a scale-up of starch biodegradation using lactic acid. This case study reduces environmental consequences. Both standard investigations are only included in the disposal stage when biodegradation occurs in biodegradable materials and extra emissions from biodegradation. Using biodegradable PBAT shopping bags instead of petrochemical plastics raises environmental consequences in most impact categories [21].

5. Carbon Footprint Calculation for Plastics

The carbon accounting methodology included CO₂ emissions from hydrocarbon conversions to monomers and polymers, polymerization, and transport. Three of the 29 lifetime phases were affected by by-products and co-products, four by waste management, and 22 by oil or gas usage and transformation. The carbon footprint was computed in kilograms of CO₂ per kg polymer and translated to kg CO₂ per unit plastic mass. It was then combined with fresh seawater microplastic pieces' elemental makeup to estimate their mass using a Gaussian total mass distribution as a function of hand-sorted mass [22]. The worldwide carbon footprint of 1 billion tons of carbon-based polymer is around 2.5% of yearly anthropogenic CO₂ emissions, representing over 8% of the anticipated annual emissions by 2035. The actual cost is likely worldwide and poses obstacles to several scenarios of carbon capture and utilization for transforming petrol and oil, the plastic components of which are increasing quickly [23]. All lifecycle phases contribute a minimum of 0.04, with some instances reaching up to 50%. Nonetheless, LPG has a minimal impact since it only emits CO₂ during the polymerization phase. CO₂ emissions from fuel use in polymer manufacture and transportation to the consumer account for 99.95% of the total emissions. The remainder is attributable to the non-equivalent incineration or disposal linked to aerobic biodegradability. The optimal scenario involves the fabrication of objects exhibiting thermal shielding properties, which may then be disposed of under appropriate circumstances.

The remaining non-biodegradable products mostly release CO₂ during polymer transformation and post-consumer disposal, which depend on incineration in facilities capable of generating electricity, such as waste-to-energy plants. On the positive side, several things adhere to the recycling paradigm, with some items being retrieved in more significant quantities [24].

5.1. Scope 1, 2, and 3 Emissions

Plastic is sold, consumed, and discarded via complicated networks. Different emission sources are engaged in these networks. Scope 1, 2, and 3 emissions are used to identify emitters. Scope 1 includes direct emissions from company-owned activities. Scope 2 covers indirect emissions from buying power or heat from a third party [25]. Activities from non-company assets cause Scope 3. Supply chain emissions, or scope 3, are sometimes several times higher than direct scope 1 and 2 emissions. Land use change emissions may contribute significantly to scope 3 for plant-based bioplastics. Deforestation and other land use changes cause habitat loss, biodiversity loss, and ecosystem service impairment [26]. Again, there is no universal rule for comparative life cycle evaluation; thus, we placed the most common approaches next to each other. In addition to land use change emissions, we show indirect emissions from the microbial breakdown of bioplastic blends in anaerobic digesters and increased feed requirements for bioplastics. The more excellent feed supply may boost rumen methane production, raising cow methane and nitrous oxide emissions [27]. As shown in Figure 1.

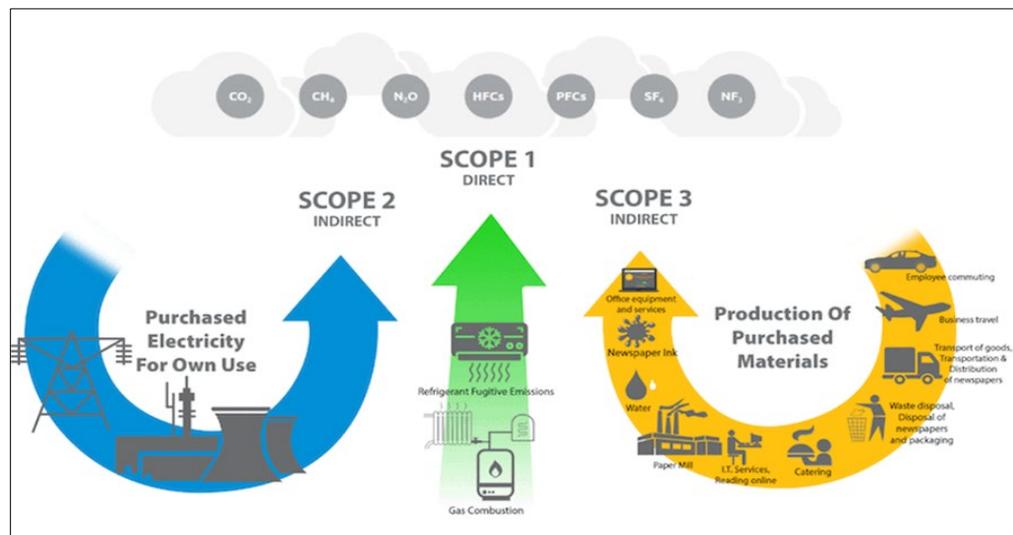


Figure 1. shows the scope of three feedstock production, processing, transportation, and waste management emission variables [28].

5.2. Carbon Accounting Methods

The carbon footprint of plastics is assessed in many ways, but the methods are simple. Plastic goods are assessed in many types of research for their entire life cycle. These studies collect quantitative data on material production, product manufacture, the supply chain, transportation, and end-of-life management, including recycling, energy recovery via incineration, and landfilling. All life cycle assessments aim to capture the most life cycle carbon associated with each product in compliance with applicable standards and implied supply chain requirements [29]. Complete life cycle assessments need precise, detailed, and accurate information on all productions, end-of-life activities and take time. Total life cycle assessments are expensive. They may need more technical advances, like facilities that recycle plastic trash into fuel. These variables favor more straightforward, cheaper assessments. Well-characterized systems provide sensible and feasible policy options.

Given these constraints, policymakers and others may be interested in other types of carbon footprints for significant materials, like plastics, to get a baseline, identify primary sources of emissions for other policies, spot significant system changes that may need to be accounted even if they are not included in current, complete life cycle assessments, or gauge whether those complex or complete life cycle assessments are in the proper. Total life cycle assessments are complex and time-consuming, requiring complete, accurate information about production and end-of-life activities [30]. Total life cycle assessments are expensive. They may need more technical advances, like facilities that recycle plastic trash into fuel. These variables favor more straightforward, and cheaper assessments. Well-characterized systems provide sensible and feasible policy options. Given these constraints, policymakers and others may be interested in other types of carbon footprints for significant materials, like plastics, to get a baseline, identify primary sources of emissions for other policies, spot significant system changes that may have to be accounted for even if they are not included in current, complete life cycle assessments, or gauge whether those complex or complete life cycle assessments are in the right as shown in Table 1 [31].

Table 1. The lifetime of each plastic to decompose [32].

Type of plastics	PET OR PETE: Polyethylene terephthalate	The most common type of plastic needs 5-10 years to decompose under perfect conditions.
	HDPE: high-density polyethene	One of the most versatile plastics needs about 100 years to decompose
	PVC: polyvinyl chloride	Never decompose
	LDPE: low-density Polyethylene	High flexible plastic needs about 500 years to decompose
	PS: polystyrene	One of the most environmentally harmful plastics needs about 50 years to decompose

6. Environmental Impact of Plastics

6.1. Greenhouse Gas Emissions

Because most polymer manufacturing facilities have decades-long lifespans, renewable energy and demand-side management are essential to greening their energy supply. The final supply alternative is carbon fixation in novel polymer synthesis processes. As long as the carbon is the fossil, polymer manufacturing requires much energy. Biology and recycling are advantageous because solar energy drives processes, and living creatures repair CO₂. One must consider the gasoline offset by recycling plastic garbage [33]. Biological CO₂ fixation contributes to novel carbon-conventional technologies for the creation of 'polymers from biomass.' In this context, building blocks are derived from biological sources and then converted into polymers by chemical processes, similar to traditional polymers. The carbon derived from the building blocks is, in contrast to the carbon from fossil organics, initially 'green', however, it is indistinguishable from carbon sourced from traditional plastics. Depending on the kind of biomass feedstock, carbon should always be seen as indirectly fixed solar energy, which, in theory, would correspond with the sequestration of an equal quantity of CO₂ via photosynthesis, provided that soil fertility is adequate as shown in Figure 2 [34].

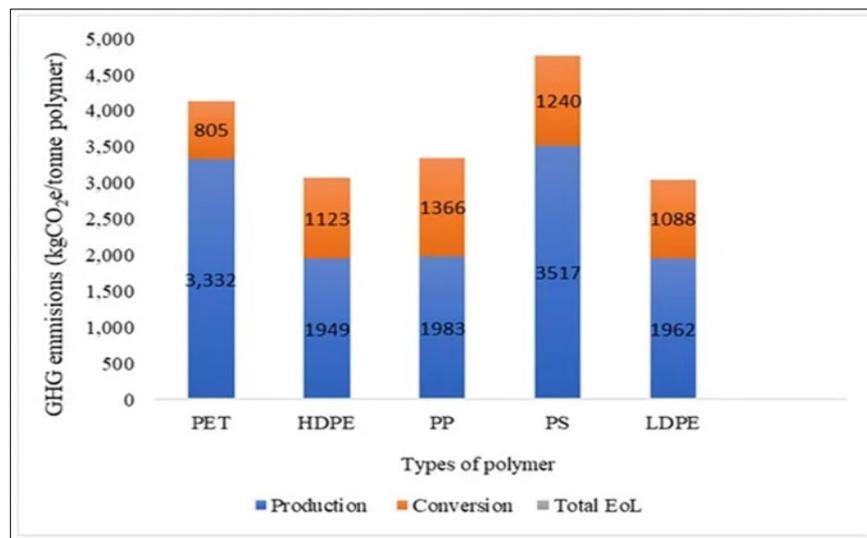


Figure 2. GHG emissions from different polymer types at the production and conversion stages [35].

6.2. Resource Depletion

Large amounts of oil will be consumed for long-term infrastructure, including building, energy, transportation, and industry, making oil depletion a significant issue. Oil and gas will remain the world's primary energy sources, but their decline may reduce plastic material supply. Once oil and gas become scarcer and more costly, new energy sources may replace them at a more significant cost and with a poorer energy return on invested energy. If oil and gas are needed to maintain energy return on investment, their depletion may slow economic growth. Peak Oil is the plastic industry's Achilles' heel for these reasons [36]. Agriculture and the food industry continue to struggle with cheap, low-quality energy, but specific sectors may be able to avoid depletion despite their crucial configuration. Oil dropping will cause two unique yet interconnected problems. In the near term, many sectors where industry optimizes output via energy-saving aspects will have permanent adverse effects. Several indicators indicate this danger, including energy shortages from depletion or restrictive regulations. They include air, ship, truck, and, to a lesser degree, rail transit; primary source and technology self-sufficiency; and strategic power to influence energy decision-making. These aspects are characterized by computations not being able to save or propose new solutions after the industry 'touches' crucial depletion thresholds. Fear of critical depletion stemmed from several factors, including our society's dependence on shale oil and communication, remote operation, and remote-control devices that transmit annual CO₂ emissions are made of polymers from ethylene and polyethylene, which have a 12-energy return on energy investment [37].

7. Mitigation Strategies for Plastic Pollution

7.1. Recycling and Circular Economy

Plastic recycling may eliminate carbon emissions. This has several benefits. Plastic garbage does not enter natural ecosystems because it becomes microplastics. Overall, crude oil demand drops. Still, linear business models dominate the sector. Ecodesign and standardized recyclable polymers are needed for all uses. Increased recycled content in all plastics requires legislation. Polymers may be chemically recycled into plastic monomers. Post-use is often preferred for short-lived polymer goods, and for durable items like building insulation and solar panels, recycling and the circular economy should be central. Transition requires incentives and norms. Solubility is needed for home recycling of 100% recyclable cigarette filters or polyethylene-based wall paint. For the transition, recycling may need to happen elsewhere. While intelligent waste processing may be conceivable, costs must be appropriately set. Economic factors may also supply market conditions [38].

7.2. Biodegradable Plastics

Plastics like polylactic acid, manufactured from carbon-neutral crops, may be biodegradable and minimize CO₂ emissions. These materials are better for single-use applications like packaging but cost more per unit weight than other polymers. These materials are widespread and growing in use; thus, technology may lower their cost and variety of properties. These materials may reduce greenhouse gas emissions, and as our manufacturing and recycling infrastructure improves, PLA may be employed in additional applications [39]. Thus, straws, commercial shopping bags, and single beverage cups are suitable applications for potentially hazardous single-use products used in significant numbers. These single-use objects may be produced under a carbon-neutral growth cycle, using renewable or nuclear carbon-free energy and capturing the CO₂ waste. This almost closes the loop. The negligible carbon footprint minimizes the carbon cycle from CO₂ conversion into materials during growth to CO₂ release via plastic burning or biodegradation. These goods transform anthropogenic ambient CO₂ into commercial products and release them when chemical bonds break in a closed-loop process as shown in Figure 3 [40].

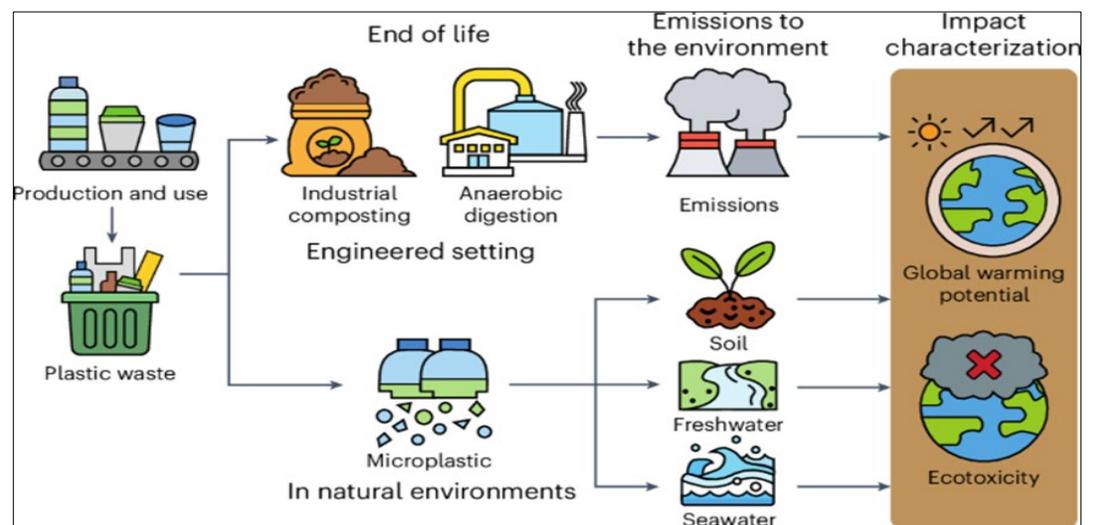


Figure 3. Plastic Impact on Global Warming [41].

8. Future Trends and Innovations

8.1. Emerging Technologies

Several new technologies might significantly reduce plastics' carbon footprint and worldwide greenhouse gas emissions. Avoiding fossil oil and gas derivatives and using renewable and plant-based feedstocks is the primary way to make sustainable plastics. Responsible firms are investing more in these new technologies, boosting their development. The production of monomers or polymers by biological processes is unique. The engineering and modification of bacteria to create tiny to medium-chain-length fatty acids for polyester polymers is novel [42]. Using plants as feedstock is called 'biorefining'. Breeding or altering plants with desired chemistry may reduce plastics' carbon impact and increase agriculture's sustainability. The relatively young subject of agricultural biotechnology may help to build more productive and sustainable agriculture. Plants include traditional farm commodities, agricultural residues, non-dietary glucose sources, invasive weeds, and waste management crops [43]. Traditional oil firms are considering biorefining for commercial use. Biotechnology may not evolve quickly enough to contribute a cleaner future if the goal is to save the present from environmental catastrophes. Old baggage and nimby attitudes impede development, but biotechnology's promise to reduce water and harmful chemical pollution implies it must proceed [44].

8.2. Sustainable Alternatives

The issue arises despite change the environmentally friendly alternatives can replace petroleum-based polymers. The CO₂ footprint, working behavior, material behavior, and economical manufacture of bioplastics or natural biopolymers are relatively limited compared to mineral-based plastics. Point two is related to the growing paucity of food-producing agricultural land. The third point addresses resource management issues and plastic trash contamination of the oceans and Earth. Polymer technology may not cause unforeseen contamination of the Earth due to structural considerations that lead to renewable energy plastics. Ultrahigh molecular weight polar yet non-dissolvable cellulose hydrocarbons from biofuel leftovers are produced utilizing green chemistry. In the past, corporate policy in a biocarbon economic structure was to study biodegradable additives and biological disintegration, not clean-ups. Living chemistry from renewable resources seems challenging, but it can be solved by 'biorefining.' Breeding or altering plants with desired chemistry may reduce plastics' carbon impact and increase agriculture's sustainability. The relatively young subject of agricultural biotechnology may build more productive and sustainable agriculture. Plants include traditional farm commodities, agricultural residues, non-dietary glucose sources, invasive weeds, and waste management crops. Traditional oil firms are considering biorefining for commercial use. Biotechnology may evolve slowly enough to contribute a cleaner future if the goal saves the present from environmental catastrophes. Old baggage and nimby attitudes impede development, but biotechnology's promise to reduce water and harmful chemical pollution implies that must be proceeded [45].

9. Conclusions

The carbon footprint of plastics is a significant environmental concern of our era. Each phase of the plastic life cycle, from raw material extraction and polymer synthesis to product use and disposal, contributes to greenhouse gas emissions and resource depletion. This analysis emphasizes that successful mitigation requires a holistic strategy that incorporates technology innovation, policy formulation, and public awareness. Shifting to a circular economy via recycling, and the use of bio-based or biodegradable polymers is a feasible approach to reducing carbon emissions. Nonetheless, these solutions need precise life cycle assessments (LCA) to guarantee that environmental benefits are not counterbalanced by unforeseen consequences elsewhere in the system. Future research should concentrate on improving polymer recycling efficiency, creating economical biodegradable substitutes, and advancing the incorporation of renewable energy in plastic production. Policymakers, companies, and consumers must cooperate to establish a sustainable framework that reduces the carbon footprint of plastics while preserving their vital function in contemporary society.

Supplementary Materials: No supplementary materials were provided.

Author Contributions: Conceptualization, A.H. and A.A.; methodology, A.H.; software, N.I.; validation, A.H., A.A. and A.O.; formal analysis, A.H. and N.I.; investigation, A.H. and F.M.; resources, A.A.; data curation, N.I. and A.O.; writing—original draft preparation, A.H.; writing—review and editing, A.A. and A.O.; visualization, N.I.; supervision, A.H.; project administration, A.H. All authors have read and agreed to the published version of the manuscript.

Funding: Please add: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study.

Acknowledgments: The authors declare no acknowledgments.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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