

1

The Climate Change Crisis: Emerging Causes and Effects

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1.1 Introduction

Climate change has rapidly escalated from a distant environmental issue to a pressing global crisis, with far-reaching consequences for ecosystems, public health, and economic systems. The intensification of global warming, primarily driven by anthropogenic greenhouse gas (GHG) emissions, is linked to changing weather patterns, biodiversity loss, and disruptions to food and water systems [1, 2]. These impacts are already observable, from rising sea levels threatening coastal infrastructure to increased disease burden in vulnerable populations [3, 4]. In addition to environmental degradation, climate change undermines economic resilience by affecting productivity, labor conditions, and the long-term viability of essential sectors such as agriculture and energy [5]. Acknowledging these interconnected threats is crucial to formulating effective mitigation strategies and fostering a transition toward sustainable, climate-resilient development pathways.

Climate change refers to long-term shifts in temperature, precipitation patterns, and other atmospheric conditions on Earth. Although natural factors such as volcanic activity and solar cycles have historically contributed to climate variability, the current trend of rapid global warming is predominantly driven by anthropogenic activities, especially the burning of fossil fuels and deforestation [6, 7]. The Intergovernmental Panel on Climate Change (IPCC) has consistently warned that if GHG emissions are not substantially curtailed, the planet will face increasingly severe and disruptive events [8]. Moreover, the effects of climate

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change are intertwined with social, political, and economic systems, making it a multidimensional global challenge beyond merely an environmental one [9, 10].

No longer a distant threat but a lived reality with wide-ranging effects on both natural systems and human society, the consequences of climate change include the intensification of extreme weather events, disruption of ecosystems, and the degradation of essential services such as food supply, water access, and public health [11]. Vulnerable populations, particularly in developing countries, are disproportionately affected due to entrenched social and economic inequalities [12]. Women and marginalized groups often face unique barriers in adapting to climate impacts, as seen in minority and gender-based advocacy challenges within international climate negotiations [13].

Sustainable technologies are crucial for addressing climate change. An emerging promising area for climate mitigation is developing and deploying nano-metal oxide catalysts. These materials have unique physicochemical properties such as high surface area, enhanced catalytic reactivity, and strong selectivity, which make them particularly effective at reducing industrial emissions, catalyzing hydrogen production, and enabling carbon dioxide (CO₂) capture conversion [14, 15]. Unlike traditional catalysts, nano-metal oxides help the development of cleaner energy systems by increasing reaction efficiencies and reducing the environmental impact of processes. Their use supports the goals of green chemistry and nanotechnology, as well as the SDGs, to build more sustainable, circular, and low-carbon economies [16, 17]. This chapter summarizes the current knowledge on the climate crisis, its drivers, implications, the role of energy production in the current climate crisis, and the need for sustainable technologies to confront it.

1.2 An Overview of Climate Change Drivers

The balance of energy entering and leaving the Earth's atmosphere is essential for maintaining global temperature and climate stability. Temperature anomalies and widespread environmental impacts occur when this balance is disturbed, especially by GHG buildup. This section examines underlying concepts such as the greenhouse effect and radiative forcing, the specific roles of primary GHGs, and the difference between natural and human-induced climate drivers.

Climate change arises from both natural processes and human activities. Natural influences include changes in solar energy, volcanic eruptions, and internal Earth system variations such as El Niño–Southern Oscillation (ENSO). While these factors can affect climate over different timescales, they alone cannot account for the rapid warming seen in recent decades [18, 19].

Anthropogenic drivers, rather than natural causes, mainly cause the recent temperature rise. Human activities have released record amounts of carbon and other pollutants into the atmosphere, overwhelming Earth's natural regulatory systems. Climate models that include both natural and human influences provide strong evidence that human activity is the leading cause of current climate change [20].

1.3 Greenhouse Effect and Radiative Forcing

The greenhouse effect is often perceived as a negative process. Still, it is indeed one of the natural processes that enable life on Earth by raising the average temperature from -18 to 15 °C by limiting energy reflection to space. Solar radiation passes through the atmosphere and warms the planet's surface. In response, Earth emits infrared radiation (IR) back into space. GHGs such as CO_2 , methane (CH_4), and water vapor absorb some of this outgoing radiation and reemit it, effectively trapping heat in the atmosphere and raising its temperature. Human activities have significantly intensified this vital process [21].

Radiative forcing refers to the change in energy flux in the atmosphere caused by factors that affect the balance between incoming and outgoing radiation [22]. Positive radiative forcing results in warming, while negative forcing causes cooling. Human-made emissions of GHGs contribute to positive radiative forcing, disrupting the energy balance and strengthening the greenhouse effect. The IPCC states that CO_2 is the main driver of this imbalance, followed by CH_4 and nitrous oxide (N_2O), which are much more potent per molecule than CO_2 (Figure 1.1).

CO_2 is the most prevalent long-lived GHG emitted by human activities, primarily through fossil fuel combustion, deforestation, and cement production. It serves as the baseline for comparing the warming potential of other gases. CH_4 , although less abundant, has over 25 times the global warming potential (GWP) of CO_2 over 100 years and is released from livestock, landfills, and fossil fuel extraction [23]. N_2O , mainly emitted from agricultural activities, has nearly 300 times the GWP of CO_2 . While present in smaller quantities, other synthetic GHGs, such as hydrofluorocarbons (HFCs) are highly potent climate forcers.

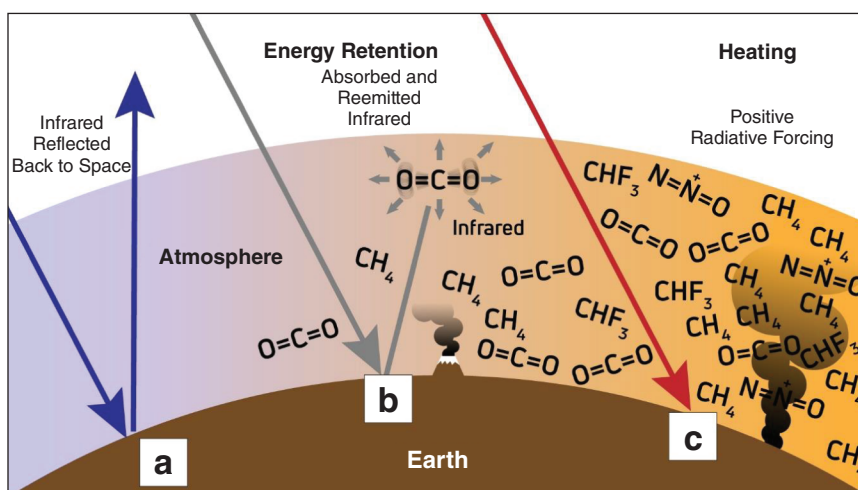


Figure 1.1 Scheme of the greenhouse effect. (a) Solar radiation gets reflected to space. (b) GHGs absorb IR and emit it back to the atmosphere, preventing heat loss. (c) Large concentrations of GHGs result in positive radiative forcing, heating the planet.

Table 1.1 Comparison of key GHGs.

GHG	Primary sources	GWP – 100 years [24]	Relative impact/abundance
Carbon dioxide (CO ₂)	Fossil fuel combustion, deforestation, cement production, and industrialization	1 (baseline)	Most prevalent (75% of GHG emissions); the primary driver of long-term warming
Methane (CH ₄)	Livestock, landfills, fossil fuel extraction	28–36	~25 × more potent than CO ₂ per molecule; accounts for ~17% of GHG emissions
Nitrous oxide (N ₂ O)	Agricultural activities (fertilizers), industrial processes	265–298	~300 × more potent than CO ₂ per molecule; contributes ~6% of radiative forcing
Hydrofluorocarbons (HFCs)	Synthetic (refrigerants, aerosols, and industrial applications)	12–14 800	Extremely potent but low atmospheric concentration; regulated under Montreal Protocol

Data source: Adapted from [25].

The cumulative effect of these gases is an increase in global mean temperatures and a rise in climate variability. This includes altered precipitation patterns, more intense storms, and extended droughts—all linked to the enhanced greenhouse effect. Reducing emissions from all major GHGs is critical for stabilizing the climate. Table 1.1 summarizes the main gases and their contribution to climate change.

1.4 Deforestation

Large-scale deforestation, particularly in tropical regions like the Amazon and Southeast Asia, significantly contributes to climate change [26]. As vital carbon sinks, forests absorb approximately 2.6 billion tons of CO₂ annually, but their destruction through logging, agricultural expansion, and urban development reverses this function. When trees are cut or burned, stored carbon is released, accounting for ~10% of global GHG emissions and intensifying the greenhouse effect. These land-use changes also disrupt local weather patterns, accelerate biodiversity loss, and reduce ecosystem resilience to climate impacts. While initiatives like REDD+ (Reducing Emissions from Deforestation and Forest Degradation) and sustainable land management offer mitigation potential, inconsistent enforcement and economic incentives continue to hinder progress.

The degradation of carbon sinks such as forests, wetlands, and peatlands both amplifies climate change and destabilizes biodiversity hotspots [27]. These ecosystems sequester vast amounts of carbon while supporting millions of species, yet their decline leads to feedback loops: warming temperatures further reduce carbon

storage capacity, while biodiversity loss weakens ecosystem services like pollination and soil fertility [28]. Protecting and restoring these habitats is essential for climate mitigation, but competing land-use demands and insufficient conservation funding pose significant challenges to reversing current trends.

Algae, including both macroalgae and microalgae, act as important carbon sinks in marine ecosystems, but their ability to sequester carbon is increasingly threatened by climate change. Rising global temperatures stress algal health, often increasing respiration rates more than photosynthesis, which reduces net carbon uptake [29]. Marine heatwaves worsen this problem by destroying large, efficient macroalgae like kelp and encouraging turf-forming algae with less sequestration potential. Ocean acidification further hampers algal carbon storage, especially for calcifying species, despite some temporary benefits from higher CO₂ levels. These temperature and chemical changes interact with shifts in nutrient availability, where increased water column stratification limits essential nutrients, and eutrophication leads to harmful blooms that release GHGs during decomposition [30].

Additional climate impacts further reduce algal carbon sequestration potential. Changes in light availability due to less ice cover may initially enhance growth but often cause long-term photoinhibition, while increased UV radiation damages cellular structures and decreases productivity [31]. Perhaps most critically, climate change is reshaping algal communities, favoring less efficient carbon sinks like turf algae over canopy-forming species. These interconnected stressors—temperature extremes, acidification, nutrient shifts, light changes, and community reorganization—reveal an apparent decline in algal carbon sink efficiency. This highlights the urgency for targeted conservation strategies to preserve algae's essential role in global carbon cycling amid accelerating climate disruption [30].

1.5 Industrialization

One of the most significant emerging causes of climate change is the rapid industrialization happening in developing countries. As nations pursue economic growth, they often rely on fossil fuels like coal, oil, and natural gas to run factories, transportation, and urban infrastructure, which, consequently, increase industrial activity, resulting in higher GHG emissions, especially CO₂, which traps heat in the atmosphere and speeds up global warming [32]. While developed countries have started shifting to cleaner energy sources, many emerging economies still depend on outdated, carbon-heavy technologies because of cost and access issues, making the climate crisis worse. Urban heat islands (UHIs) exacerbate energy consumption, air and water quality issues, and public health challenges, particularly affecting low-income populations in tropical and subtropical regions. This phenomenon highlights the need for targeted resilience policies and socioeconomic impact mitigation strategies [33].

An effect of industrialization is the increased waste production [34]. Poor waste management practices, particularly in urban areas, are emerging as a growing contributor to climate change [35]. Landfills filled with organic waste produce CH₄, a GHG over 25 times more potent than CO₂ in trapping heat. As global populations grow and

consumption increases, so does the volume of waste, leading to higher CH₄ emissions. Additionally, industrial processes, such as oil and gas extraction, release CH₄ through leaks and flaring. While CH₄ remains in the atmosphere for a shorter time than CO₂, its immediate impact on global temperatures is substantial [36]. Addressing these emissions through better waste processing, recycling, and stricter industry regulations is crucial to slowing climate change.

1.6 Significant Implications

1.6.1 Rising Temperatures

One of climate change's most direct and measurable effects is the steady rise in global average temperatures. Since preindustrial times, Earth's surface has already warmed by over 1.1 °C, and without decisive global mitigation efforts, projections indicate that warming could exceed 2 °C by the end of the century [37]. This warming trend is strongly linked to an increased frequency and intensity of extreme weather events, including heatwaves, storms, wildfires, and floods [38].

Heatwaves are becoming more frequent, particularly in urban areas where the heat island effect exacerbates temperature spikes. These events strain public health systems and infrastructure, reduce labor productivity, and disproportionately impact the elderly and socioeconomically disadvantaged populations [39]. Moreover, extreme heat poses significant risks for people with preexisting health conditions such as diabetes, amplifying the burden on healthcare systems.

Temperature shifts affect food production more than water or sunlight [40]. Climate change can also modify the viable cultivation areas of diverse crops [41, 42]. These shifts may exacerbate deforestation due to the expansion of farmland at the expense of forested areas [43]. A dire example is the prolonged drought in the Horn of Africa (2020–2023), where record-high temperatures and failed rainy seasons led to catastrophic crop failures and livestock losses. In Somalia, Ethiopia, and Kenya, millions faced acute food insecurity, with over 20 million people requiring emergency aid [44]. Rising temperatures also increase pest outbreaks, such as desert locust swarms, which devastated East African farmlands in 2020, destroying crops and pastureland.

Warmer ocean temperatures are also contributing to stronger hurricanes and cyclones, which lead to increased devastation in coastal regions through flooding and wind damage [45]. Simultaneously, wildfires have escalated in both size and frequency, destroying ecosystems, homes, and lives while releasing additional GHGs into the atmosphere, thus reinforcing the warming cycle [46].

These climate disruptions are environmental and also humanitarian challenges, disproportionately affecting vulnerable communities and exacerbating health and gender-based inequalities [47].

1.6.2 Sea-level Rise

Sea-level rise is one of the most clear and measurable effects of human-caused climate change, mainly due to warming oceans expanding and land ice melting.

Satellite altimetry data shows that the global average sea level has increased by about 3.7 mm per year since 2006, nearly three times the rate seen for most of the 20th century. This faster rise is especially worrying because more than 600 million people live in low-elevation coastal areas that are vulnerable even to small sea level increases. The processes that cause this include not only melting from Greenland and Antarctic ice sheets but also complex feedback effects like reduced reflectivity from less Arctic sea ice and possible destabilization of glaciers that end in the ocean.

The impacts of sea-level rise show significant regional differences due to factors like ocean circulation patterns, gravitational effects from ice loss, and vertical land movement. For example, many tropical areas experience sea-level rise rates 20–30% higher than the global average because of subsidence and ocean dynamics. Climate models predict that even under moderate emission scenarios (RCP 4.5), global mean sea level could increase by 0.5–0.8 m by 2100, with the possibility of much larger rises if certain ice sheet tipping points are reached. These predictions have serious implications for coastal landforms, including more shoreline erosion, increased nuisance flooding, and the potential for some low-lying island nations and coastal wetlands to become permanently submerged. The long timescales involved in sea-level rise mean these effects will last for centuries, even with strong climate change mitigation efforts.

The world's oceans serve as a crucial buffer against climate change by absorbing a significant portion of atmospheric CO₂. However, this absorption leads to ocean acidification, a chemical process that lowers seawater pH, disrupting marine ecosystems and the biological processes that sustain them [48]. The acidification process impairs the ability of marine organisms, especially calcifying species, to build and maintain their calcium carbonate structures.

Among the most impacted are coral reefs, which are essential to global marine biodiversity. Acidification hampers coral calcification, contributing to bleaching events and the collapse of reef ecosystems [49]. Studies across the Pacific Basin confirm that coral reef systems are increasingly vulnerable to combined stressors from warming and acidification, jeopardizing the stability of these ecosystems [50]. The resulting decline in reef health compromises the structural complexity of reefs and reduces habitat availability for thousands of marine species [51].

These ecological impacts extend to human communities as well. Fisheries that depend on reef-associated species face declining yields, and small-scale fishing economies, particularly in the Pacific Islands, are highly exposed to the consequences of acidification and reef degradation [52]. As coral ecosystems degrade, coastal protection also weakens, increasing vulnerability to erosion and storm surge damage [53].

1.6.3 Extreme Weather Occurrences

The rising frequency and severity of extreme weather events are some of the most visible and destructive signs of climate change. Scientific evidence shows clear trends toward stronger tropical cyclones, longer heatwaves, more intense rainfall, and larger, more destructive wildfires. These changes are caused by fundamental

thermodynamic processes. A warmer atmosphere can hold more moisture, resulting in heavier rainfall and flooding, while higher ocean surface temperatures provide extra energy for tropical storms. Attribution studies have shown that many recent extreme events, like the 2021 Pacific Northwest heatwave and Hurricane Harvey's record rainfall in 2017, would have been highly unlikely without human-caused climate change. The combined impact of these events puts pressure on infrastructure, disrupts ecosystems, and challenges communities' ability to adapt worldwide.

The socioeconomic impacts of extreme weather are significant and often disproportionately affect vulnerable populations with limited resources for recovery. Multiyear droughts can destroy agricultural production and lead to water shortages, as observed in recent crises across the Mediterranean and Horn of Africa. Conversely, increasing extreme precipitation events frequently cause devastating flooding, harming homes, transportation systems, and essential facilities. Wildfires, driven by hotter, drier conditions, have become more common in areas from the western United States to Australia, with wide-reaching effects on air quality and biodiversity. These events not only cause immediate physical and economic damages but also pose long-term systemic risks, including population displacement and disruptions to global supply chains. As climate models forecast further intensification of extreme weather under all plausible emission scenarios, the urgency for improved early warning systems, resilient infrastructure, and adaptive land-use planning grows.

1.6.4 Public Health

In recent decades, changing environmental threats have increased the impacts of climate change, creating complex and overlapping risks. The appearance of new ecological hazards like micro- and nano-pollutants and persistent chemical residues, often linked to rapid technological progress, raises new concerns for ecosystems and public health [22]. These human-made stressors worsen the public health crises caused by climate change, which appear through both direct health harms and systemic disruptions to health factors. Extreme heat events, increasing in frequency and severity, disproportionately affect vulnerable groups such as the elderly and those with chronic illnesses. Additionally, stronger storms and wildfires cause trauma, displacement, and strain on medical systems. Meanwhile, changing climate conditions spread vector-borne diseases like malaria and dengue to new areas, putting populations at risk of unfamiliar health threats. These issues demand urgent action to include climate adaptation strategies in public health plans to prevent worsening problems and risks.

The public health effects of climate change go beyond immediate disasters, undermining long-term health stability through environmental degradation and socioeconomic pressures. Falling agricultural yields and decreased nutritional quality of crops—caused by rising CO₂ levels and changing rainfall patterns—threaten food security, leading to malnutrition and related illnesses. At the same time, climate-boosted air pollution from wildfires and industrial sources increases respiratory and heart problems, straining healthcare systems worldwide. Marginalized

communities, often least prepared to adapt, face greater risks due to a lack of infrastructure, limited healthcare access, and increased exposure to environmental hazards. As climate change interacts with new pollutants and legacy contaminants, a comprehensive approach is essential—one that includes emissions reduction, equitable health policies, and efforts to address the root causes of environmental problems and injustice.

Climate change is intensifying air pollution by accelerating the formation of ground-level ozone and increasing the frequency and severity of wildfires and dust storms. These environmental shifts significantly deteriorate air quality, with severe public health consequences. For instance, higher temperatures and wildfire smoke have been shown to worsen particulate matter exposure, especially in already polluted regions [54]. This combination creates synergistic risks that magnify respiratory and cardiovascular impacts [55].

Respiratory conditions such as asthma, chronic obstructive pulmonary disease (COPD), and bronchitis are increasingly common, especially among children, the elderly, and vulnerable communities exposed to poor air quality and extreme weather [56]. Furthermore, prolonged exposure to air pollution, especially from wildfire smoke has been linked not only to exacerbation of chronic respiratory illness but also to higher rates of infections, including respiratory pathogens [57].

Cardiovascular diseases, already a leading cause of global mortality, are further amplified by air pollution, which can trigger inflammatory and oxidative stress responses in the cardiovascular system [54]. Simultaneously, wildfire-related PM_{2.5} pollution has been shown to disproportionately impact lower socioeconomic and minority communities, compounding public health disparities [58].

The broader socioeconomic consequences are equally concerning. Increased healthcare costs, reduced labor productivity, and heightened pressure on public health systems are direct outcomes of worsening air quality and climate-driven health burdens [59]. These trends collectively undermine community resilience and economic development on both local and global scales.

1.7 The Role of Energy Production and Use in Accelerating Climate Change

Fossil fuel combustion is the primary driver of anthropogenic carbon emissions, releasing vast quantities of CO₂ into the atmosphere. When coal, oil, and natural gas are burned for energy, the carbon that had been stored underground for millions of years is rapidly oxidized, reacting with oxygen to form CO₂. This process disrupts the natural carbon cycle, where geological sequestration once balanced atmospheric carbon levels. Since the Industrial Revolution, CO₂ concentrations have risen by over 50%, from 280 ppm to over 420 ppm today (https://osf.io/preprints/osf/het6n_v1), with fossil fuels accounting for roughly 75% of global GHG emissions (Figure 1.2). The energy sector—power generation, transportation, and industry—is the dominant contributor, with coal being the most carbon-intensive per unit of energy produced [60].

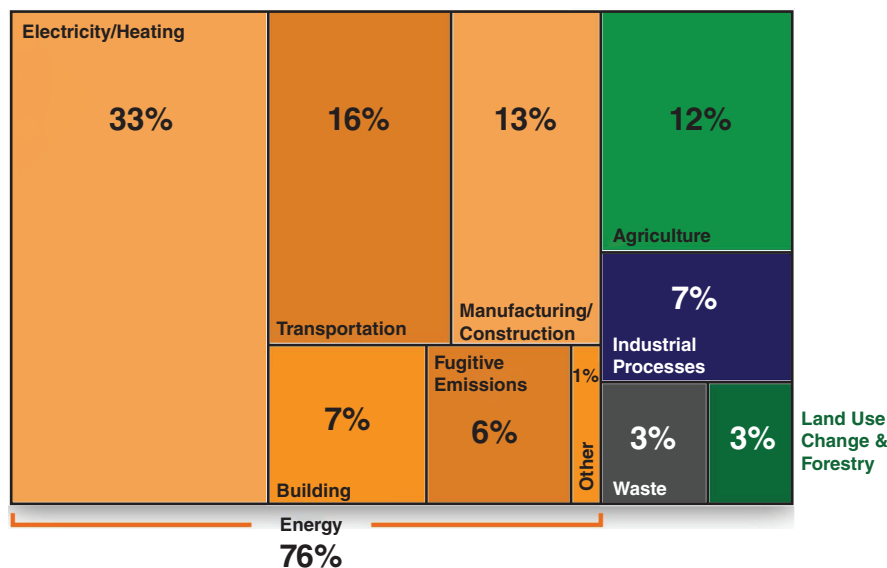


Figure 1.2 Distribution of GHG emissions by sector.
Data source: [61] / World Resources Institute / CC BY 4.0.

According to Dutta (2021), burning fossil fuels for the obtention of energy, heating, electricity, transportation, and industry contributes two-thirds of anthropogenic GHGs [61]. The impacts of these emissions are significant, intensifying climate change through the greenhouse effect. Despite progress in renewable energy, fossil fuels still provide about 80% of the world's energy, maintaining reliance on high-emission infrastructure. Mitigation strategies, such as carbon capture and storage (CCS), switching to natural gas (which emits approximately 50% less CO₂ than coal), and policy measures like carbon pricing, are aimed at reducing emissions. However, reaching net-zero targets requires systemic shifts toward renewable energy, greater energy efficiency, and decarbonization across all sectors to counteract the legacy of fossil fuel dependence.

1.8 Economic and Geopolitical Outlook

Global demand for fossil fuels has plateaued in some developed economies but continues to rise in emerging markets, particularly in Asia. China and India, driven by rapid industrialization and urbanization, are the largest consumers of coal. At the same time, the United States and Europe rely more heavily on natural gas due to its lower carbon intensity. Oil remains indispensable for transportation, constituting nearly 90% of the sector's energy supply. The International Energy Agency (IEA) projects that fossil fuel demand may peak by 2030, although this hinges on aggressive policy interventions and the widespread adoption of renewable energy. Fossil fuel markets remain volatile, influenced by geopolitical conflicts, supply

chain disruptions, and fluctuating demand. The 2022 energy crisis, exacerbated by Russia's invasion of Ukraine, showed the risks of reliance on hydrocarbon imports. Conversely, oil-exporting nations face economic instability as decarbonization policies threaten long-term demand. Subsidies for fossil fuels, estimated at US\$7 trillion annually, distort energy markets and slow the transition to cleaner alternatives [62].

Despite significant progress, current strategies for reducing carbon emissions from burning fossil fuels face significant limitations that hinder their ability to meet global climate goals. Technological solutions, such as CCS, remain energy-intensive, expensive, and limited in scale, with around 50 large-scale projects operating worldwide as of 2024 [63]. While renewable energy use is increasing quickly, it still faces problems with inconsistent output, storage difficulties, and dependence on fossil fuel-based infrastructure for manufacturing and maintaining the power grid. Policy measures, such as carbon pricing and emissions trading schemes, often encounter political opposition, uneven adoption across countries, and prices that are too low to inspire genuine change.

Without strong leadership and societal recognition of necessary changes, vulnerabilities to climate change impacts will increase [64]. Additionally, the ongoing growth of fossil fuel infrastructure, especially in developing countries, locks in future emissions, while market-driven transitions are not keeping pace with the urgent demands of climate science. Without widespread systemic reforms, international cooperation, and accelerated innovation, these issues risk undermining efforts to limit global warming to 1.5 °C, thereby increasing the vulnerability of societies to the growing impacts of climate change. Insufficient Nationally Determined Contributions (NDCs) could lead to warming of 3.0–3.5 °C, increasing vulnerability to climate impacts like flooding and drought, particularly in hotspots such as West Africa, India, and North America [65].

1.9 Global Initiatives and Agreements to Reduce Climate Impacts

International climate treaties, such as the Kyoto Protocol and the Paris Agreement, along with their subsequent extensions, establish vital frameworks for global cooperation in reducing GHG emissions. These agreements operate on the principle of common but differentiated responsibilities, recognizing that developed countries (the most significant historical emitters) should take the lead in cutting emissions while supporting developing nations in their shift to sustainable economies. The Paris Agreement introduced NDCs, which permit each country to set its own emission reduction goals while maintaining transparency through regular reporting and review mechanisms. This flexibility has encouraged broader participation, with nearly every country now committed to some form of climate action.

However, despite these advances, significant challenges remain in aligning global efforts with the Agreement's most ambitious goal: limiting global temperature rise to 1.5 °C above preindustrial levels, especially with 2024 as the first year above the 1.5 °C threshold [66]. Current NDCs, even if fully implemented, would still result

in warming of about 2.5–2.9 °C by 2100, significantly exceeding the safe threshold needed to avoid catastrophic outcomes [67]. This gap shows a critical paradox: while the 1.5 °C target is often criticized for lacking sufficient ambition, it's also seen as nearly impossible to achieve under current policies [68]. Bridging this gap requires stronger enforcement mechanisms, enhanced financial support for developing nations, and accelerated policy implementation to ensure that commitments are translated into tangible outcomes.

1.10 Obstacles

One of the key weaknesses of current climate agreements is the lack of binding enforcement mechanisms. Unlike the Kyoto Protocol, which imposed legally binding emission cuts on developed nations (albeit with limited success), the Paris Agreement relies on voluntary pledges and peer pressure to drive compliance. While this approach has secured near-universal participation, it has also led to inconsistent progress. Some countries have strengthened their NDCs over time, while others lag or even backtrack on commitments. Strengthening accountability could involve stricter monitoring, independent verification of emissions data, and consequences for noncompliance, such as trade sanctions or exclusion from climate financing programs.

Another major obstacle is the inadequate flow of climate finance to developing countries, which often lack the resources to invest in renewable energy, climate resilience, and low-carbon infrastructure. Developed nations pledged to mobilize US\$100 billion annually by 2020 to support mitigation and adaptation efforts in the Global South, yet this target has been repeatedly missed [69]. Without sufficient funding, many vulnerable nations cannot transition away from fossil fuels or build defenses against rising sea levels, droughts, and extreme weather events. Expanding climate finance—through mechanisms like the Green Climate Fund, debt relief for climate-vulnerable nations, and private-sector investments—is essential to ensuring equitable progress.

Even when countries set ambitious NDCs, bureaucratic delays, political resistance, and economic reliance on fossil fuels often slow down implementation. For example, despite global promises to phase out coal, many nations continue to approve new coal-fired power plants due to energy security concerns or lobbying by the fossil fuel industry. A faster transition needs not only stricter regulations but also just transition policies that support workers and communities dependent on high-carbon industries. Retraining programs, green job creation, and social safety nets can help reduce economic disruptions and increase public support for climate action [70].

1.11 Systemic Change

While international agreements are crucial, they must be complemented by systemic changes in energy, agriculture, transportation, and urban planning. Subnational actors—such as cities, corporations, and financial institutions—play

an increasingly important role in driving innovation and filling gaps left by national governments. Initiatives like the C40 Cities network and the Science-Based Targets initiative (SBTi) demonstrate how local and private-sector leadership can accelerate decarbonization [71].

Ultimately, the success of global climate agreements relies on whether nations can move beyond rhetoric and engage in swift, coordinated action. Enhancing enforcement, boosting financial support, and accelerating policy implementation are essential steps to bridge the gap between current commitments and the missed 1.5 °C target. Without these efforts, the paradox of being both unattainable and insufficient will persist, leaving the world on a perilous path toward irreversible climate damage [72, 73].

1.12 The Importance of Creating Sustainable Technology to Combat Climate Change

The development of more sustainable technology is a vital part of this global effort. Sustainable technologies such as renewable energy systems, energy-efficient infrastructure, and carbon capture solutions provide practical ways to decouple economic growth from environmental harm. By focusing on innovation in clean energy, circular manufacturing, and smart urban planning, societies can reduce their carbon footprints while building long-term resilience. The shift to sustainable technology is an environmental, economic, and social need and opportunity, creating new industries, green jobs, and energy independence for countries worldwide.

However, the widespread adoption of sustainable technology faces challenges, including high initial costs, policy barriers, and uneven access across regions. To overcome these obstacles, governments, corporations, and research institutions must collaborate to increase investments, simplify regulatory frameworks, and promote equitable technology transfer. Emerging innovations like green hydrogen, next-generation batteries, and AI-driven climate modeling have great potential but need coordinated support to reach commercialization. Additionally, public awareness and behavioral changes are essential for creating demand for sustainable solutions. By combining technological advancements with systemic policy reforms and societal engagement, a sustainable future that fights climate change while promoting global equity and prosperity can be achieved.

Catalysis plays a crucial role in reducing GHG emissions by improving the efficiency of chemical reactions across industries. Catalysts decrease energy needs, reduce unwanted byproducts, and support cleaner processes in sectors like petroleum refining, automotive exhaust treatment, and renewable fuel production. Their ability to speed up reactions under gentler conditions makes them essential for reaching net-zero goals and moving toward sustainable industrial practices.

Among emerging solutions, nano-metal oxide catalysts have gained attention for their high surface area, tunable properties, and stability under harsh conditions. Materials such as cerium oxide (CeO₂), titanium dioxide (TiO₂), and zinc oxide (ZnO) show excellent redox activity and selectivity, making them ideal for

environmental applications. Their nanostructured form further boosts catalytic performance, offering a promising way to replace traditional, often scarce or toxic, catalytic materials [74].

These advanced catalysts are being deployed in critical climate mitigation strategies, including CO₂ capture and conversion, green hydrogen production via water splitting, and air pollution control through photocatalytic degradation of pollutants. For instance, nano-catalysts can transform captured CO₂ into fuels or plastics, while also improving the efficiency of electrolyzers for hydrogen generation. By integrating these innovations, industries can significantly reduce their carbon footprint while maintaining economic viability.

While renewable energy and advanced technologies promise decarbonization, their production and disposal generate hazardous pollutants. Solar panels, batteries, and electronics release nano-pollutants (e.g., silicon nanoparticles) and heavy metals (e.g., lead, cadmium) into soil and water, while industrial waste from manufacturing often lacks proper recycling infrastructure. These contaminants accumulate in ecosystems, posing risks to human health and wildlife. A circular economy approach, improving material recovery, safer chemical alternatives, and stricter regulations, is needed to minimize trade-offs between technological progress and environmental harm [75].

The rise of nanotechnology and industrial expansion has introduced persistent pollutants, including toxic heavy metals (e.g., mercury, arsenic) and synthetic nanoparticles, into air, water, and food chains [76]. These contaminants resist natural degradation, bioaccumulate in organisms, and cause long-term ecological damage. For example, microplastics and nano waste from electronics infiltrate marine systems, while mining waste leaches heavy metals into groundwater. Monitoring and remediation efforts lag behind pollutant dispersion, underscoring the need for global standards on waste management and more sustainable material design.

Traditional catalytic processes in industries like petroleum refining and chemical manufacturing rely on platinum-group metals (PGMs) and toxic reagents, which are energy-intensive and often generate harmful byproducts (e.g., NO_x, SO₂). While catalysts improve reaction efficiency, their environmental footprint from mining rare metals to emissions during use undermines sustainability goals. Transitioning to bio-based or earth-abundant catalysts (e.g., iron, enzymes) could reduce these impacts, but scalability and cost barriers persist. Green chemistry and its twelve principles are an initiative towards a sustainable chemical industry. Green chemistry focuses on designing chemical products and processes that minimize environmental harm by reducing or eliminating hazardous substances [77]. It promotes principles like atom economy, renewable feedstocks, and energy efficiency to cut waste, lower emissions, and enhance sustainability. By replacing toxic solvents, developing biodegradable materials, and improving catalytic processes, green chemistry aims to make industries from pharmaceuticals to manufacturing cleaner and more resource-efficient. This shift addresses pollution and aligns with circular economy goals, ensuring long-term ecological and economic benefits aligned with UN SDGs [78].

Conventional catalysts, though critical for fuel production and pollution control (e.g., catalytic converters), frequently depend on scarce, expensive materials like

palladium and rhodium. Their extraction and processing contribute to significant carbon emissions and ecological damage, while catalyst deactivation over time generates hazardous waste [77]. Innovations in catalyst design, such as single-atom catalysts or photocatalytic systems, could enhance efficiency and reduce reliance on finite resources. Still, industrial adoption remains slow due to technical and economic constraints.

The shift toward sustainable chemical processes demands alternatives to fossil-derived feedstocks and toxic reagents. Electrocatalysis, photocatalysis, and biocatalysis offer promising pathways, using renewable energy or enzymes to drive reactions with minimal waste. For instance, photocatalysts like TiO_2 can break down pollutants under sunlight, while engineered enzymes enable low-temperature industrial processes. However, stability, reaction rates, and large-scale deployment must be addressed to make these alternatives viable for the global industry.

These challenges add to traditional climate stressors and require a broader, interdisciplinary understanding of climate dynamics. Responding effectively and efficiently calls for integrated strategies involving environmental monitoring, land use policy, industrial innovation, and energy system transformation.

1.13 Conclusion

Climate change has quickly shifted from a distant environmental issue to an urgent worldwide crisis, with wide-reaching effects on ecosystems, public health, and economies. The increase in global warming, mainly caused by human-made GHG emissions, is connected to severe weather events, loss of biodiversity, and disruptions to food and water supplies. Tackling these linked threats requires effective mitigation strategies and a move toward climate-resilient, sustainable development paths.

The scientific consensus, as outlined by the IPCC, attributes current warming trends (1.1 °C above preindustrial levels) overwhelmingly to human activities, especially fossil fuel burning and deforestation. Without significant reductions in GHG emissions, the planet will face increasing climate extremes—heatwaves, storms, wildfires, and floods—with cascading socioeconomic impacts. Ocean acidification, caused by CO_2 absorption, is harming marine ecosystems, especially coral reefs that support fisheries and coastal protection. Air pollution, worsened by ground-level ozone and wildfire smoke, raises respiratory and cardiovascular health issues, disproportionately impacting vulnerable populations. Climate-related disruptions to education, infrastructure, and labor productivity further intensify these challenges.

Emerging contributors to climate change include rapid fossil fuel-dependent industrialization in developing economies, large-scale deforestation, and inadequate waste management (a significant source of CH_4 emissions). Despite advances in renewable energy, persistent barriers hinder progress: CCS remains energy-intensive and costly, renewable intermittency challenges grid stability, and political resistance weakens carbon pricing policies. Additionally, producing and disposing of renewable technologies generates hazardous pollutants, such as nanoparticles and heavy metals, creating new environmental trade-offs.

Innovative solutions are critical to overcoming these limitations. Catalysis is pivotal in reducing emissions by optimizing chemical reactions across industries, minimizing energy use and waste. Nano-metal oxide catalysts (e.g., CeO₂, TiO₂, and ZnO) offer enhanced surface reactivity, selectivity, and stability, enabling breakthroughs in CO₂ conversion, green hydrogen production, and air pollution control. Unlike traditional catalysts, these nanomaterials align with green chemistry principles, supporting circular, low-carbon economies.

The future of climate-friendly catalysis lies in earth-abundant materials, AI-driven catalyst design, and solar-fuel systems. However, technological advances must be paired with stronger policy frameworks, including equitable implementation of international agreements like the Paris Agreement, increased funding for clean energy transitions, and stricter regulations on industrial pollutants. By integrating innovation with systemic reforms, catalysis can become a cornerstone of global climate mitigation, helping societies achieve net-zero targets while maintaining economic viability.

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