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Research Article

Climate Change: Key Contributors and Sustainable Solutions

Khalid Mohamed Omemen [1*], Mona Othman Aldbbah[1]

[1] Higher Institute of Science and Technology, Khoms, Libya

*Corresponding author: khalidomeamn@gmail.com

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Abstract: Climate change, driven by both natural and anthropogenic factors, represents one of the most pressing challenges of the 21st century. The primary contributors to climate change include greenhouse gas emissions from human activities, such as the burning of fossil fuels, deforestation, and industrial processes, as well as natural events like volcanic eruptions and variations in solar radiation. Among these, carbon dioxide (CO_2) and methane (CH_4) are the most significant greenhouse gases, with their rising concentrations in the atmosphere intensifying the greenhouse effect and contributing to global warming. This paper explores the key drivers of climate change and examines the wide-ranging environmental, social, and economic impacts. In response to these challenges, the paper also reviews sustainable solutions, including the transition to renewable energy, improvements in energy efficiency, carbon capture technologies, reforestation, and sustainable agricultural practices. The potential for innovation in green technologies, along with policy frameworks that promote international cooperation and climate resilience, is discussed as a means to mitigate and adapt to climate change. Ultimately, addressing climate change requires a global, multi-faceted approach to reduce emissions, protect ecosystems, and ensure a sustainable future for generations to come.

Keywords: Climate Change, Carbon Dioxide, Methane, Sustainable Solutions.

1. Introduction

Climate change, driven by a variety of factors, represents one of the most significant challenges facing humanity in the 21st century. The key contributors to climate change are primarily human-induced, with the most notable being the emission of greenhouse gases (GHGs) into the atmosphere. These gases, such as carbon dioxide (CO_2), methane (CH4), and nitrous oxide (N2O), are released through the combustion of fossil fuels, industrial processes, deforestation, and agricultural activities. The accumulation of these gases enhances the greenhouse effect, trapping heat and leading to global warming. The consequences of this warming are widespread, encompassing rising global temperatures, changing precipitation patterns, increasing frequency of extreme weather events, and rising sea levels [1,2].

Global warming refers to the "rise in the Earth's surface average temperature," a phenomenon primarily driven by the increased concentration of greenhouse gases (GHGs), including water vapor, methane, ozone, carbon dioxide, chlorofluorocarbons (CFCs), and nitrous oxide. The greenhouse effect, which is integral to maintaining Earth's habitability, plays a crucial role in regulating the planet's temperature. In the absence of these gases, the Earth's surface temperature would be excessively low, rendering life unsustainable. However, the heightened concentration of GHGs in the atmosphere has precipitated the alarming phenomenon of global warming [3,4].

The Earth's atmosphere is primarily composed of nitrogen, oxygen, and argon, with other gases present in trace amounts, including greenhouse gases (GHGs) and various pollutants, as illustrated in Table 1. The proportion of the major permanent gases—nitrogen, oxygen, and argon—remains relatively constant, whereas the concentration of trace gases, such as carbon dioxide, methane, nitrous oxide, and ozone, fluctuates on a daily, seasonal, and annual basis. Greenhouse gases possess the unique ability to absorb and re-emit infrared radiation due to the specific vibrational modes of their atomic structures, distinguishing them from the primary constituents of the atmosphere.

Table 1. The gaseous composition of the Earth's atmosphere.

Gas name	Percentage (%)
Nitrogen	78
Oxygen	21
Argon	0.9
Carbon dioxide	0.0935
Neon	0.004675
Helium	0.001299
Methane	0.00042
Nitrous oxide	0.000078
Ozone	0.00001

The Table 1 provided presents a table that details the composition of Earth's atmosphere in terms of the percentage of various gases. The major components, namely nitrogen (78%) and oxygen (21%), together account for approximately 99% of the atmosphere's total composition. These gases, classified as permanent gases, remain relatively constant in their proportions. Argon, which constitutes 0.9% of the atmosphere, is another stable gas that plays a minimal role in atmospheric processes but is noteworthy for its inert properties. In contrast, the remaining gases—carbon dioxide, neon, helium, methane, nitrous oxide, and ozone—are present in trace amounts, yet they have significant implications for atmospheric and environmental processes, despite their low concentrations. Carbon dioxide (0.0935%) is a key greenhouse gas (GHG), with its role in trapping heat in the atmosphere directly contributing to the global warming phenomenon. Methane (0.00042%), nitrous oxide (0.000078%), and ozone (0.00001%) are also potent greenhouse gases, though their concentrations are much lower. Despite their minute presence, they have a disproportionately large effect on the Earth’s climate, primarily due to their enhanced heat-trapping properties compared to carbon dioxide [5-11].

Beyond greenhouse gas emissions, other contributing factors include land use changes, such as deforestation and urbanization, which disrupt natural carbon sinks and exacerbate the problem. Additionally, overexploitation of natural resources, coupled with unsustainable agricultural and industrial practices, further accelerates the degradation of ecosystems and the atmosphere. To mitigate the adverse effects of climate change, sustainable solutions are imperative. Key strategies include transitioning to renewable energy sources, such as solar, wind, and hydropower, to reduce reliance on fossil fuels. Implementing energy efficiency measures across sectors, from transportation to building construction, can also substantially lower emissions. Furthermore, fostering reforestation and afforestation initiatives can restore carbon sinks and help mitigate the effects of deforestation [12-17]. Technological innovations, such as carbon capture and storage (CCS) technologies, have emerged as potential tools for directly addressing the excess CO_2 in the atmosphere. Sustainable agricultural practices, including the adoption of agroforestry and precision farming, can further contribute to reducing emissions and enhancing resilience to climate impacts. Table 2 provides an overview of recent studies focused on climate change, highlighting their key contributions to understanding and addressing the various dimensions of this global issue. The studies featured in this table encompass a wide range of topics, including climate adaptation strategies.

Table 2. Recent studies on climate change and main contributions.

Ref.	Year	Contribution	Target
[18]	2024	This article examines the direct impacts of climate change, focusing on extreme weather events such as droughts, floods, and wildfires, which are becoming more prevalent as global temperatures rise. The study begins by exploring the potential consequences of climate change on these extreme events, emphasizing how they are expected to increase in frequency and intensity. It then shifts to analyzing how these events influence the release and transformation of contaminants in terrestrial, aquatic, and atmospheric environments. Droughts and floods alter the behavior of both inorganic and organic contaminants in soil and water, affecting their mobility and transport across ecosystems. In contrast, wildfires lead to the release and dispersion of organic contaminants into the atmosphere, exacerbating air pollution.	Climate Change
[19]	2024	This article explores the intersection of public policy and climate change, emphasizing the necessity of adapting strategies to ensure sustainable futures. Through a comprehensive literature review, the study synthesizes and evaluates a range of scholarly works, policy papers, and case studies that address the relationship between climate change adaptation and public policy. The aim is to examine the evolving nature of policy frameworks, strategies, and practices in response to the increasing challenges posed by climate change. By identifying key trends and insights, the article seeks to contribute to the ongoing development of effective public policies that can mitigate the impacts of climate change and promote resilience in the face of global environmental changes.	Climate Change
[20]	2024	This study evaluates the implications of climate change adaptation and mitigation strategies (CCAMS) on biodiversity and forest ecosystem services (ES) in Sweden's production forests. The assessment synthesized findings from 51 scientific reviews, comparing the effects of CCAMS against standard forestry practices. The strategies considered include mixed-species stands, continuous cover forestry, altered rotation lengths, conversion to non-native tree species, logging residue extraction, stand fertilization, and modified ditching/draining practices.	Climate Change

Equally important is the need for comprehensive policy frameworks at both national and international levels. Climate change mitigation and adaptation require robust governance, including the enforcement of carbon pricing mechanisms, the development of green technologies, and international cooperation on climate accords, such as the Paris Agreement. Social engagement and education are also crucial in fostering public awareness and encouraging behavioral changes that support sustainable practices. Ultimately, addressing climate change requires a holistic approach that integrates technological, policy, and societal efforts, all underpinned by a commitment to sustainable development. Only through collective global action can the trajectory of climate change be altered, ensuring a more resilient and sustainable future for generations to come.

2. The Primary Factors of Global Warming

Global warming is driven by a complex interplay of natural events and anthropogenic emissions, both of which contribute to the rise in Earth's average temperature. Natural events, such as variations in solar radiation, volcanic eruptions, and changes in Earth's orbit, have historically influenced the planet's climate, but human activities have increasingly become the dominant force behind recent warming. Among the key anthropogenic emissions, carbon dioxide (CO_2) and methane (CH_4) play particularly significant roles in enhancing the greenhouse effect. Carbon dioxide, primarily released from the burning of fossil fuels and deforestation, has been the main contributor to the accelerated warming of the planet. Methane, while present in smaller quantities, is much more potent than CO_2 in trapping heat. Figure 1 illustrates the primary factors of global warming. Understanding the combined impact of natural factors and human-induced emissions is essential for developing effective strategies to mitigate global warming and its associated risks.

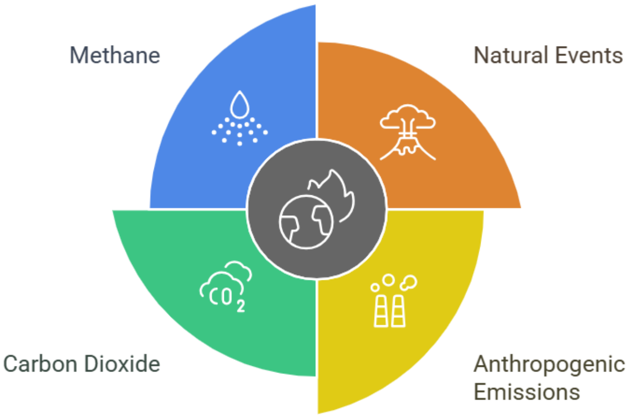

Figure 1. illustrates the primary factors of global warming.

A. Natural Events

In terms of natural events, the Earth's climate has undergone significant fluctuations throughout geological history, driven by various natural phenomena. These include changes in solar radiation emitted by the Sun, volcanic eruptions, and variations in the amount of solar radiation incident on Earth, as governed by the Milankovitch cycles. The Milankovitch cycle refers to a long-term pattern that recurs approximately every 10,000 years, responsible for initiating natural periods of global cooling and warming. This cycle is influenced by three primary factors: eccentricity, obliquity, and precession. Eccentricity pertains to the periodic alteration in the shape of Earth's orbit, shifting from more circular to elliptical configurations, which affects the distance between the Earth and the Sun [21,22]. Obliquity refers to the variation in the tilt of Earth's axis, which influences the intensity of seasonal changes. Precession, on the other hand, is the wobbling motion of Earth's axis, affecting the orientation of the planet relative to the Sun over long periods. Collectively, these three factors contribute to gradual changes in Earth's climate over thousands of years, playing a fundamental role in shaping natural climate cycles and transitions between glacial and interglacial periods. While these natural drivers have historically governed climate patterns, the current rate of climate change is largely driven by human activities, distinguishing modern global warming from previous natural cycles. Understanding these natural events, however, is essential for distinguishing between anthropogenic and natural climate influences [23,24].

The Sun is the ultimate source of energy for the Earth's climate system. Variations in solar radiation—how much energy the Sun emits—can influence the global temperature. Over the course of the Earth's history, solar radiation has fluctuated due to various factors, such as changes in the Sun's energy output, sunspot cycles, and the Earth's position relative to the Sun. Solar irradiance has been known to vary on both short-term (11-year solar cycle) and long-term (centuries) timescales. It is import to highlight that NASA satellites have been continuously monitoring solar irradiance—the rate at which the Sun emits energy—since 1978 [25,26]. Data collected over this period indicate a very slight decline in solar irradiance. To assess the potential influence of variations in solar radiation on Earth's climate, long-term estimations have been conducted. These studies reveal that changes in solar radiation account for, at most, 10% of the observed warming during the 20th century. This suggests that solar activity alone cannot be the primary driver of recent global warming. Furthermore, if the warming were predominantly caused by increased solar activity, the entire atmospheric column would exhibit a uniform warming trend. However, observations contradict this expectation. Scientists have detected a cooling trend in the upper layers of the atmosphere (the stratosphere) alongside a pronounced warming trend in the lower layers (the troposphere). This pattern is consistent with the effects of greenhouse gases trapping heat near Earth's surface, rather than changes in solar radiation. These findings underscore the dominant role of anthropogenic factors, such as greenhouse gas emissions, in driving recent climate change [27,28].

In addition, volcanic eruptions are another natural event that can influence Earth's climate, though their impact is often short-lived. When volcanoes erupt, they release large amounts of gases and particulates into the atmosphere, including sulfur dioxide (SO2), ash, and water vapor. Sulfur dioxide, in particular, reacts in the atmosphere to form sulfate aerosols, which have a cooling effect by reflecting incoming solar radiation back into space. This phenomenon can lead to a temporary decrease in global temperatures. While volcanic eruptions can induce short-term cooling, they are not responsible for the long-term warming observed over recent decades. The cooling effects of volcanic aerosols are typically short-lived, lasting from months to a few years. The most significant example of volcanic cooling in the modern era was the eruption of Mount Pinatubo in 1991, which caused a temporary global temperature drop of about 0.5°C. However, the warming caused by the increased concentration of greenhouse gases in the atmosphere far outweighs the cooling effects of volcanic activity [29-31].

Moreover, the Milankovitch cycles refer to long-term variations in Earth's orbit and axial tilt, which influence the amount and distribution of solar radiation reaching the planet's surface. These cycles, which operate over tens of thousands to hundreds of thousands of years, are driven by three main factors: eccentricity, obliquity, and precession. Eccentricity refers to changes in the shape of Earth’s orbit, ranging from nearly circular to more elliptical over a 100,000-year cycle. These changes affect the distance between the Earth and the Sun, altering the amount of solar energy received. Obliquity is the tilt of Earth's axis, which varies between 22.1° and 24.5° over a 41,000-year cycle [32,33]. The tilt affects the severity of seasons and the distribution of solar radiation between the poles and the equator. Precession refers to the wobble in Earth’s rotational axis, which changes the orientation of the planet’s axis over a 26,000-year cycle. This affects the timing of the seasons in relation to Earth's position in its orbit. These cycles have played a significant role in triggering periods of glacial and interglacial cycles throughout Earth's history [23,33]. For instance, the transition from ice ages to warmer periods has been linked to shifts in the Milankovitch cycles. However, the current period of global warming cannot be attributed to these natural cycles, as they operate over much longer timescales and do not account for the rapid rise in temperatures observed since the industrial revolution. In fact, the current warming trend is occurring at a pace far faster than what would be expected from natural cycles alone.

B. Anthropogenic Emissions:

Water vapor is the most abundant greenhouse gas in Earth's atmosphere, and it plays a critical role in regulating the planet’s temperature. However, its role in global warming is somewhat distinct from that of other greenhouse gases such as carbon dioxide (CO_2), methane (CH4), and nitrous oxide (N2O). While water vapor is a naturally occurring gas, its concentrations in the atmosphere can be indirectly influenced by anthropogenic activities, contributing to an enhanced greenhouse effect. Understanding the relationship between water vapor and anthropogenic emissions is essential to comprehending the broader mechanisms driving global warming [34,35].

In this direction, water vapor acts as a powerful greenhouse gas by trapping heat in the atmosphere. It absorbs infrared radiation emitted by the Earth's surface and re-radiates it back toward the ground, thereby maintaining Earth’s temperature at a level conducive to life. Without water vapor, the Earth's surface temperature would be significantly lower, and life as we know it would not be possible. However, unlike CO_2, methane, and other long-lived greenhouse gases, water vapor does not remain in the atmosphere for long periods. Its concentration in the atmosphere is highly dependent on temperature, as warm air can hold more moisture than cold air. As the Earth's surface temperature rises, more water evaporates from oceans, lakes, rivers, and soil, increasing the concentration of water vapor in the atmosphere. This creates a feedback loop: the warming caused by anthropogenic emissions of CO_2 and other GHGs leads to increased water vapor in the atmosphere, which in turn amplifies the initial warming [36,37]. This feedback mechanism is one of the most potent processes driving climate change.

C. Carbon dioxide

Carbon dioxide (CO_2) is widely recognized as one of the most significant contributors to global warming and climate change. As a greenhouse gas (GHG), CO_2 plays a central role in trapping heat within the Earth's atmosphere, leading to the rise in global temperatures that has been observed over the past century. Figure 2 illustrates CO_2 emissions from fossil fuels and land-use change, World.

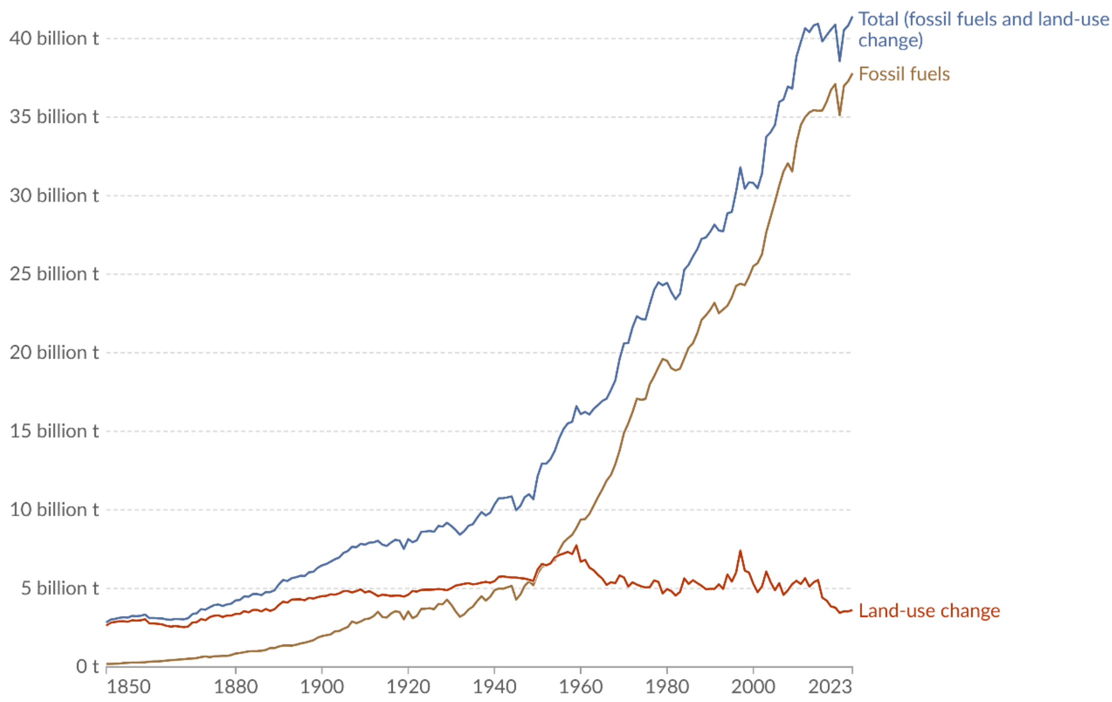

Figure 2. CO_2 emissions from fossil fuels and land-use change, World.

The primary source of anthropogenic CO_2 emissions is the combustion of fossil fuels, including coal, oil, and natural gas, which release vast amounts of CO_2 into the atmosphere. Understanding the role of CO_2 in global warming is essential for identifying effective mitigation strategies and addressing the ongoing climate crisis [38,39]. Moreover, the greenhouse effect is a natural process by which certain gases in the Earth's atmosphere, including carbon dioxide, methane, and water vapor, trap heat from the Sun. This process allows the Earth to maintain temperatures that are conducive to life. Solar radiation from the Sun reaches the Earth's surface, where some of it is absorbed, and the rest is radiated back toward space as infrared radiation (heat). Greenhouse gases absorb and re-radiate this heat, preventing it from escaping into space, thus warming the atmosphere [39,40]. Figure 3 demonstrates annual CO_2 emissions by world region.

This interactive chart provides a detailed breakdown of global CO_2 emissions by region. Historical data reveal that, until well into the 20th century, Europe and the United States overwhelmingly dominated global emissions. In 1900, over 90% of global emissions originated from these two regions, and by 1950, they still contributed to more than 85% of annual emissions. However, the distribution of emissions has undergone a profound shift in recent decades. The latter half of the 20th century witnessed a substantial increase in emissions from other regions, particularly Asia, with China emerging as a significant contributor. Presently, Europe and the United States collectively account for less than one-third of global emissions.

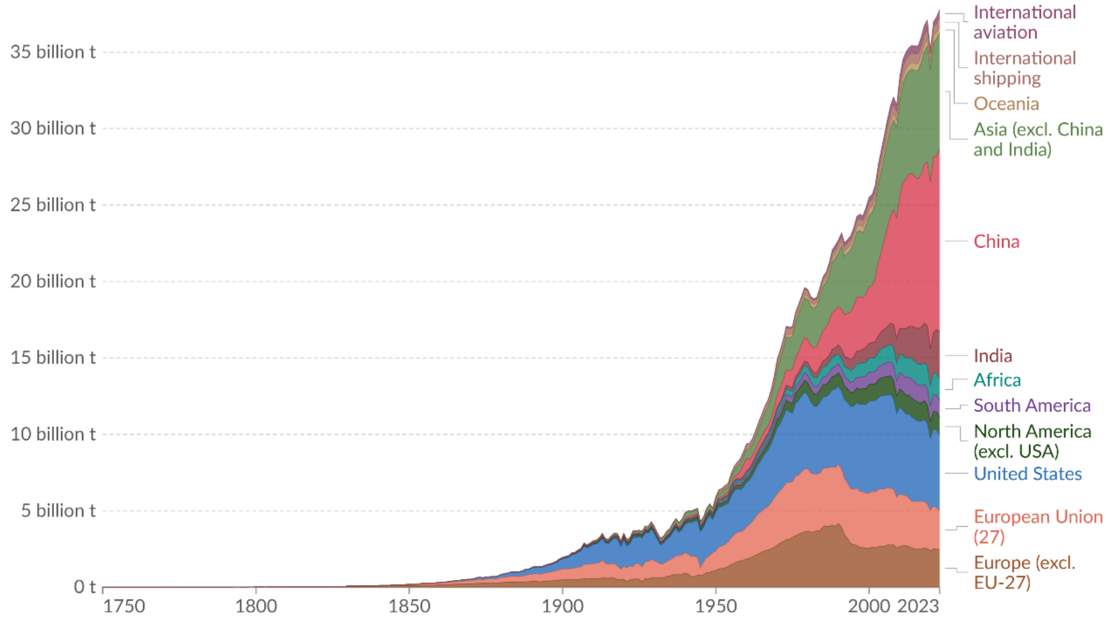

Figure 3. Annual CO_2 emissions by world region

D. Methane

The climatic impact of greenhouse gases is primarily determined by two critical factors: their atmospheric lifetime and their energy absorption capacity. Methane, for instance, has a significantly shorter atmospheric residence time compared to carbon dioxide (CO_2)—approximately 12 years versus several centuries—but exhibits a much greater capacity for energy absorption during its time in the atmosphere. Figure 4 shows sources of methane emissions, 2023.

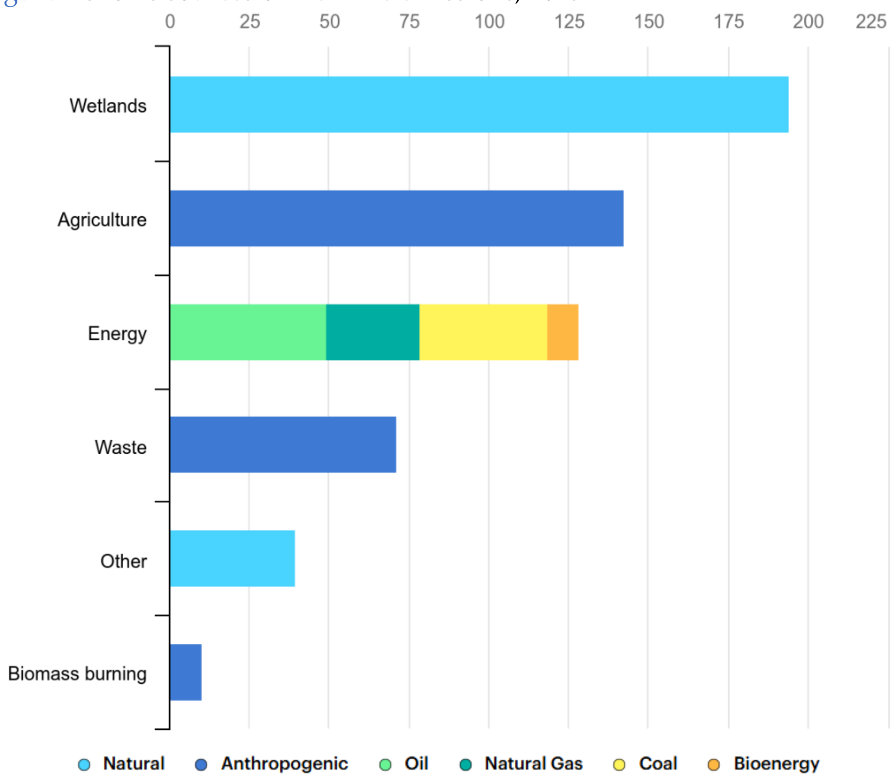

Figure 4. Sources of methane emissions, 2023.

To quantify the relative impact of methane in terms of CO_2 equivalence (CO_2-eq), various methodologies have been developed. The most widely utilized metric is the Global Warming Potential

(GWP), which applies conversion factors based on specified time horizons. For example, when considering a 20-year timeframe (GWP20), one tonne of methane is equivalent to 82–87 tonnes of CO_2. Over a 100-year timeframe (GWP100), this equivalence decreases to approximately 30 tonnes of CO_2. Alternative frameworks, such as the Global Temperature Potential (GTP), provide a more direct linkage between methane emissions and the anticipated temperature increase in a specific future year. In this analysis, we adopt the GWP100 metric, equating one tonne of methane to 30 tonnes of CO_2-eq.

Irrespective of the chosen conversion factor, methane is an exceptionally potent greenhouse gas, necessitating rapid and sustained reductions in emissions from the energy sector to achieve the critical target of limiting global warming to 1.5°C. Beyond its climate impacts, methane significantly influences air quality by contributing to the formation of ground-level (tropospheric) ozone, a hazardous pollutant with detrimental effects on both human health and ecosystems. Additionally, methane leaks pose serious risks, including explosion hazards and adverse health implications, further underscoring the urgency of addressing methane emissions comprehensively.

In this context, Methane (CH_4) is one of the most potent greenhouse gases in the Earth's atmosphere, and it plays a significant role in the process of global warming. Although methane is present in much smaller quantities than carbon dioxide (CO_2), its global warming potential (GWP) is far greater. Over a 20-year period, methane is estimated to be about 84 times more effective at trapping heat in the atmosphere than CO_2, and it remains a critical target for climate change mitigation. Understanding the role of methane in global warming is essential for developing strategies to reduce its emissions and address the climate crisis. Like other greenhouse gases, methane contributes to the greenhouse effect, a process in which certain gases in the Earth's atmosphere trap heat from the Sun and prevent it from escaping back into space. This trapped heat warms the Earth's surface and lower atmosphere, maintaining temperatures that allow life to thrive. Methane, as a potent greenhouse gas, absorbs and re-emits infrared radiation, enhancing the natural greenhouse effect [41-43].As a result, even relatively small increases in methane concentrations can have a disproportionate impact on global warming. Methane emissions come from both natural and anthropogenic sources, with human activities accounting for a significant portion of the methane released into the atmosphere. The primary anthropogenic sources of methane emissions include:

- Agriculture

Agriculture is the largest source of human-generated methane emissions, with livestock farming being the principal contributor. Ruminant animals, such as cattle, sheep, and goats, produce methane during digestion through a process known as enteric fermentation. Methane is released from the animals' digestive systems and expelled through burping. The increasing demand for meat and dairy products has contributed to a rise in methane emissions from this sector. Additionally, rice paddies, which create anaerobic (oxygen-free) conditions, are another significant source of methane emissions in agriculture.

- Fossil Fuel Extraction and Use

The extraction, transportation, and processing of fossil fuels, including oil, natural gas, and coal, are major contributors to methane emissions. Methane is often released during the extraction process from coal mines (coal mine methane) and from natural gas drilling and production facilities. Leaks from pipelines, storage tanks, and during the transport of natural gas also contribute to methane emissions. Methane can be released unintentionally during the extraction process, and a lack of regulation or inadequate infrastructure can exacerbate these emissions.

- Landfills:

Landfills, which collect and store waste, are another significant source of methane emissions. Organic waste, such as food scraps and paper, decomposes anaerobically in landfills, producing methane as a by-product. As urban populations grow and waste generation increases, the volume of methane emitted from landfills continues to rise. Methane from landfills is typically released into the atmosphere unless it is captured and utilized for energy production.

- Wastewater Treatment: The treatment of wastewater, particularly from sewage systems and industrial processes, generates methane as organic materials break down anaerobically. Methane emissions from wastewater treatment plants can be substantial, particularly in areas where the infrastructure for waste treatment is outdated or inefficient.

- Wetlands and Natural Sources: While anthropogenic sources dominate methane emissions, natural sources also play a role. Wetlands are the largest natural source of methane, as they provide anoxic conditions conducive to methane-producing microbes. Methane is produced as organic matter decomposes in waterlogged soils. Other natural sources include termites, wildfires, and oceans, but these contribute much smaller amounts compared to human-driven activities.

Nitrous oxide (N_2O) is a potent greenhouse gas that plays a significant role in global warming and climate change. Although it exists in much smaller concentrations in the atmosphere than carbon dioxide (CO_2) or methane (CH_4), its global warming potential (GWP) is far greater. Nitrous oxide has a GWP approximately 298 times higher than CO_2 over a 100-year period, making it a critical contributor to the enhanced greenhouse effect. Additionally, nitrous oxide is a long-lived gas, remaining in the atmosphere for an extended period, and it also plays a role in the depletion of the ozone layer. Understanding the sources, effects, and mitigation strategies related to nitrous oxide is crucial for addressing its contribution to global warming. While natural sources account for a significant portion of global N_2O emissions, human activities have caused a dramatic increase in its concentration in the atmosphere. The major sources of nitrous oxide emissions include:

- Agricultural Activities

Agriculture is by far the largest source of anthropogenic nitrous oxide emissions. The primary source within agriculture is the use of synthetic fertilizers, which contain nitrogen compounds. When these fertilizers are applied to soils, microbes in the soil convert the nitrogen in the fertilizers into nitrous oxide through a process known as nitrification and denitrification. This conversion process is highly dependent on factors such as soil type, moisture, and temperature, and it becomes more intense with the overuse of nitrogen fertilizers.

- Fossil Fuel Combustion

The burning of fossil fuels, particularly in industrial processes and transportation, also contributes to the release of nitrous oxide, though it is not as significant as agricultural sources. Nitrous oxide is produced during the combustion of fossil fuels, especially when fuel nitrogen is present, and it can be released during both industrial and vehicle emissions. Additionally, the production of certain chemicals, such as adipic acid (used in the production of nylon), also emits N_2O as a by-product.

- Wastewater Treatment

Nitrous oxide is also released during the treatment of wastewater. The processes of sewage treatment and the decomposition of organic material in municipal waste systems can lead to the formation of N_2O. Wastewater treatment plants, especially those utilizing certain treatment technologies such as biological denitrification, can release nitrous oxide into the atmosphere.

- Biomass Burning

Biomass burning, which includes the burning of forests, agricultural residues, and other organic materials, releases nitrous oxide into the atmosphere. The burning process results in the release of nitrogen compounds, which are converted into N_2O as they interact with high temperatures and oxygen.

- Natural Sources

While anthropogenic sources dominate the increase in nitrous oxide emissions, natural sources still contribute to the overall atmospheric concentration. These include emissions from soils, oceans, and wetlands. Soil emissions of nitrous oxide are driven by microbial processes, especially in tropical and subtropical regions. Oceans and wetlands release nitrous oxide as well, although their contribution is smaller than that of agricultural activities.

Thus, Nitrous oxide is a potent greenhouse gas with a global warming potential much greater than that of carbon dioxide, and it plays a significant role in exacerbating climate change. While the primary source of anthropogenic N_2O emissions are agriculture, particularly through the use of nitrogen fertilizers and livestock manure, other sectors such as fossil fuel combustion, wastewater treatment, and biomass burning also contribute to emissions. The long atmospheric lifetime of nitrous oxide and its role in ozone depletion make it a critical target for mitigation.

3. Sustainable Solutions to Mitigate Climate Change

Given the complexity and scale of the problem, addressing climate change requires a multi-faceted approach that targets the principal contributors and offers sustainable solutions across various sectors as demonstrated in Figure 5.

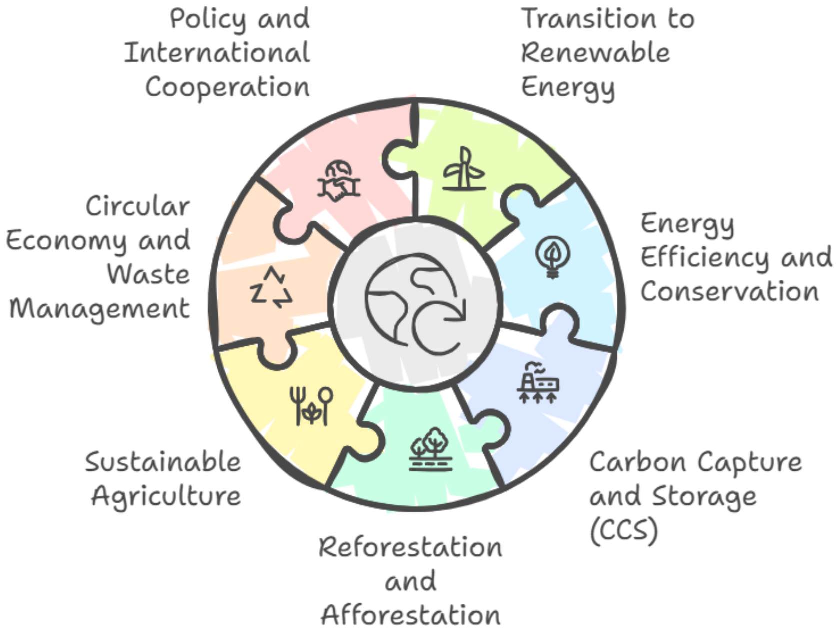

Figure 5. Several sustainable solutions to reduce climate change.

- Transition to Renewable Energy

The transition from fossil fuels to renewable energy sources is one of the most effective strategies for reducing GHG emissions. Renewable energy technologies such as solar, wind, geothermal, and hydropower are abundant, sustainable, and produce little to no direct GHG emissions during operation [44-53]. Investments in energy storage technologies, smart grids, and decentralized energy production will be critical in ensuring a reliable and resilient energy system that can support a low-carbon economy. The shift to renewable energy is not only beneficial for reducing emissions but also for improving energy security, creating green jobs, and reducing dependence on imported fossil fuels.

- Energy Efficiency and Conservation

Improving energy efficiency across all sectors—industry, transportation, residential, and commercial—can significantly reduce energy consumption and associated emissions [54,55]. Technological innovations, such as energy-efficient appliances, LED lighting, electric vehicles, and energy-efficient building materials, play a crucial role in minimizing energy waste [56-59]. Moreover, embracing energy conservation practices, such as turning off unused appliances, improving insulation, and adopting sustainable transportation options (e.g., public transit, cycling, and walking), can further reduce emissions.

- Carbon Capture and Storage (CCS)

Carbon capture and storage (CCS) technologies offer a potential solution for mitigating the impacts of existing emissions. CCS involves capturing CO_2 emissions from power plants and industrial sources and storing them underground or using them for enhanced oil recovery. While the technology is still in the developmental stage, it has the potential to reduce emissions from sectors that are difficult to decarbonize, such as cement, steel, and chemical production [60,61].

- Reforestation and Afforestation

Reforestation (restoring forests that have been degraded or destroyed and afforestation planting new forests in areas that were previously not forested) are critical strategies for carbon sequestration. Forests absorb and store CO_2, and their restoration can help mitigate the impact of deforestation. In addition to carbon sequestration, reforestation and afforestation efforts enhance biodiversity, improve soil health, and prevent soil erosion, offering additional environmental benefits [62,63].

- Sustainable Agriculture

Sustainable farming practices, including crop rotation, agroforestry, no-till farming, and precision agriculture, can reduce emissions from agriculture while enhancing soil health, increasing water efficiency, and improving resilience to climate impacts. Furthermore, shifting to plant-based diets and reducing food waste are key actions in reducing the carbon footprint of the agricultural sector [64,65].

- Circular Economy and Waste Management

The transition to a circular economy, which prioritizes reducing, reusing, and recycling materials, can help mitigate climate change by minimizing waste and reducing the need for resource extraction. Sustainable waste management practices, such as composting organic waste, improving recycling systems, and reducing plastic use, can significantly reduce methane emissions from landfills and minimize overall environmental impact [66,67].

- Policy and International Cooperation

Effective climate change mitigation requires strong policy frameworks and international cooperation. Carbon pricing mechanisms, such as carbon taxes or emissions trading systems, can provide financial incentives for businesses to reduce emissions. International agreements, like the Paris Agreement, provide a framework for countries to commit to emissions reductions and hold each other accountable. Governments must also invest in climate adaptation strategies, such as building resilient infrastructure, improving early warning systems for extreme weather events, and protecting vulnerable communities from the effects of climate change [68,70].

The challenge of climate change is vast and complex, but through concerted global efforts, technological innovation, and comprehensive policy strategies, it is possible to mitigate its impacts. By addressing the principal contributors to climate change, such as greenhouse gas emissions, deforestation, industrial practices, and agriculture, and by implementing sustainable solutions such as renewable energy adoption, energy efficiency, carbon capture, reforestation, and sustainable agriculture.

4. Challenges of Climate Change

Climate change represents one of the most pressing global challenges of the 21st century, with wide-ranging impacts on ecosystems, economies, and human societies. The challenge of climate change is multifaceted, involving complex scientific, social, political, and economic factors. Below, this article explores the major challenges associated with addressing climate change, ranging from the physical impacts of global warming to the barriers to effective mitigation and adaptation strategies as illustrated in Figure 6.

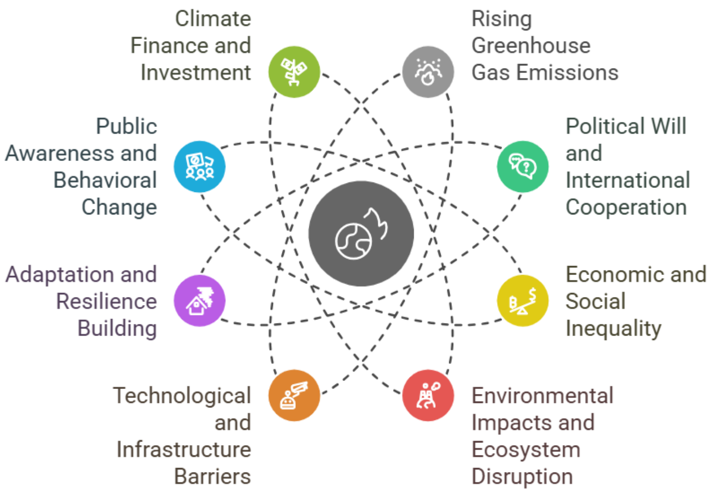

Figure 3. Major challenges of climate change.

A. Rising Greenhouse Gas Emissions

One of the central challenges of climate change is the continuing increase in greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Despite international agreements such as the Paris Agreement, global emissions have continued to rise, driven by factors such as industrialization, energy consumption, and agricultural practices. Fossil fuel combustion for energy production remains the largest source of CO_2 emissions, and the demand for energy continues to grow, particularly in developing economies. The primary challenge is to reduce emissions while balancing economic growth, particularly in developing nations. Transitioning away from fossil fuels and achieving widespread adoption of renewable energy technologies is essential but difficult. Political resistance, vested interests, and the financial costs of the transition present significant barriers to emission reductions.

B. Political Will and International Cooperation

Addressing climate change requires unprecedented levels of global cooperation. Climate change is a transboundary issue, affecting all countries regardless of borders, and international agreements are needed to create a coordinated response. However, political will to tackle climate change is often lacking, especially in countries where economic interests, such as those related to fossil fuel industries, hold significant political power. In addition, the lack of a binding enforcement mechanism in global agreements means that countries may fail to meet their climate targets, undermining collective action. Securing political commitment across diverse nations with varying levels of development, priorities, and capacities for climate action is one of the most challenging aspects of addressing climate change. Furthermore, the uneven distribution of climate impacts requires developed nations to take on a larger share of responsibility for emissions reductions and financial support for developing countries.

C. *Economic and Social Inequality*

The impacts of climate change are felt most severely by vulnerable populations, including those in low-income communities, developing countries, and marginalized groups. These groups often have the least capacity to adapt to climate change and are more exposed to its effects, such as extreme weather events, sea-level rise, and disruptions to food and water security. Additionally, the transition to a low-carbon economy may displace workers in industries such as fossil fuel extraction, leading to job losses and economic hardship. The challenge of climate change is not just one of reducing emissions, but also addressing the social and economic inequities that exist. Ensuring that climate policies are equitable, and that vulnerable communities are supported in both adaptation and transition processes, is crucial to ensuring that climate action does not exacerbate inequality.

D. Environmental Impacts and Ecosystem Disruption

The physical impacts of climate change, such as rising temperatures, extreme weather events, sea-level rise, and changing precipitation patterns, are already being observed. These changes are disrupting ecosystems and biodiversity, which in turn have cascading effects on food security, water availability, and human health. Coastal areas are particularly vulnerable to rising sea levels, while regions dependent on agriculture are facing more frequent droughts, floods, and shifting growing seasons. Protecting biodiversity and ecosystems while adapting to the consequences of climate change is a significant challenge. Efforts to mitigate the impacts of climate change must consider the need to preserve the natural systems that provide essential services, such as carbon sequestration, water filtration, and habitat for wildlife.

E. Technological and Infrastructure Barriers

While there are numerous technological solutions available to reduce greenhouse gas emissions and mitigate climate change, widespread adoption of these technologies is hindered by various barriers, including high costs, infrastructure limitations, and the need for significant investment. Renewable energy technologies, such as solar and wind power, need further advancements in storage capacity and grid integration to become more effective at scale. Additionally, carbon capture and storage (CCS) technologies, which are critical for reducing emissions from hard-to-decarbonize industries, are still in the developmental stage and face significant technical and financial hurdles.

F. Adaptation and Resilience Building

Even with significant efforts to reduce greenhouse gas emissions, the effects of climate change are already being felt. Adaptation to climate change, particularly in vulnerable regions, is therefore a critical challenge. This includes developing infrastructure that is resilient to extreme weather events, improving agricultural practices to cope with changing climate conditions, and strengthening early warning systems for natural disasters. Moreover, addressing the mental health and social impacts of climate-related disasters is also an important aspect of building resilience. The challenge of adaptation lies in ensuring that vulnerable populations have access to the necessary resources, knowledge, and technologies to adapt to climate change. At the same time, efforts must be made to ensure that adaptation strategies do not increase inequality or contribute to environmental degradation.

G. Public Awareness and Behavioral Change

Climate change requires significant changes in individual behavior and societal practices, particularly in consumption patterns, waste management, and transportation. Raising awareness about the urgency of the climate crisis and encouraging individuals to adopt sustainable behaviors is a substantial challenge. Overcoming cultural, economic, and social barriers to behavior change is difficult, particularly in high-income countries where lifestyles are heavily reliant on fossil fuels and resource-intensive consumption. Engaging the public and fostering behavioral change, particularly in high-emission sectors such as transportation and food production, requires widespread education, incentives, and changes in social norms. The challenge is to align individual and societal actions with global climate goals.

H. Climate Finance and Investment

Addressing climate change will require substantial financial investments in both mitigation and adaptation efforts. Developing countries, in particular, face significant challenges in financing climate action, given their limited resources. Climate finance mechanisms, such as the Green Climate Fund, aim to provide support, but the scale of the investment needed is far greater than current commitments. Additionally, private sector investment in clean technologies and infrastructure is crucial, but it is often constrained by economic uncertainty and the perceived risks of investing in climate-related initiatives. Securing adequate financing for climate action remains one of the most significant obstacles.

The challenges of climate change are vast and interconnected, involving complex scientific, political, social, and economic dimensions. While the effects of climate change are already being felt, and the window of opportunity to take decisive action is narrowing, addressing these challenges presents both risks and opportunities. By focusing on reducing emissions, improving resilience, protecting vulnerable populations, and driving technological innovation, it is possible to mitigate the impacts of climate change and create a more sustainable and equitable future. The challenge, however, lies in the global coordination, political will, and resources required to make meaningful progress on these critical issues.

5. Conclusions

Climate change is an intricate, global phenomenon that poses significant environmental, social, and economic risks. Its causes and effects are deeply interconnected with human activities, and understanding both the key contributors and sustainable solutions is essential to effectively mitigate its impacts. The primary contributors to climate change—greenhouse gas emissions from energy production, industrial activities, deforestation, and agriculture—are well-documented. As noted, carbon dioxide (CO_2) and methane (CH_4) are the leading greenhouse gases responsible for the enhanced greenhouse effect, trapping heat in the atmosphere and causing the planet's temperature to rise. The intensification of this effect is driving a cascade of changes in the Earth's climate, including rising sea levels, extreme weather events, disruptions to ecosystems, and widespread human displacement. While natural phenomena, such as solar radiation variations and volcanic eruptions, have historically influenced the Earth's climate, the current rate of change far exceeds the natural variability and is largely attributed to human actions. The burning of fossil fuels remains the dominant source of CO_2 emissions, which are primarily linked to energy production, transportation, and industrial processes. These activities have created a feedback loop, where rising temperatures from increased CO_2 concentrations exacerbate environmental degradation and human vulnerabilities. The transition away from fossil fuels to renewable energy sources, such as solar, wind, and hydropower, offers a viable solution to drastically reduce CO_2 emissions. However, this shift presents several challenges, including infrastructure limitations, the need for massive investments in renewable energy, and the adaptation of energy grids to accommodate decentralized and intermittent energy sources.

Methane, despite being present in lower concentrations than CO_2, is another potent greenhouse gas, with a global warming potential many times higher than CO_2 over short periods. Methane is primarily released from agriculture (especially livestock production), landfills, and fossil fuel extraction. Mitigating methane emissions requires integrated strategies that include adopting sustainable agricultural practices, improving waste management systems, and reducing methane leaks from oil and gas infrastructure. The implementation of these solutions is often met with resistance due to their perceived economic and logistical challenges, but they offer high rewards in terms of climate mitigation.

Deforestation is a significant contributor to climate change, as forests act as carbon sinks, absorbing CO_2 from the atmosphere. When forests are cleared for agriculture or urbanization, the carbon stored in trees is released back into the atmosphere, exacerbating climate change. Reforestation and afforestation efforts are essential in mitigating these impacts, as forests help restore biodiversity, improve air and water quality, and provide livelihoods. The challenge lies in balancing development needs with conservation efforts and ensuring that sustainable forest management practices are prioritized.

Beyond mitigating emissions, adapting to the impacts of climate change is equally critical. The shifting climate conditions—ranging from rising sea levels to changing precipitation patterns—demand that communities and industries adapt to new realities. Sustainable solutions for climate adaptation include developing climate-resilient infrastructure, improving agricultural practices to cope with altered growing seasons, and protecting vulnerable populations through robust health systems and disaster response plans. Moreover, the role of policy frameworks in addressing climate change cannot be overstated. Governments play a pivotal role in setting climate goals, regulating emissions, and facilitating the transition to a low-carbon economy. International agreements, such as the Paris Agreement, provide a platform for countries to commit to emissions reductions and collaborate on climate solutions. However, challenges remain in ensuring compliance and enforcing commitments, as political and economic interests often undermine climate action. The private sector, alongside governments, has an essential role to play in driving innovation, investing in green technologies, and reducing emissions.

Moreover, technological innovation offers another avenue for climate change mitigation and adaptation. Emerging technologies, such as carbon capture and storage (CCS), direct air capture (DAC), and advanced renewable energy storage, hold significant potential in reducing atmospheric CO_2 levels and providing clean energy solutions. However, these technologies are still in the early stages of development and face considerable cost and scalability challenges. Continued investment in research and development is crucial to overcoming these barriers.

In conclusion, addressing climate change requires a holistic, integrated approach that combines mitigation, adaptation, innovation, and policy reform. Sustainable solutions, while feasible, necessitate collaboration across sectors and countries, alongside significant investments in clean technologies, renewable energy, and conservation. The challenges are considerable, but the opportunities for creating a sustainable future—through cleaner energy, sustainable agriculture, climate-resilient infrastructure, and stronger governance—are immense. The pathway forward demands urgent action, long-term commitment, and a shared vision for protecting the planet for future generations.

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ORCID
Khalid Mohamed Aomemen https://orcid.org/0009-0005-5963-4272
Mona Othman Aldbbah https://orcid.org/0009-0008-2581-0188

References

[1] K. Abbass, M. Z. Qasim, H. Song, M. Murshed, H. Mahmood, and I. Younis, "A review of the global climate change impacts, adaptation, and sustainable mitigation measures," *Environ. Sci. Pollut. Res. Int.*, vol. 29, no. 28, pp. 42539–42559, 2022.

[2] P. De Frenne *et al.*, "Forest microclimates and climate change: Importance, drivers and future research agenda," *Glob. Chang. Biol.*, vol. 27, no. 11, pp. 2279–2297, 2021.

[3] W. U. H. Shah, Y. Lu, J. Liu, A. Rehman, and R. Yasmeen, "The impact of climate change and production technology heterogeneity on China's agricultural total factor productivity and production efficiency," *Sci. Total Environ.*, vol. 907, no. 168027, p. 168027, 2024.

[4] L. Kemp *et al.*, "Climate Endgame: Exploring catastrophic climate change scenarios," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 119, no. 34, p. e2108146119, 2022.

[5] L. Berrang-Ford *et al.*, "A systematic global stocktake of evidence on human adaptation to climate change," *Nat. Clim. Chang.*, vol. 11, no. 11, pp. 989–1000, 2021.

[6] E. Sesana, A. S. Gagnon, C. Ciantelli, J. Cassar, and J. J. Hughes, "Climate change impacts on cultural heritage: A literature review," *Wiley Interdiscip. Rev. Clim. Change*, vol. 12, no. 4, 2021.

[7] S. Skendžić, M. Zovko, I. P. Živković, V. Lešić, and D. Lemić, "The impact of climate change on agricultural insect pests," *Insects*, vol. 12, no. 5, p. 440, 2021.

[8] M. W. Jones *et al.*, "Global and regional trends and drivers of fire under climate change," *Rev. Geophys.*, vol. 60, no. 3, 2022.

[9] Q. Hassan *et al.*, "Saudi Arabia energy transition: Assessing the future of green hydrogen in climate change mitigation," *Int. J. Hydrogen Energy*, vol. 55, pp. 124–140, 2024.

[10] H. Olya, N. Kim, and M. J. Kim, "Climate change and pro-sustainable behaviors: application of nudge theory," *J. Sustain. Tour.*, vol. 32, no. 6, pp. 1077–1095, 2024.

[11] H. Sato, J. Mizoi, K. Shinozaki, and K. Yamaguchi-Shinozaki, "Complex plant responses to drought and heat stress under climate change," *Plant J.*, vol. 117, no. 6, pp. 1873–1892, 2024.

[12] J. M. Slingo and M. E. Slingo, "The science of climate change and the effect of anaesthetic gas emissions," *Anaesthesia*, vol. 79, no. 3, pp. 252–260, 2024.

[13] Y. Feng *et al.*, "Shift in algal blooms from micro- to macroalgae around China with increasing eutrophication and climate change," *Glob. Chang. Biol.*, vol. 30, no. 1, p. e17018, 2024.

[14] Y. F. Nassar *et al.*, "Carbon footprint and energy life cycle assessment of wind energy industry in Libya," *Energy Convers. Manag.*, vol. 300, no. 117846, p. 117846, 2024.

[15] M. Khaleel, Z. Yusupov, A. Ahmed, A. Alsharif, Y. Nassar, and H. El-Khozondar, "Towards sustainable renewable energy," *Appl. Sol. Energy*, vol. 59, no. 4, pp. 557–567, 2023.

[16] S. Islam and K. M. A., "Climate change information for regional impact and for risk assessment," in *Climate Change 2021 – The Physical Science Basis*, Cambridge, England: Cambridge University Press, 2023, pp. 1767–1926.

[17] M. Khaleel *et al.*, "Evolution of emissions: The role of clean energy in sustainable development," *Chall. Sustain.*, vol. 12, no. 2, pp. 122–135, 2024.

[18] S. Bolan *et al.*, "Impacts of climate change on the fate of contaminants through extreme weather events," *Sci. Total Environ.*, vol. 909, no. 168388, p. 168388, 2024.

[19] D. Suprayitno, S. Iskandar, K. Dahurandi, T. Hendarto, and F. J. Rumambi, "Public Policy in the Era of Climate Change: Adapting Strategies for Sustainable Futures," *Migr. Lett*, vol. 21, pp. 945–958, 2024.

[20] A. Felton, S. Belyazid, J. Eggers, E.-M. Nordström, and K. Öhman, "Climate change adaptation and mitigation strategies for production forests: Trade-offs, synergies, and uncertainties in

biodiversity and ecosystem services delivery in Northern Europe," *Ambio*, vol. 53, no. 1, pp. 1–16, 2024.

[21] J. Luterbacher *et al.*, "The importance and scientific value of long weather and climate records; Examples of historical marine data efforts across the globe," *Climate*, vol. 12, no. 3, p. 39, 2024.

[22] A. May and M. Crok, "Carbon dioxide and a warming climate are not problems," *Am. J. Econ. Sociol.*, 2024.

[23] A. M. Szyniszewska *et al.*, "Beyond the present: How climate change is relevant to pest risk analysis," *Bull. OEPP*, vol. 54, no. S1, pp. 20–37, 2024.

[24] J. P. Gwynn, V. Hatje, N. Casacuberta, M. Sarin, and I. Osvath, "The effect of climate change on sources of radionuclides to the marine environment," *Commun. Earth Environ.*, vol. 5, no. 1, pp. 1–20, 2024.

[25] R. Mackey, "Rhodes Fairbridge and the idea that the solar system regulates the Earth's climate," *J. Coast. Res.*, vol. 50, no. sp1, 2007.

[26] M. Santosh, D. I. Groves, and C.-X. Yang, "Habitable planet to sustainable civilization: Global climate change with related clean energy transition reliant on declining critical metal resources," *Gondwana Res.*, vol. 130, pp. 220–233, 2024.

[27] R. Zahedi, E. Sadeghitabar, M. Khazaee, R. Faryadras, and A. Ahmadi, "Potentiometry of wind, solar and geothermal energy resources and their future perspectives in Iran," *Environ. Dev. Sustain.*, 2024.

[28] R. Reda, M. Stumpo, L. Giovannelli, T. Alberti, and G. Consolini, "Disentangling the solar activity–solar wind predictive causality at Space Climate scales," *Rend. Lincei Sci. Fis. Nat.*, vol. 35, no. 1, pp. 49–61, 2024.

[29] M. Krichen, M. S. Abdalzaher, M. Elwekeil, and M. M. Fouda, "Managing natural disasters: An analysis of technological advancements, opportunities, and challenges," *Internet of Things and Cyber-Physical Systems*, vol. 4, pp. 99–109, 2024.

[30] J. A. Akinyoola, A. Oluleye, and I. E. Gbode, "A review of atmospheric aerosol impacts on regional extreme weather and climate events," *Aerosol Sci. Eng.*, vol. 8, no. 3, pp. 249–274, 2024.

[31] F. Arthur *et al.*, "The impact of volcanism on Scandinavian climate and human societies during the Holocene: Insights into the Fimbulwinter eruptions (536/540 AD)," *Holocene*, vol. 34, no. 5, pp. 619–633, 2024.

[32] J. Liang *et al.*, "The control of milankovitch cycles on climate and sea-level changes: A time series and nonlinear analysis of the asmari formation in the dezful embayment, Iran," *Social Science Research Network*, 2024.

[33] T. Yang *et al.*, "Milankovitch cycles recorded by the Late Permian volcanic ash layers in southwestern China," *Mar. Pet. Geol.*, vol. 161, no. 106671, p. 106671, 2024.

[34] X. Li, B. Peachey, and N. Maeda, "Global warming and anthropogenic emissions of water vapor," *Langmuir*, vol. 40, no. 14, pp. 7701–7709, 2024.

[35] M. A. Franco *et al.*, "Aerosol optical depth and water vapor variability assessed through autocorrelation analysis," *Meteorol. Atmos. Phys.*, vol. 136, no. 2, 2024.

[36] Z. Wang, Y. Lei, H. Che, B. Wu, and X. Zhang, "Aerosol forcing regulating recent decadal change of summer water vapor budget over the Tibetan Plateau," *Nat. Commun.*, vol. 15, no. 1, p. 2233, 2024.

[37] Y. Lang *et al.*, "Mechanisms and quantification: How anthropogenic aerosols weaken the East Asian summer monsoon," *Npj Clim. Atmos. Sci.*, vol. 8, no. 1, pp. 1–13, 2025.

[38] P. Elavarasi, K. Doruk, K. S. C. Bose, P. Ramamoorthy, Manojkumar, and N. Venu, "Modern Agro techniques for carbon sequestration to mitigate climate change," *International Journal of Environment and Climate Change*, vol. 14, no. 3, pp. 755–759, 2024.

[39] I. A. M. Shalihah, "Analysis of the perceptions of non-forestry and environmental students in Jabodetabek on the role of Moringa oleifera in climate change mitigation," *proirofonic*, vol. 1, no. 1, pp. 342–347, 2024.

[40] A. B. Omotoso and A. O. Omotayo, "The interplay between agriculture, greenhouse gases, and climate change in Sub-Saharan Africa," *Reg. Environ. Change*, vol. 24, no. 1, 2024.

[41] R. Kumar *et al.*, "Breakthrough innovations in carbon dioxide mineralization for a sustainable future," *Rev. Environ. Sci. Biotechnol.*, vol. 23, no. 3, pp. 739–799, 2024.

[42] L. Zhang *et al.*, "Inventory of methane and nitrous oxide emissions from freshwater aquaculture in China," *Commun. Earth Environ.*, vol. 5, no. 1, pp. 1–11, 2024.

[43] N. Chandra *et al.*, "Methane emissions decreased in fossil fuel exploitation and sustainably increased in microbial source sectors during 1990–2020," *Commun. Earth Environ.*, vol. 5, no. 1, pp. 1–15, 2024.

[44] Y. F. Nassar *et al.*, "Assessing the viability of solar and wind energy technologies in semi-arid and arid regions: A case study of Libya's climatic conditions," *Appl. Sol. Energy*, vol. 60, no. 1, pp. 149–170, 2024.

[45] Y. Nassar *et al.*, "Solar and wind atlas for Libya," *Int. J. Electr. Eng. and Sustain.*, pp. 27–43, 2023.

[46] A. M. Kelly and R. D. Ngo Nguéda Radler, "Does energy consumption matter for climate change in Africa? New insights from panel data analysis," *Innovation and Green Development*, vol. 3, no. 3, p. 100132, 2024.

[47] T. A. Kurniawan *et al.*, "Unlocking synergies between waste management and climate change mitigation to accelerate decarbonization through circular-economy digitalization in Indonesia," *Sustain. Prod. Consum.*, vol. 46, pp. 522–542, 2024.

[48] C. U. Akpuokwe, A. O. Adeniyi, S. S. Bakare, and N. E. Eneh, "Legislative responses to climate change: A global review of policies and their effectiveness," *Int. j. appl. res. soc. sci.*, vol. 6, no. 3, pp. 225–239, 2024.

[49] M. Khaleel *et al.*, "Emerging issues and challenges in integrating of solar and wind," *Int. J. Electr. Eng. and Sustain.*, pp. 1–11, 2024.

[50] M. Khaleel *et al.*, "An optimization approaches and control strategies of hydrogen fuel cell systems in EDG-integration based on DVR technology," *J. Eur. Syst. Autom.*, vol. 57, no. 2, pp. 551–565, 2024.

[51] "View of performance evaluation of MG systems interfaced with wind turbines employing DFIG technology," *Ijees.org*. [Online]. Available: https://ijees.org/index.php/ijees/article/view/82/44. [Accessed: 17-Jan-2025].

[52] M. Khaleel, Z. Yusupov, M. Guneser, H. El-Khozondar, A. Ahmed, and A. A. Alsharif, "Towards hydrogen sector investments for achieving sustainable electricity generation," *jsesd*, vol. 13, no. 1, pp. 71–96, 2024.

[53] I. Imbayah, M. Hasan, H. El-Khozondare, M. Khaleel, A. Alsharif, and A. Ahmed, "Review paper on green hydrogen production, storage, and utilization techniques in Libya," *jsesd*, vol. 13, no. 1, pp. 1–21, 2024.

[54] W. Chen, M. Alharthi, J. Zhang, and I. Khan, "The need for energy efficiency and economic prosperity in a sustainable environment," *Gondwana Res.*, vol. 127, pp. 22–35, 2024.

[55] X. Wang, Y. Lu, C. Chen, X. Yi, and H. Cui, "Total-factor energy efficiency of ten major global energy-consuming countries," *J. Environ. Sci. (China)*, vol. 137, pp. 41–52, 2023.

[56] A. Alsharif *et al.*, "Impact of electric Vehicle on residential power distribution considering energy management strategy and stochastic Monte Carlo algorithm," *Energies*, vol. 16, no. 3, p. 1358, 2023.

[57] A. Alsharif, A. A. Ahmed, M. M. Khaleel, A. S. Daw Alarga, O. S. M. Jomah, and I. Imbayah, "Comprehensive state-of-the-art of vehicle-to-grid technology," in *2023 IEEE 3rd International*

Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA), 2023.
[58] M. Khaleel *et al.*, “Electric vehicles in China, Europe, and the United States: Current trend and market comparison,” *Int. J. Electr. Eng. and Sustain.*, pp. 1–20, 2024.
[59] M. M. Khaleel, A. A. Ahmed, and A. Alsharif, “Energy Management System Strategies in Microgrids: A Review,” *The North African Journal of Scientific Publishing (NAJSP)*, vol. 1, no. 1, pp. 1–8, 2023.
[60] T. W. Kim, H. C. Yoon, and J. Y. Lee, “Review on carbon capture and storage (CCS) from source to sink; part 1: Essential aspects for CO2 pipeline transportation,” *Int. J. Greenhouse Gas Control*, vol. 137, no. 104208, p. 104208, 2024.
[61] R. Sen and S. Mukherjee, “Recent advances in microalgal carbon capture and utilization (bio-CCU) process vis-à-vis conventional carbon capture and storage (CCS) technologies,” *Crit. Rev. Environ. Sci. Technol.*, pp. 1–26, 2024.
[62] С. Т. И. Сорокина Т.и., “Economic principles of reforestation and afforestation in the tyumen region,” *Экономика и предпринимательство*, no. 4(165), pp. 1266–1269, 2024.
[63] R. M. Orquera *et al.*, “Design of seed transfer zones and assessment of germplasm collections of Neltuma alba for reforestation and afforestation purposes in Argentina,” *New Forests*, vol. 56, no. 1, 2025.
[64] Sustainable Agriculture Network (SAN), M. McCord, O. Bach, and Sustainable Agriculture Network (SAN), “mproving sustainable agricultural principles and practices: the Sustainable Agriculture Network (SAN),” in *Burleigh Dodds Series in Agricultural Science*, Burleigh Dodds Science Publishing Limited, 2025, pp. 243–260.
[65] L. E. Fackrell, S. Humphrey, R. Loureiro, A. G. Palmer, and J. Long-Fox, “Overview and recommendations for research on plants and microbes in regolith-based agriculture,” *npj Sustain. Agric.*, vol. 2, no. 1, 2024.
[66] E. Ebrahimzadehsarvestani, E. M. Sarvestani, H. Safarzadeh, M. Enayati, and F. Di Maria, “Implementing circular economy in healthcare waste: Technological innovations and process management,” *J. Solid Waste Technol. Manag.*, vol. 51, no. 1, pp. 14–24, 2025.
[67] D. Zhao, Y. Chen, H. Yuan, and D. Chen, “Life cycle optimization oriented to sustainable waste management and circular economy: A review,” *Waste Manag.*, vol. 191, pp. 89–106, 2025.
[68] L. Paroussos, A. Mandel, K. Fragkiadakis, P. Fragkos, J. Hinkel, and Z. Vrontisi, “Climate clubs and the macro-economic benefits of international cooperation on climate policy,” *Nat. Clim. Chang.*, vol. 9, no. 7, pp. 542–546, 2019.
[69] C. Oberlack and K. Eisenack, “Alleviating barriers to urban climate change adaptation through international cooperation,” *Glob. Environ. Change*, vol. 24, pp. 349–362, 2014.
[70] P. J. J. Welfens, “Conclusion: International cooperation and the climate protection concept,” in *Global Climate Change Policy*, Cham: Springer International Publishing, 2022, pp. 371–422.