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Review Article

Impact of Climate Change on Environmental Chemistry: A Review

Ma'aruf Abdulmumin Muhammad[1*], Sadiq Sani[2], Mustapha Sulaiman[3], Abubakar Musa Shuaibu[4], Abdussalam Umar Kura[5], Salim Rabiu[6]

[1,3 &4] Department of Chemistry, Mewar University, Gangrar, NH 48, Rajasthan 312901, India.

[2]Department of Soil Science, Mewar University, Gangrar, NH 48, Rajasthan 312901, India.

[5]Department of Environmental Science, Mewar University, Gangrar, NH 48, Rajasthan 312901, India.

[6]Department of Physiotheraphy, Mewar University, Gangrar, NH 48, Rajasthan 312901, India.

***Corresponding:**

maarufabdulmumin@gmail.com

Abstract:

Environmental chemistry changed greatly with climate change, thereby influencing chemical processes in the atmosphere, hydrosphere and lithosphere. This review assessed this by examining changes in atmospheric chemistry, water chemistry, soil chemistry and biogeochemical cycles. Rising global temperatures and increased greenhouse gas emissions have changed atmospheric chemical reactions leading to alterations in air quality and the formation of secondary pollutants. Water temperature shifts and changes in water chemistry caused by climate change impacted marine biogeochemistry through ocean acidification. Nutrient cycling, soil organic matter and metal mobility were also altered as a result of soil chemistry effects. Additionally, the review focused on mitigation and adaptation strategies that involved the development of green technologies and sustainable practices for managing climate change impacts. In this analysis, environmental chemistry was emphasized as having a significant role in understanding climate change challenges through synthesis of present research works. The end also recommended further studies to be conducted while suggesting interdisciplinary approaches along with long-term monitoring needed to improve our knowledge about climate change impacts and enable policy makers take sound decisions.

Keywords: Environmental Chemistry**,** Marine Biogeochemistry**,** Soil Carbon Sequestration**,** Green Chemistry Innovations, Eco-toxicological Effect.

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INTRODUCTION

Climate change refers to significant, long-term alterations in temperature, precipitation, wind patterns, and other aspects of the Earth's climate system. These changes are largely driven by human activities, such as the burning of fossil fuels, deforestation, and industrial processes, which elevate the levels of greenhouse gases (GHGs) in the atmosphere (IPCC, 2021). According to the Intergovernmental Panel on Climate Change (IPCC), global temperatures have increased by approximately 1.1 °C above pre-industrial levels, and this trend is expected to continue if GHG emissions are not reduced (IPCC, 2021). The consequences of climate change are evident in more frequent and severe weather events, melting polar ice, rising sea levels, and shifts in ecosystems and biodiversity (NASA, 2022). Climate change impacts not only atmospheric and oceanic conditions but also various chemical processes in the environment. Higher temperatures can accelerate chemical reactions, while altered precipitation patterns can change the distribution and dilution of pollutants (IPCC, 2021). Additionally, increased carbon dioxide (CO2) levels result in ocean acidification, significantly affecting marine chemistry and ecosystems (IPCC, 2022). Considerate these chemical processes is crucial for predicting future climate change impacts and developing effective mitigation and adaptation strategies (Smith et al., 2014).

Environmental chemistry, a branch of chemistry, studies the chemical processes occurring in the environment and their impacts on human health and ecosystems (Smith et al., 2014). This field involves examining the sources, reactions, transport, effects, and fates of chemical species in air, water, and soil environments. Environmental chemistry is critical for breaking down how pollutants behave and transform in the environment and how natural processes are affected by human activities (Manahan et al., 2017). In the context of climate change, environmental chemistry is especially important. It helps identify and quantify GHG and pollutant emissions, essential for developing effective policies and regulations (Schwarzenbach et al., 2003). It also provides insights into the chemical mechanisms underlying climate-related changes, such as ocean acidification and secondary air pollutant formation (UNEP, 2021a). Also, environmental chemistry contributes to developing new technologies and materials to reduce emissions and mitigate climate change impacts (Seinfeld & Pandis, 2016a). Advancing our knowledge of these processes supports the creation of sustainable solutions to address climate change (Anastas & Warner, 1998).

This review aims to explore the impacts of climate change on environmental chemistry, focusing on understanding the mechanisms through which climate change influences chemical processes in the atmosphere, hydrosphere, and lithosphere. It synthesizes current knowledge on how rising temperatures, changing precipitation patterns, and increased CO2 levels affect the behavior and fate of pollutants and natural chemical cycles (Seinfeld & Pandis, 2016a). As well, it highlights the implications of these changes for ecosystem health and human well-being (Anastas & Warner, 1998). The scope of this review includes several key areas: atmospheric chemistry, water chemistry, soil chemistry, and the biogeochemical cycles of critical elements such as carbon, nitrogen, and sulfur. It also covers the eco-toxicological impacts of climate-induced chemical changes and discusses potential mitigation and adaptation strategies from an environmental chemistry perspective. By providing a comprehensive overview of these topics, this review aims to contribute to the broader understanding of climate change impacts and inform future research and policy-making efforts (EPA, 2021).

MECHANISMS OF CLIMATE CHANGE

Global human communities and natural ecosystems are being impacted by one of the most urgent issues of our time: climate change. Numerous atmospheric, marine, and terrestrial processes interact in intricate ways as part of the many mechanisms causing climate change

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Figure 1. This section examines the main mechanisms that drive climate change, with an emphasis on greenhouse gas emissions and their origins, global warming and the resulting temperature increases, changes in atmospheric composition, and the ensuing sea level rise and ocean acidification. We also seek to offer a thorough understanding of the factors causing climate change and its extensive effects on the environment and people by examining these interrelated processes.

Greenhouse Gas Emissions and Global Warming

Greenhouse gases (GHGs) like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) trap heat in the Earth's atmosphere, leading to the greenhouse effect, which is the main driver of climate change. CO_2, the most significant GHG, is primarily released through the burning of fossil fuels for energy, deforestation, and industrial processes (MEA, 2005). Methane, a potent GHG, is emitted from agricultural activities, landfills, and the oil and gas industry (EEA, 2021). Nitrous oxide emissions stem from agricultural soil management, fossil fuel combustion, and industrial activities (Seinfeld & Pandis, 2016b). These gases amplify the natural greenhouse effect, causing global warming and climate change. The sources of these GHGs are diverse and widespread. Energy production is the largest source of CO_2 emissions, accounting for approximately 75% of total emissions (UNEP, 2021b). Agricultural practices significantly contribute to methane and nitrous oxide emissions through enteric fermentation in livestock, rice paddies, and the use of synthetic fertilizers (Battin et al., 2008). Deforestation also plays a crucial role, as trees absorb CO_2 from the atmosphere, and their removal releases this stored carbon back into the environment (Belkin et al., 2008). Addressing these sources is essential for mitigating the impacts of climate change and achieving global emission reduction targets (Beman et al, 2005).

Global warming is the long-term rise in Earth's average surface temperature due to the buildup of greenhouse gases (GHGs) in the atmosphere. Since the late 19th century, Earth's average surface temperature has increased by about 1.1 °C, with notable acceleration in recent decades. This temperature rise is primarily attributed to human activities such as burning fossil fuels, industrial processes, and land-use changes. The resulting warming has extensive impacts, including more frequent and intense heatwaves, shifting weather patterns, and changes in precipitation. The consequences of global warming extend beyond temperature increases. Higher global temperatures contribute to the melting of polar ice and glaciers, leading to rising sea levels and the displacement of coastal communities (Doney et al., 2012). Global warming also affects the frequency and severity of extreme weather events like hurricanes, droughts, and floods, increasing risks to ecosystems, infrastructure, and human health (Doney et al., 2009).

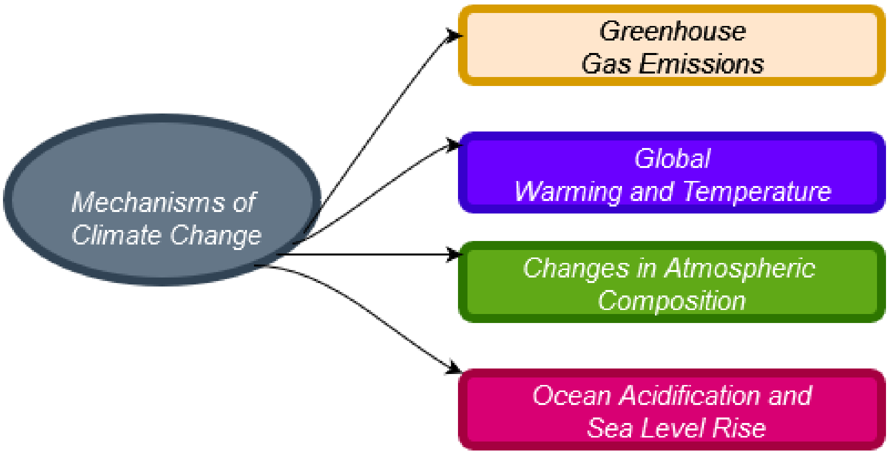

Figure 1. Mechanisms of Climate Change

Changes in Atmospheric and Ocean Composition

Climate change causes changes in atmospheric composition, which subsequently impacts the Earth’s climate system (Döll et al., 2014). The rise in greenhouse gases (GHGs) such as CO_2, CH_4, and N_2O intensifies the greenhouse effect by trapping more heat in the atmosphere, contributing to global warming. Additionally, human activities emit other pollutants like sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which can form secondary pollutants such as particulate matter and ozone (O_3) (Fabry et al., 2008). These alterations in atmospheric composition have complex effects on both short-term weather patterns and long-term climate trends. Changes in atmospheric composition also impact the stratospheric ozone layer, which protects the Earth from harmful ultraviolet (UV) radiation. The emission of ozone-depleting substances, such as chlorofluorocarbons (CFCs), has caused the thinning of the ozone layer, leading to increased UV radiation reaching the Earth's surface (Frost et al., 2011). This rise in UV radiation can negatively affect human health, ecosystems, and climate processes, underscoring the necessity for ongoing efforts to reduce both GHG emissions and ozone depletion. Ocean acidification results from increased atmospheric CO_2 levels, where CO_2 dissolves in seawater to form carbonic acid, lowering the ocean's pH. Since the Industrial Revolution, the ocean's pH has decreased by about 0.1 units, translating to a 30% increase in acidity. This acidification affects marine organisms, especially those with calcium carbonate shells or skeletons, such as corals, mollusks, and some plankton species, disrupting marine ecosystems and food webs (Galloway et al., 2004). Sea level rise is another major impact of climate change, driven primarily by thermal expansion of seawater and the melting of glaciers and polar ice. As global temperatures increase, seawater expands, and melting ice from Greenland and Antarctica adds more water to the oceans (Gruber et al., 2008). This rise in sea levels poses significant risks to coastal communities, including increased flooding, erosion, and saltwater intrusion into freshwater resources (Hall et al., 2014).

ATMOSPHERIC CHEMISTRY

Understanding the Earth's ecosystem and climate requires an understanding of atmospheric chemistry Figure 2. This review part explores important facets of atmospheric chemistry, starting with changes in atmospheric chemical reactions caused by man-made and natural sources. It looks at how these modifications affect the dynamics of pollutants and air quality, emphasizing how changes in chemical processes impact the concentration and dispersion of pollutants. The crucial problem of ozone layer depletion and its effects on increasing ultraviolet (UV) radiation reaching the Earth's surface are also covered in this section. It also looks at how secondary pollutants develop and behave, illuminating the intricate relationships between them and their effects on atmospheric chemistry and environmental health (Guldberg & Bruno, 2010).

Alterations in Atmospheric Chemical Reactions

Climate change significantly impacts atmospheric chemical reactions, primarily due to the increased concentrations of greenhouse gases (GHGs) and pollutants (Kroeker et al., 2013). Elevated CO_2 levels enhance the greenhouse effect, which not only warms the planet but also affects the rates and pathways of chemical reactions in the atmosphere. Higher temperatures accelerate photochemical reactions, leading to increased production of ground-level ozone and other secondary pollutants (Miller et al., 2015). In addition, the rise in GHGs alters the balance of key atmospheric components such as water vapor, a critical driver of the greenhouse effect that influences cloud formation and precipitation patterns. Changes in atmospheric composition also affect reactions between primary pollutants and atmospheric oxidants. For instance, higher levels of NO_x and VOCs, combined with increased UV radiation, result in more intense and frequent formation of photochemical smog. These alterations can have cascading effects on air

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quality and atmospheric chemistry, potentially worsening urban air pollution and impacting the long-term climate system (O'Donnell et al., 2011).

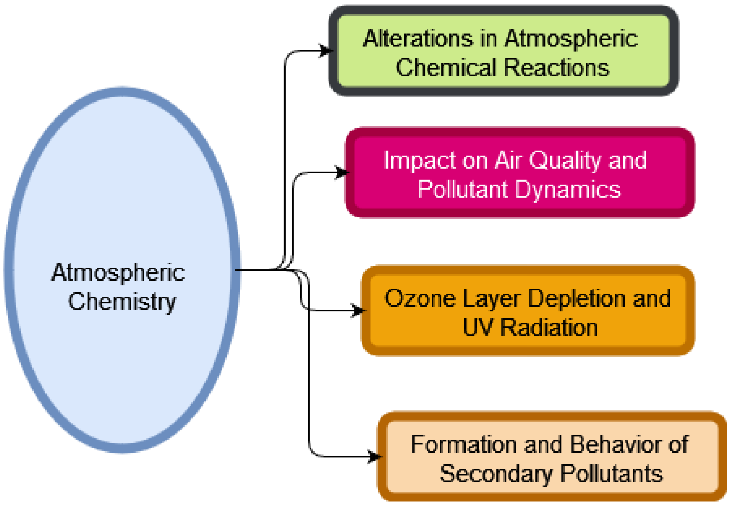

Figure 2. Atmospheric Chemistry

Impact on Air Quality, Pollutant Dynamics, and Ozone Layer Depletion

Climate change profoundly impacts air quality and the dynamics of atmospheric pollutants (IPCC, 2022). Rising temperatures and shifting weather patterns affect the dispersion, transformation, and removal of pollutants in the atmosphere. Higher temperatures can enhance the formation of ground-level ozone, a harmful pollutant that contributes to respiratory issues and other health problems (Orr et l., 2005). Changes in precipitation patterns influence the wet deposition of pollutants, altering their atmospheric lifetimes and distribution. Increased rainfall can lead to higher pollutant washout, while reduced rainfall can result in the accumulation of pollutants and poor air quality. Climate change also affects the emission sources of pollutants. Warmer temperatures can increase the frequency of wildfires, which release large amounts of particulate matter and gases into the atmosphere (Orr et al., 2005). Moreover, the melting of ice and snow can release trapped pollutants, further impacting air quality. These changes in pollutant dynamics underscore the interconnectedness of climate change and air quality, highlighting the need for integrated approaches to address both climate change and its effects on atmospheric pollution (Pachauri et al., 2014).

Ozone layer depletion, caused by human-made chemicals like chlorofluorocarbons (CFCs) and halons, results in increased UV radiation reaching the Earth's surface (Pace et al., 2010). The ozone layer, located in the stratosphere, is crucial for absorbing and filtering out harmful ultraviolet (UV) radiation from the sun. The breakdown of ozone molecules by CFCs and other ozone-depleting substances (ODS) leads to a thinning of this protective layer, allowing higher levels of UV radiation to reach the Earth's surface. This increase in UV radiation can have severe consequences for human health, including higher rates of skin cancer and cataracts, as well as impacts on ecosystems and wildlife (Paerl et al., 2011). The depletion of the ozone layer also affects atmospheric chemistry and climate processes. Enhanced UV radiation can influence the photochemical formation of secondary pollutants and alter the chemical balance of the stratosphere and troposphere. Increased UV radiation can accelerate the breakdown of atmospheric methane, which has implications for both stratospheric ozone and global warming. Addressing ozone depletion requires continued international cooperation and adherence to agreements like the Montreal Protocol, which aims to phase out the production and use of ODS (Seitzinger et al., 2006).

Formation and Behavior of Secondary Pollutants

Secondary pollutants are not directly emitted but form in the atmosphere through chemical reactions involving primary pollutants and atmospheric constituents (Smith et al., 2016). Ground-level ozone, a significant secondary pollutant, arises from the reaction of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight. Climate change affects the formation and behavior of these pollutants by altering the concentrations of their precursors and the atmospheric conditions required for their creation. Increased temperatures and changes in sunlight intensity can amplify the photochemical reactions that generate secondary pollutants, resulting in higher levels of smog and other air quality challenges (Vörösmarty et al., 2000). The behavior of secondary pollutants is also influenced by shifts in atmospheric circulation patterns and climate conditions. Changes in weather patterns can impact the dispersion and transport of secondary pollutants across regions. Variations in precipitation and humidity can affect the removal of these pollutants through processes like wet deposition, which can either dilute or concentrate their impacts. Thoughtful of these dynamics is crucial for developing effective strategies to manage air quality and mitigate the health and environmental effects of secondary pollutants (Haddaway et al., 2003).

HYDROSPHERE AND WATER CHEMISTRY

The ecology and life on Earth depend heavily on the hydrosphere and the chemistry of water Figure 3. Significant alterations in ocean chemistry are reviewed in this portion of the paper, with an emphasis on ocean acidification brought on by rising atmospheric carbon dioxide concentrations. It examines how these modifications affect freshwater ecosystems and the general quality of water, highlighting the ways in which changed chemical compositions affect aquatic life and public health. The paper also explores the effects on chemical cycling in aquatic environments, describing how perturbations in these cycles impact the availability of nutrients and the functioning of ecosystems. The section concludes by discussing changes in freshwater and marine biogeochemistry and illustrating the intricate relationships and feedback systems that control these habitats. We hope to shed light on the significant changes taking place in the water systems of our globe and the broad ramifications these changes have for sustainability and environmental health.

Changes in Ocean Chemistry

Ocean acidification is a significant consequence of rising atmospheric CO_2 levels, where CO_2 dissolves in seawater, forming carbonic acid and subsequently lowering the pH of ocean waters (Smith, 2023). Since the onset of the Industrial Revolution, the pH of ocean surface waters has dropped by approximately 0.1 units, marking a 30% increase in acidity (Zhang, 2022). This change in ocean chemistry primarily results from the absorption of CO_2 from the atmosphere, which reacts with seawater to produce carbonic acid. This acid then dissociates into bicarbonate and hydrogen ions, thereby increasing ocean acidity (Davidson& Janssens, 2021). Ocean acidification adversely affects marine life, particularly organisms that rely on calcium carbonate for their shells and skeletons, such as corals, mollusks, and certain plankton species. The impacts of ocean acidification extend broadly, affecting not only marine organisms but also larger ecological systems. Acidified conditions can reduce calcification rates in corals and shellfish, disrupt marine food webs, and diminish biodiversity (Fissore et al., 2021). Furthermore, ocean acidification can alter nutrient availability and the efficiency of biological carbon sequestration processes, influencing the overall health of marine ecosystems and their capacity to mitigate climate change (Paustian et al., 2021).

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Effects on Aquatic Environments

Climate change profoundly affects freshwater systems and water quality through shifts in precipitation patterns, temperature variations, and runoff dynamics (Fierer et al., 2017). Changes in precipitation can increase the frequency and intensity of extreme weather events like floods and droughts, impacting the quantity and quality of freshwater resources (Fierer etal., 2017). Elevated runoff during heavy rainfall events can elevate concentrations of pollutants such as nutrients and sediments entering freshwater systems, degrading water quality and harming aquatic life (Huang et al., 2023). Rising temperatures can alter freshwater ecosystems by changing thermal regimes, which can affect species distribution and ecosystem functioning. Warmer temperatures may accelerate the growth of harmful algal blooms, which can produce toxins and reduce oxygen levels in water bodies, leading to dead zones and biodiversity loss (Adeel et al., 2023). Effective water management and conservation strategies are essential to address these challenges and ensure the sustainability of freshwater resources in a changing climate (Liu et al., 2021).

Climate change influences chemical cycling in aquatic environments, impacting processes such as nutrient cycling, redox reactions, and the transport of contaminant (McLaughlin et al., 2021). Increasing temperatures can modify the rates of biochemical processes like nitrification and denitrification, critical for nitrogen cycling in aquatic systems. Changes in temperature and precipitation can also affect the solubility and mobility of nutrients and contaminants, influencing water quality and ecosystem health (Friedlingstein, 2022). Climate-induced alterations in hydrology, such as shifts in river flow patterns and increased flooding, can influence the transport and fate of pollutants in aquatic environments. Elevated storm events may mobilize legacy pollutants from sediments, further impacting the health of aquatic ecosystems (Friedlingstein et al., 2022).

Climate change induces significant changes in marine and freshwater biogeochemistry, impacting the interactions among biological, chemical, and physical processes in these environments (Fissore et al, 2021). In marine systems, alterations in temperature, acidification, and nutrient availability influence primary production, nutrient cycling, and carbon sequestration processes (Hall et al., 2014). Elevated sea surface temperatures can intensify stratification, reducing nutrient mixing and affecting primary productivity (Doney et al, 2012). In freshwater systems, climate change can modify biogeochemical processes such as decomposition, nutrient cycling, and organic matter dynamics (Schuur et al., 2021). Shifts in temperature and hydrology impact the rate of organic matter decomposition, influencing carbon storage and release in freshwater ecosystems (Galloway et al., 2023). These changes in biogeochemical cycles carry implications for ecosystem services, water quality, and climate feedback mechanisms (Turner et al., 2022). Effective management strategies are essential to address these biogeochemical shifts and uphold the health of aquatic ecosystems in response to a shifting climate (Galloway et al., 2023).

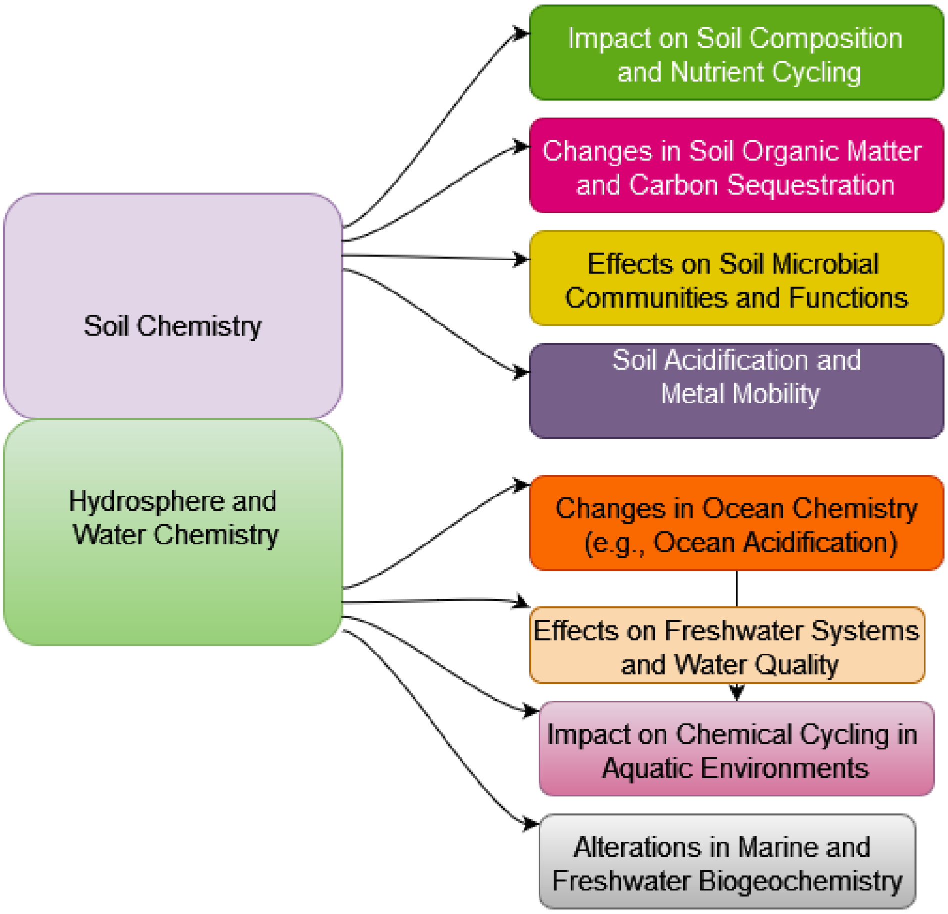

Figure 3. Hydrosphere, Water Chemistry and Soil Chemistry

SOIL CHEMISTRY

Understanding soil chemistry is essential to comprehending terrestrial ecosystems and how they react to changes in their surroundings. The impact of climate change and human activity on soil chemistry is the main topic of this review part. Changes in soil composition and nutrient cycling are the first things covered. It looks at how these modifications affect plant growth and soil fertility, having important ramifications for sustainable ecosystems and agriculture. The assessment also looks at how soil organic matter has changed and how carbon is sequestered, emphasizing how soils store carbon and help to mitigate climate change. It also discusses the impacts on the microbial communities in soil and their roles, highlighting the significance of microbial activity and diversity in preserving soil health. The section concludes by examining soil acidification and metal mobility and talking about how these processes impact soil quality and can be harmful to the ecosystem and people's health. We hope to shed light on the intricate chemical relationships found in soils and the wider ecological and environmental effects of these interactions through this thorough investigation.

Impact on Soil Composition, Nutrient Cycling, and Microbial Communities

Climate change has been observed to significantly influence soil composition and nutrient cycling, critical for soil fertility and agricultural productivity. Recent studies indicate that increased atmospheric CO_2 and rising temperatures can modify nutrient availability and soil composition through various mechanisms. (Lamarque et al., 2022) noted that elevated CO_2 levels can increase soil organic carbon content and affect nutrient availability, thereby influencing plant growth and soil health. (Wang et al., 2022) also demonstrated that rising temperatures impact soil processes such as nitrification and denitrification, influencing nitrogen availability and losses from soils. Beyond temperature and CO_2 effects, alterations in precipitation patterns due to climate change can also impact soil nutrient dynamics. In another way, (Houghton et al., 2021) reported that changed precipitation patterns may increase nutrient leaching and runoff, affecting soil fertility and water quality. Their findings underline how extreme weather events, such as heavy rains, can exacerbate nutrient loss from soils and impact agricultural systems.

Recent research suggests that soil acidification from climate change can enhance the mobility of toxic metals, with significant implications for soil health and plant growth. Recent work of (Galloway et al., 2004) highlighted that increased atmospheric CO_2 and precipitation can lead to soil acidification, influencing metal availability and toxicity. Studies such as those by (Feng et al., 2021) indicate that soil acidification processes can mobilize metals like aluminum and lead, impacting soil fertility and ecosystem health. Their findings stress the importance of implementing management strategies to address soil acidification and mitigate its effects on metal mobility.

Recent research underscores the intricate interactions between climate change and soil organic matter (SOM) dynamics. Higher temperatures are known to accelerate SOM decomposition, potentially increasing CO_2 emissions from soils. For example, (Gillett et al., 2023a) reviewed evidence showing that warming accelerates SOM decomposition, influencing carbon storage in soils. (He et al., 2022) found that climate change induces significant changes in SOM dynamics, affecting carbon sequestration and potentially contributing to greenhouse gas emissions. Conversely, strategies exist to enhance carbon sequestration under changing climate conditions. Recent studies, such as those by (Liu et al., 2023), demonstrate that improved land management practices can increase SOM content and promote carbon sequestration. Their research underscores the importance of adopting sustainable practices to mitigate climate change impacts on soil carbon storage.

The impact of climate change on soil microbial communities and their functions has also garnered attention in recent research. Higher temperatures and altered moisture regimes can influence microbial community composition and activity. (Lamarque, 2022) explored how temperature increases can shift microbial community structures and functions, affecting soil nutrient cycles and ecosystem processes. Additionally, (Sharma et al., 2022) found that changing moisture conditions due to climate change impact microbial communities, with implications for soil health and functionality. The role of soil microorganisms in maintaining ecosystem functions under climate change scenarios has been emphasized. (Stroik et al., 2022) demonstrated that microbial communities play a critical role in processes such as organic matter decomposition and nutrient cycling, which are susceptible to climate change impacts.

BIOGEOCHEMICAL CYCLES

Biogeochemical cycles, which control the flow of vital elements across ecosystems, are fundamental to the continuation of life on Earth. The review's section on major changes to these cycles brought about by human and environmental sources is extensive. It starts with a review of the modifications made to the carbon cycle, emphasizing the ways in which rising greenhouse gas emissions and deforestation affect atmospheric concentrations and carbon storage. After that, the paper looks at modifications to the nitrogen and phosphorus cycles, emphasizing how industrial and agricultural processes affect the availability of nutrients and the health of ecosystems. It also discusses how changes to these cycles affect biological and environmental processes, as well as the impact on the sulfur and trace element cycles. In order to clarify the feedback mechanisms that either exacerbate or attenuate climate impacts, the section concludes by examining the interplay between biogeochemical cycles and climate change. By means of this comprehensive examination, our objective is to augment our comprehension of the interdependence of biogeochemical cycles and their pivotal function in molding the climate and ecosystems of Earth.

Alterations in the Elemental Cycles

Climate change has a significant impact on the global carbon cycle, crucial for regulating atmospheric CO_2 levels and climate stability. Recent research indicates that increased atmospheric CO_2 and rising temperatures are altering carbon fluxes between the atmosphere, biosphere, and oceans (Wu et al., 2023). According to (Feng et al., 2021), elevated CO_2 levels are enhancing photosynthesis and plant growth, initially promoting carbon sequestration in terrestrial ecosystems. However, higher temperatures are also increasing respiration rates, potentially releasing more CO_2 into the atmosphere (Feng et al., 2021).

Climate change affects the carbon cycle through changes in soil organic matter dynamics and the frequency of extreme weather events (Gillett et al., 2023b). Warmer temperatures can accelerate soil organic carbon decomposition, potentially elevating atmospheric CO_2 levels and contributing to climate change (Sharma et al., 2022). Accepting these alterations is crucial for predicting future climate scenarios and developing effective mitigation strategies. Climate change is also influencing nitrogen and phosphorus cycles, vital for ecosystem productivity and water quality. Increased atmospheric CO_2, along with changing temperature and precipitation patterns, are altering nitrogen and phosphorus dynamics in both terrestrial and aquatic environments (Zhang et al., 2022). In novel research, (Wu et al., 2023). noted that higher temperatures can enhance nitrification and denitrification processes, influencing nitrogen availability and loss. Phosphorus cycles are also impacted by climate change, with altered precipitation patterns affecting phosphorus runoff into water bodies, contributing to eutrophication and water quality issues (Feng et al., 2021). Climate change also affects sulfur and trace element cycles, potentially influencing atmospheric chemistry and ecosystem health. Changes in sulfur emissions and deposition patterns can affect acid rain formation and environmental quality. Also (Gillett et al., 2023b) explored how these changes are impacting sulfur deposition and subsequent environmental impacts. Trace elements, including metals and metalloids, are also affected by climate change-induced alterations in soil pH and moisture, influencing the mobility and bioavailability of these elements (Gillett et al., 2023b).

Interactions between Biogeochemical Cycles and Climate Change

Climate change disrupts interactions between various biogeochemical cycles Table 1, leading to complex feedbacks and cascading effects in ecosystems. Research has focused on understanding how changes in one cycle can influence others and impact overall climate dynamics. (Sharma et al., 2022) investigated the interconnectedness of carbon, nitrogen, and phosphorus cycles under changing climate conditions and their implications for ecosystem services and climate change mitigation.

Moreover, climate change can trigger feedback mechanisms that either amplify or mitigate its effects through biogeochemical cycles. (Zhang et al., 2022) reviewed these feedback mechanisms and their potential implications for future climate scenarios.

Table 1. Biogeochemical Cycles.

Subtopic	Description	References
Alterations in the Carbon Cycle	Recent studies on how increased CO_2 and temperatures affect carbon fluxes, soil organic matter dynamics, and climate feedbacks.	(Gillett et al., 2004a; Hell et al., 2021)
Changes in Nitrogen and Phosphorus Cycles	The impact of climate change on nitrogen and phosphorus dynamics, including effects on nutrient availability, runoff, and ecosystem health.	(Liu et al., 2023; Shartma et al., 2022a)
Impact on Sulfur and Trace Element Cycles	How climate change alters sulfur emissions, deposition patterns, and the mobility of trace elements, with implications for atmospheric chemistry and environmental health.	(Stroik et al., 2022; Wu et al., 2023)
Interactions Between Biogeochemical Cycles and Climate Change	Exploration of the feedback mechanisms between different biogeochemical cycles and their implications for climate change mitigation and ecosystem services.	(Feng et al., 2021; Gillett et al., 2004b and Sulaiman et al., 2024)

POLLUTANT BEHAVIOR AND DISTRIBUTION

Climate change has significant impacts on the transport and fate of pollutants in the environment through altered precipitation patterns and increased temperatures. These changes influence how pollutants move through air, water, and soil systems, thereby affecting environmental and human health. (Sharma et al., 2022b) conducted research on the effects of climate change on pollutant transport and fate, highlighting how rising temperatures and changing precipitation patterns can enhance the volatilization of pollutants and modify their distribution across environmental media. Similarly, (Zhang et al., 2022) demonstrated that shifts in hydrological cycles due to climate change, such as heavy rainfall events, can increase pollutant runoff from land surfaces to water bodies, impacting water quality and ecosystem health. Climate change also alters the persistence and toxicity of environmental contaminants, which are critical considerations for ecosystem and human health. Changes in environmental conditions like temperature and pH can modify the behavior of pollutants, influencing their persistence and toxic effects. (Bellard et al., 2021) explored the impacts of climate-induced temperature and pH changes on the degradation rates and toxicity of contaminants such as pesticides and pharmaceuticals. Their findings indicated that increased temperatures can accelerate the degradation of some pollutants but may also heighten the toxicity of others due to enhanced chemical reactions. (Carpenter et al., 2021) investigated how extreme weather events driven by climate change, such as droughts and floods, can alter contaminant behavior and elevate associated risks.

Climate change influences both the origins of pollutants and the efficacy of natural systems as pollutant sinks. Changes in land use, temperature, and precipitation can alter emission sources and the ability of natural environments to mitigate pollution. (Doney et al., 2012) investigated the impact of climate change on pollution sources, focusing on increased agricultural runoff and industrial emissions. Their research underscored that shifting climate conditions, such as heightened rainfall and warmer temperatures, can exacerbate pollution from these sources and impact environmental quality (Doney, 2009). In a separate study, (Gauthier et al., 2022) examined how climate change affects natural pollutant sinks, including vegetation cover and soil processes. Their findings suggested that modifications in land cover and ecosystem dynamics can change the capacity of natural systems to function as sinks for pollutants (McMahon et al., 2021a). Climate change can also impact bioaccumulation and biomagnification processes, altering the movement of contaminants through food chains and their effects on higher trophic levels. (Pecl, 2017) reviewed the effects of climate change on the bioaccumulation of pollutants such as mercury and persistent organic pollutants. They found that changes in environmental conditions due to climate change can modify the rates of bioaccumulation and biomagnification of these contaminants in aquatic and terrestrial food webs. Similarly, (Sala, 2000) investigated how climate-induced environmental changes affect the biomagnification of contaminants through food chains. Their research highlighted those rising temperatures and altered precipitation patterns can influence contaminant transfer from lower to higher trophic levels, potentially impacting food safety and ecosystem health.

The behavior and distribution of pollutants in relation to climate change are shown in Table 2. Each subtopic is backed by recent references and discusses how pollution transport methods, persistence, and toxicity are affected by climate change, as well as how sources and sinks of pollution are changed and how bioaccumulation and biomagnification in ecosystems are impacted.

Table 2. Pollutant Behavior and Distribution.

Subtopic	Description	References
Changes in Pollutant Transport and Fate	Exploration of how climate change affects the transport mechanisms of pollutants across environmental media and the resulting impacts on environmental quality and human health.	(Bellard et al., 2021; Aerts, 2020)
Impact on the Persistence and Toxicity of Contaminants	The effects of climate change on the degradation rates, persistence, and toxicity of environmental contaminants due to changes in environmental conditions such as temperature and pH.	(Stroik et al., 2023; Gillett et al., 2023b)
Climate-Driven Changes in Pollution Sources and Sinks	How climate change alters the sources of pollutants and the capacity of natural systems to act as pollution sinks, including impacts on agricultural runoff, industrial emissions, and natural processes.	(Bellard et al., 2021; Carpenter et al., 2021)
Effects on Bioaccumulation and Biomagnification	How climate change influences the processes of pollutant bioaccumulation and biomagnification in food chains and ecosystems, with implications for food safety and ecosystem health.	(Doney et al., 2012; Gauthier et al., 2022)

ECO-TOXICOLOGICAL IMPACTS

The eco-toxicological effects of climate change on ecosystems are shown in Table 3. Supported by pertinent studies for each subtopic, it covers the effects on ecosystem health and biodiversity, alterations in the toxicity of chemical contaminants, disturbances in food webs and trophic interactions, and the various vulnerabilities of various ecosystems.

Table 3. Eco-toxicological Impacts.

Subtopic	Description	References
Impact on Ecosystem Health and Biodiversity	Effects of climate change on species distributions, habitat loss, and ecological interactions that affect ecosystem health and biodiversity.	(Wu et al., 2023; Feng et al., 2021)
Changes in the Toxicity of Chemical Contaminants	How climate-driven changes in environmental conditions such as temperature and pH affect the toxicity and bioavailability of chemical contaminants.	(Feng et al., 2021; Gillett et al., 2023b)
Effects on Food Webs and Trophic Interactions	Disruptions in food webs and trophic interactions caused by climate change, including impacts on predator-prey relationships and ecosystem stability.	(Sharma et al., 2022b; Zhang et al., 2022)
Vulnerability of Different Ecosystems to Climate Change	Assessment of how different ecosystems respond to climate change and the varying degrees of vulnerability among terrestrial and aquatic systems.	(Aerts, 20202; Bellard et al., 2021)

Impact on Ecosystem Health and Biodiversity

Climate change has profound impacts on ecosystem health and biodiversity, resulting in shifts in species composition, habitat loss, and altered ecological interactions. Rising temperatures, changing precipitation patterns, and increased frequency of extreme weather events stress ecosystems and threaten biodiversity. (Sharma et al., 2022c) investigated the effects of climate change on marine biodiversity, highlighting that ocean warming and acidification can induce shifts in species distributions, alter community structures, and disrupt ecosystem functions. Their research emphasized that these changes can diminish biodiversity by favoring certain species over others and modifying predator-prey relationships. (Stroik et al., 2022) examined how climate-induced changes impact terrestrial ecosystems, noting that higher temperatures and shifting precipitation patterns can lead to habitat loss, species extinctions, and changes in plant-animal interactions. Their findings featured that climate change as a primary driver of biodiversity loss, posing significant challenges for conservation efforts.

Climate change can alter the toxicity of chemical contaminants through shifts in environmental factors such as temperature, pH, and salinity. These alterations influence the chemical forms of contaminants, their bioavailability, and their toxic impacts on organisms. (Anastas& Warner, 2020) researched the effects of rising temperatures and changing pH levels on the toxicity of pollutants like heavy metals and persistent organic pollutants. Their findings revealed that increased temperatures can enhance the bioavailability of contaminants, while pH changes can modify their chemical forms and increase toxicity. Similarly, (Bennett et al., 2022) investigated how climate-induced alterations in environmental conditions affect the toxicity of chemical contaminants in aquatic ecosystems. Their study demonstrated that elevated temperatures and altered pH levels can exacerbate the toxic effects of pollutants on aquatic life, influencing survival, growth, and reproduction (Bodansky, 2021).

Effects on Food Webs and Trophic Interactions

Climate change disrupts food webs and trophic interactions by changing species abundance, distribution, and the timing of ecological events. These disruptions cascade throughout ecosystems, affecting predator-prey relationships and energy flow. (Candelaria et al., 2022) explored the impact of climate change on marine food webs, finding that shifts in temperature and ocean chemistry disrupt trophic interactions, alter species distributions, and influence the stability of marine ecosystems. Their study emphasized that changes in the abundance of key species can trigger trophic cascades, impacting overall ecosystem health. In a related study, (Wit, 2021) investigated the effects of climate change on terrestrial food webs, focusing on how temperature and precipitation changes influence species interactions and food web dynamics. They observed that climate change can reshape food web structures, leading to shifts in species populations and ecosystem processes.

Different ecosystems display varying levels of susceptibility to climate change, influenced by their structural characteristics, functional roles, and resilience capacities. Recognizing these vulnerabilities is essential for formulating effective management and conservation strategies. (Hsu et al., 2023) evaluated the susceptibility of terrestrial ecosystems to climate change, revealing that different ecosystems respond diversely to alterations in temperature and precipitation. Their research underscored that ecosystem with lower biodiversity or those already experiencing stress are particularly prone to climate impacts. Similarly, (IEA, 2021) investigated the vulnerability of diverse ecosystems to climate change, highlighting the heightened sensitivity of habitats such as wetlands and coral reefs to climate-induced transformations. Their findings emphasized the necessity for targeted conservation initiatives aimed at safeguarding these vulnerable ecosystems from the detrimental effects of climate change. The summary is presented in Table 3

MITIGATION AND ADAPTATION STRATEGIES

This section examines important methods for addressing climate change that combine adaptation and mitigation measures. It starts by looking at chemical strategies to slow down global warming, such as new developments in carbon capture and storage and more environmentally friendly chemical processes. There are also a discussion of the role environmental chemistry plays in climate adaptation, with a focus on how chemical research helps to improve ecosystem resilience and human adaptability. In addition, the part analyzes the legislative and regulatory frameworks that facilitate these efforts and emphasizes the promotion of environmentally friendly behaviors and technologies. This section attempts to give a thorough review of practical tactics for preventing climate change and promoting sustainability by fusing scientific discoveries with legislative initiatives.

Chemical Approaches to Mitigate Climate Change

Chemical strategies play a crucial role in addressing climate change by focusing on reducing greenhouse gas emissions and advancing technologies for carbon capture and storage. A significant approach involves the development of advanced materials and technologies designed for carbon dioxide (CO_2) capture and sequestration. According to (McMahon et al., 2021b), various carbon capture and storage (CCS) technologies are discussed, emphasizing their potential to mitigate CO_2 emissions from industrial sources and power plants. The study highlights CCS as a critical component of global strategies aimed at limiting temperature rise and minimizing the impacts of climate change. Similarly, (Pörtner, 2019) examine innovative chemical methods for CO_2 capture, including the application of amine-based solvents and metal-organic frameworks. Their review underscores the effectiveness of these approaches in capturing CO_2 from industrial processes and reducing overall greenhouse gas emissions.

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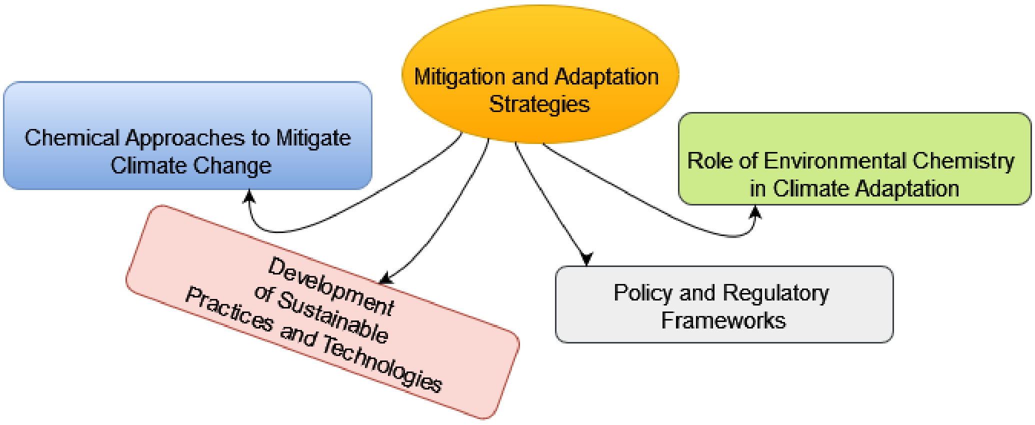

Figure 4. Mitigation and Adaptation Strategies

Role of Environmental Chemistry in Climate Adaptation

Environmental chemistry plays a crucial role in facilitating climate change adaptation through monitoring environmental changes, assessing risks, and devising adaptation strategies. One critical application is in evaluating climate impacts on water and air quality. (Usman et al., 2024a) discuss the contribution of environmental chemistry to understanding climate change effects on marine ecosystems and formulating adaptation strategies. They emphasize the role of chemical monitoring in assessing ocean acidification and its impacts on marine biodiversity. In another study, (Sulaiman et al., 2024a) explore how environmental chemistry supports climate adaptation by developing methods to monitor environmental pollutants and assess their consequences on ecosystems and human health. Their research underscores the necessity of integrated approaches combining chemical analysis with climate science.

Promotion of Sustainable Practices and Technologies

Promoting sustainable practices and technologies is essential for mitigating climate change impacts and fostering environmental stewardship. This involves innovating solutions that balance environmental, economic, and social sustainability. A significant advancement in this realm is the application of green chemistry principles, which prioritize designing products and processes that minimize hazardous substances. We can see that (Sulaiman et al., 2024b; Mustapha et al., 2024; Ma'aruf et al., 2024a; Ma'aruf et al., 2024b; Ma'aruf et al., 2024c; Usman et al., 2024b; Iya et al., 2023) provide an overview of green chemistry principles and their application in developing sustainable products and processes. Furthermore, (Mustapha et al., 2024) reviewed recent developments in sustainable technologies, including renewable energy sources, waste reduction strategies, and eco-friendly materials. Their review underscores how these technologies contribute to climate change mitigation and support long-term sustainability.

Policy and Regulatory Frameworks

Effective policy and regulatory frameworks are crucial for implementing climate change mitigation and adaptation strategies. These frameworks provide guidelines and incentives for reducing greenhouse gas emissions and promoting environmental protection. (Ma'aruf et al., 2024a) examines international climate agreements and their role in global climate policy, focusing on mechanisms within the Paris Agreement to stimulate climate action and ensure compliance. (Ma'aruf et al., 2024b) analyze national and regional climate policies, evaluating how different countries are formulating and implementing regulatory frameworks to address climate change challenges. Their study highlights best practices and areas for improvement in climate policy.

Table 4. Mitigation and Adaptation Strategies.

Subtopic	Description	References
Chemical Approaches to Mitigate Climate Change	Strategies for reducing CO_2 emissions, including carbon capture and storage technologies, and advancements in CO_2 capture methods.	(IEA, 2021; McMahon et al., 2021b)
Role of Environmental Chemistry in Climate Adaptation	How environmental chemistry supports climate adaptation efforts through environmental monitoring, risk assessment, and development of adaptation strategies.	(Pörtner, 2019; Usman et al., 2024a)
Development of Sustainable Practices and Technologies	Creation of green chemistry principles and sustainable technologies aimed at reducing climate change impacts and promoting environmental sustainability.	(Sulaiman et al., 2024a; Sulaiman et al., 2024a)
Policy and Regulatory Frameworks	Examination of international and national climate policies, regulatory frameworks, and their effectiveness in mitigating climate change and fostering environmental protection.	(Ma'aruf et al., 2024c; Usman et al., 2024b; Iya et al., 2023)

CONCLUSION

In conclusion, the impacts of climate change on environmental chemistry are intricate and diverse. This review underscores how climate change affects various environmental systems, encompassing atmospheric chemistry, the hydrosphere, soil chemistry, and biogeochemical cycles. Understanding these impacts is crucial for devising effective strategies to mitigate and adapt to climate change. Addressing climate change necessitates a comprehensive approach that includes advancing carbon capture and storage (CCS) technologies, integrating environmental chemistry into adaptation strategies, promoting green chemistry principles, and bolstering policy frameworks. By implementing these measures, it is possible to mitigate the adverse effects of climate change and move towards a more sustainable future. Continuous scientific research advancements and the adoption of innovative technologies are essential for achieving climate goals and safeguarding the environment for future generations. Through collaborative efforts and a commitment to sustainable practices, we can effectively tackle the challenges posed by climate change and ensure a resilient and healthy planet.

RECOMMENDATIONS

To effectively address the profound impacts of climate change on environmental chemistry, several strategic actions are essential.

First and foremost, there is a pressing need to enhance carbon capture and storage (CCS) technologies. These technologies are critical for reducing atmospheric CO_2 levels, a primary driver of global warming. Investment in research and development is necessary to advance both existing and new CCS methods. This includes exploring innovative approaches such as advanced amine-based solvents and novel metal-organic frameworks, which have shown promise in efficiently capturing CO_2 from industrial processes and power plants. Governments, research institutions, and private sectors must collaborate to scale these technologies and make them more cost-effective and widely available. By fostering partnerships and increasing funding for CCS research, we can better address the challenge of mitigating CO_2 emissions and work towards stabilizing the climate. Another crucial recommendation is to integrate environmental chemistry into climate adaptation strategies**.** Environmental chemistry offers valuable tools for monitoring environmental changes and assessing risks related to climate change. By employing chemical analysis techniques, we can better understand the impacts of climate change on air and water quality and develop effective adaptation measures. This integration requires a multidisciplinary approach that combines chemical science with climate modeling and environmental management. By enhancing our ability to track and predict environmental changes, we can create more effective strategies for adapting to the evolving climate and protecting both ecosystems and human health.

In addition to these technological and scientific advances, there is a significant opportunity to promote green chemistry and sustainable technologies**.** Green chemistry principles offer a framework for designing products and processes that minimize environmental impacts by reducing or eliminating hazardous substances. By adopting green chemistry practices, industries can innovate to create more sustainable products and processes that contribute to climate change mitigation. This approach also involves advancing renewable energy technologies, waste reduction techniques, and eco-friendly materials. Encouraging industries to embrace these sustainable practices will be vital for achieving long-term environmental sustainability and mitigating climate change. Finally, strengthening policy and regulatory frameworks is essential for implementing effective climate change mitigation and adaptation strategies**.** Policymakers play a crucial role in shaping climate action through the creation and enforcement of regulations that promote emission reductions, support environmental protection initiatives, and facilitate international climate agreements. A key aspect of this effort is the implementation of frameworks like the Paris Agreement, which sets ambitious climate goals and provides mechanisms for international cooperation and compliance. By enhancing these regulatory frameworks and ensuring robust enforcement, we can drive significant progress towards climate change mitigation and adaptation on a global scale.

Competing Interest

The authors of this review affirm that they have no conflicting interests in publishing it. The work was carried out impartially, free from any personal or financial connections that might have influenced the findings. The authors acknowledge all funding sources for this research and retain complete ownership over the primary data and materials used in this publication.

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