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Exploring Climate Change Mitigation: Innovative Technologies and Strategies for Carbon Dioxide Removal

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ABSTRACT

Over the past several decades, a persistent and gradual elevation in atmospheric carbon dioxide (CO_2) concentration has been observed. This rise in CO_2 levels contributes to the greenhouse effect, resulting in the trapping of more heat at the planet's surface and subsequent global warming. Based on current trends, it is projected that the global temperature will rise by approximately 1.5 °C between the years 2030 and 2052. In light of this, it becomes imperative to mitigate global warming by undertaking substantial actions to reduce CO_2 emissions. One approach to address this challenge is the sequestration of carbon dioxide, whereby it is captured from the atmosphere and utilized to produce valuable products. This has the potential to not only reduce the amount of CO_2 in the atmosphere but also lower the cost associated with emissions reduction. Carbon dioxide, when present above ambient levels, can be directly employed in processes such as enhanced oil recovery, where it is injected into oil wells. Additionally, it can be chemically transformed into materials, chemicals, or fuels, such as methanol, cement, biochar, and fuel production. While no single technology can fully address climate change, several innovative approaches have been developed to assist in reducing atmospheric CO_2 levels. These include direct air capture, cloud treatment, biomass-based construction, restoration of blue carbon habitats, and enhanced weathering. These methods and strategies for carbon dioxide sequestration are explored and described in order to counteract the adverse effects of CO_2 and other greenhouse gases on climate change and global warming. It is crucial to recognize that numerous industries and companies play a substantial role in generating CO_2 emissions. Nonetheless, it is feasible to mitigate the concentration of this gas through various measures, both pre and post-emission, thereby reducing its impact on the environment. Therefore, this study aimed to explore and describe innovative approaches and strategies for carbon dioxide sequestration in order to mitigate the adverse effects of CO_2 and other greenhouse gases on climate change and global warming.

Keywords: Carbon sequestration; Climate change; CO_2 utilization; Greenhouse gas emission; Technologies to capture CO_2.

INTRODUCTION

Climate is a fundamental concept that cannot be overlooked due to its vital role in the existence of life. The production of food, which serves as the primary source of sustenance for all living organisms, is heavily influenced by environmental conditions. Thus, the unpredictability associated with climate change poses a significant risk to billions of lives (Harris, 2022). Since the late 1800s, the Earth's global average air temperature has witnessed an increase of 0.3 to 0.6 ºC. Projections indicate that by the year 2100, the global average surface air temperature may rise by 1 to 3.5 ºC (Hamburg *et al.*, 1997).

The First Installment of the Fifth Assessment Report (AR5) by the Intergovernmental Panel on Climate Change (IPCC) reaffirmed previous warnings regarding anthropogenic-induced global warming. The assessment highlighted potential declines in global food yields starting in the 2030s due to rising temperatures and an escalation in the frequency and severity of extreme climatic events (De Pryck, 2021). Additionally, ecosystems and biodiversity face the risk of significant losses (Fouad *et al.*, 2023). The report further emphasized the hazards associated with anthropogenic global warming. Among anthropogenic greenhouse gases (GHGs), carbon dioxide (CO_2) is the primary contributor to the greenhouse effect, accounting for approximately 50% of the radiative forcing that drives global climate change (Reddy *et al.*, 2010). Since the onset of the Industrial Revolution, CO_2 levels have risen by 39% (Wright and Boorse, 2011). The Sixth Assessment Report (AR6) of the IPCC in 2022 revealed that annual GHG emissions between 2010 and 2019 exceeded those of previous decades. In 2019, total anthropogenic GHG emissions reached 59±6.6 $GtCO_2$-eq, representing a 12% increase compared to 2010 and a 54% increase from 1990. The largest absolute increase in emissions by 2019 originated from CO_2 emissions from industry and fossil fuels, followed by methane (CH_4). Consequently, the establishment or promotion of carbon (C) sinks and the reduction of anthropogenic CO_2 emissions are two crucial measures in mitigating GHG concentrations in the atmosphere. This review aims to present an overview of greenhouse gas emissions records and their impact on global warming. It will review ten carbon dioxide utilization pathways and cutting-edge technologies to achieve net-zero emissions by 2050.

Global Greenhouse Gas Emissions: A Scientific Perspective

The global greenhouse gas (GHG) emissions, as rep-

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orted by the Intergovernmental Panel on Climate Change (IPCC) in 2014, highlight a concerning trend. The period from 2010 to 2019 witnessed the highest recorded net anthropogenic GHG emissions in history. The increase in greenhouse gas (GHG) emissions since 2010 has been extensively documented (IPCC, 2022) (Figure 1). Carbon dioxide (CO_2) is primarily generated through the combustion of fossil fuels. Additionally, indirect human activities such as deforestation, agricultural practices, and soil degradation can contribute to CO_2 emissions. On the other hand, land can serve as a sink for CO_2 through processes like soil restoration, reforestation, and other carbon sequestration initiatives. Furthermore, reducing soil moisture can lead to a decrease in CO_2 re-emissions (De Pryck, 2021).

Methane (CH_4) and Nitrous Oxide (N_2O) Emissions

Methane (CH_4) emissions arise from various sources such as biomass burning, waste management, agricultural practices, and energy utilization. Nitrous oxide (N_2O) emissions predominantly stem from agricultural activities, particularly the use of fertilizers. Additionally, the burning of fossil fuels also releases N_2O.

Fluorinated Gases (F-gases)

Fluorinated gases (F-gases), which encompass hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), are primarily produced by industrial processes, refrigeration systems, and the use of various consumer products. Overall, understanding the sources and implications of global GHG emissions is crucial for developing effective mitigation strategies and addressing the challenges posed by climate change.

Sectoral Contributions to Global Greenhouse Gas Emissions: An In-depth Analysis

In addition to the global greenhouse gas (GHG) emissions discussed earlier, it is essential to consider the emissions associated with various economic sectors. The Intergovernmental Panel on Climate Cha-nge (IPCC, 2022) has reported consistent increases in emissions for all greenhouse gases (Figure 2).

Electricity and Heat Production

The combustion of coal, natural gas, and oil for heat and electricity generation is the primary contributor to global GHG emissions in this sector.

Industry

GHG emissions from the industrial sector primarily result from the local burning of fossil fuels for energy purposes. Additionally, emissions from waste management activities and non-energy-related chemical and mineral transformation processes are also included in this sector. However, emissions from agriculture, forestry, and other related activities are accounted for separately.

Land Use

The cultivation of crops, animal husbandry, and deforestation are the major sources of GHG emissions in this sector. It is important to note that emissions mitigated by ecosystems, which involve carbon storage in biomass, decomposition of organic matter, and soil processes, are not included in this calculation (Food and Agriculture Organization (FAO), 2014).

Transportation

The burning of fossil fuels for land, rail, air, and sea transportation is the primary cause of GHG emissions in the transportation sector. Approximately 95% of the energy used for transportation worldwide is derived from petroleum-based fuels, predominantly gasoline and diesel.

Buildings

GHG emissions in this sector arise from on-site energy production and the combustion of fuels for residential heating and cooking purposes.

It is crucial to understand the contributions of each sector to global GHG emissions in order to develop effective mitigation strategies and address the challenges posed by climate change.

Climate Change and its Impacts

Climate change, resulting from global warming, is a significant environmental phenomenon characterized by long-term alterations in Earth's weather patterns at the local, regional, and global levels (NASA, 2022). This complex issue is influenced by various factors and has far-reaching impacts on the planet. The primary driver of climate change is human activities, particularly the combustion of fossil fuels, which leads to an increase in greenhouse gas concentrations in the atmosphere, consequently raising the average surface temperature of the Earth. In addition to the human-induced factors, climate change can also be influenced

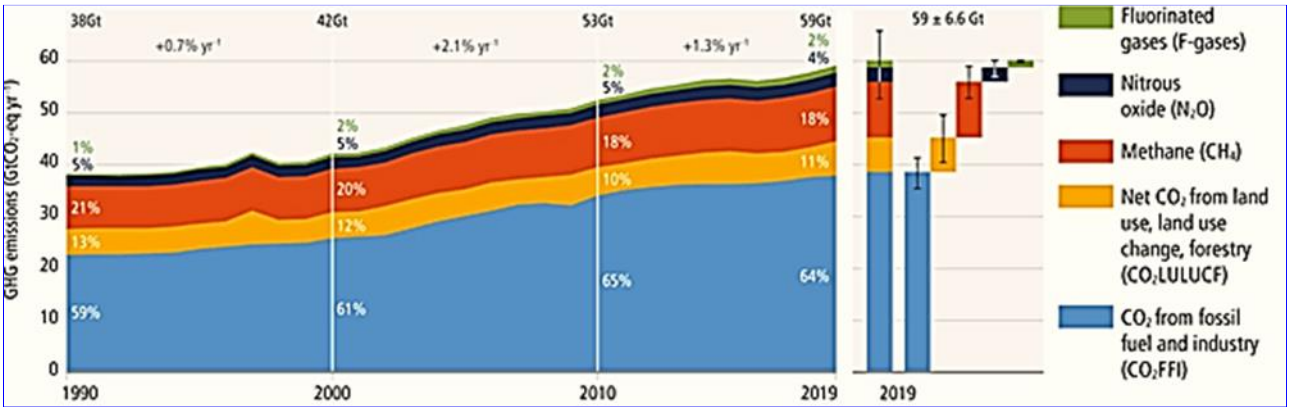

Figure (1): Trends in global anthropogenic greenhouse gas emissions: A visual analysis (1990-2019) by IPCC (2022).

by internal variability and natural factors. Internal variability includes cyclical ocean patterns and phenomena like the Pacific Decadal Oscillation, while natural factors encompass volcanic activity, variations in the Sun's energy output, and changes in the Earth's rotation. These factors can potentially contribute to the complexity and variability of climate change.

To study climate change, scientists utilize a range of tools and data sources, including computer models, ground-based measurements, atmospheric observations, and satellite data. These resources provide insights into the past, present, and future climate trends, helping to improve our understanding of the mechanisms and impacts of climate change.

It is widely acknowledged among the scientific community that global temperatures will continue to rise in the foreseeable future, primarily driven by human-induced greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC), a global body of over 1,300 scientists, projects a temperature increase of 2.5 to 10 degrees Fahrenheit over the next century (Field *et al*., 2014). This warming trend poses significant risks and challenges, particularly for vulnerable regions like African nations (Boko *et al*., 2007). Changes in precipitation patterns and distribution may disrupt the water balance, resulting in fluctuations in droughts and floods.

Numerous studies have demonstrated temporal and geographical variations in climate change, highlighting regional disparities in temperature and precipitation changes. Therefore, consequences of climate change can be summarized as follow:

Rising temperatures

Climate change is causing an increase in average global temperatures, leading to heatwaves, longer and more intense heat events, and rising sea surface temperatures.

Changes in precipitation patterns

Shifts in precipitation patterns are occurring, resulting in changes in rainfall distribution, increased frequency of extreme weather events such as heavy rainfall and droughts, and altered water availability.

Sea-level rise

As global temperatures rise, glaciers and ice sheets melt, contributing to sea-level rise. This poses a significant threat to coastal regions, leading to increased coastal erosion, flooding, and saltwater intrusion into freshwater sources.

Changes in ecosystems:

Climate change affects ecosystems and biodiversity. Species may face habitat loss, altered migration patterns, changes in phenology (timing of biological events), and increased risk of extinction.

Ocean acidification

Increased carbon dioxide (CO_2) emissions are leading to the acidification of the oceans, which impacts marine ecosystems, particularly coral reefs and shell-forming organisms.

Extreme weather events

Climate change is associated with an increase in the frequency and intensity of extreme weather events such as hurricanes, cyclones, floods, and wildfires.

These variations emphasize the need for localized and context-specific approaches in adapting to and mitigating the impacts of climate change.

To mitigate greenhouse gas emissions, it is crucial to develop and promote carbon sinks in the biosphere, which effectively reduce industrial CO_2 emissions (Montagnini and Nair, 2004). Implementing strategies to enhance carbon sequestration and employing renewable energy sources are key steps towards mitigating climate change and ensuring a sustainable future.

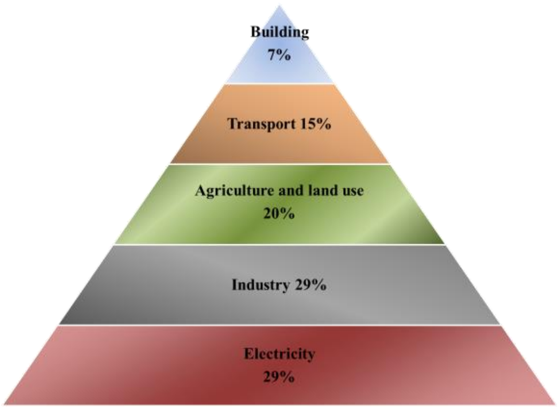

Figure (2): Global GHG Emissions by sector: Percentage of CO_2 emissions (IPCC, 2022).

Carbon Sequestration: Processes and Significance in Mitigating Global Warming

Carbon sequestration plays a crucial role in mitigating global warming by capturing and storing carbon dioxide (CO_2) from the atmosphere. This process involves various mechanisms that contribute to reducing greenhouse gas emissions and slowing down the pace of climate change.

One of the primary natural processes of carbon sequestration is photosynthesis, which occurs in plants and other photosynthetic organisms. Through photosynthesis, plants absorb CO_2 from the atmosphere and convert it into organic compounds, such as carbohydrates, while releasing oxygen as a byproduct. This process not only helps to remove CO_2 from the air but also provides the foundation for the formation of biomass. Biomass, including forests, grasslands, and other vegetation, acts as a significant carbon sink, storing large amounts of carbon over long periods. As plants grow, they continue to absorb CO_2 through photosynthesis and incorporate it into their tissues. This stored carbon remains locked away, preventing its release back into the atmosphere (Metz *et al.*, 2005).

Another natural process of carbon sequestration is the storage of carbon in soils. Soil organic carbon is derived from the decomposition of plant and animal residues, which adds carbon to the soil (Lal, 2004). Additionally, certain agricultural practices, such as conservation tillage and cover cropping, can enhance soil carbon sequestration.

Apart from natural processes, there are also technological approaches to carbon sequestration. One such method is carbon capture and storage (CCS), which involves capturing CO_2 emissions from industrial sources, such as power plants, and injecting it deep underground for long-term storage. This prevents the CO_2 from being released into the atmosphere and contributing to global warming. The significance of carbon sequestration in mitigating global warming cannot be overstated. By removing CO_2 from the atmosphere and storing it in natural sinks or utilizing technological methods, carbon sequestration helps to offset greenhouse gas emissions. This process contributes to the stabilization of atmospheric CO_2 concentrations and reduces the overall impact of human activities on climate change.

Furthermore, carbon sequestration not only helps mitigate global warming but also offers co-benefits for ecosystem health and biodiversity. The preservation and restoration of natural carbon sinks, such as forests and wetlands, not only store carbon but also provide habitats for numerous plant and animal species. Forests, in particular, support a wide range of biodiversity and play a crucial role in water regulation, soil protection, and the provision of ecosystem services. By promoting carbon sequestration, we can simultaneously enhance the resilience and sustainability of ecosystems, safeguarding their ability to adapt to changing climate conditions and supporting the overall health of our planet. Generally, the co-benefits of carbon sequestration beyond climate change mitigation, emphasizing the importance of preserving natural carbon sinks for ecosystem health and biodiversity conservation.

Strategies for sequestering carbon dioxide (CO_2)

In the context of global warming and climate change, historical efforts for carbon dioxide (CO_2) sequestration have primarily focused on utilizing elevated CO_2 concentrations to create economically valuable products. This approach involves using CO_2 in processes such as enhanced oil recovery or chemically converting it into materials, chemicals, and fuels. These strategies offer the potential for large-scale implementation at a low cost (Figure 3).

Chemical Production and Sustainable Goods

One innovative approach to CO_2 sequestration is the production of CO_2 chemicals. By breaking down CO_2 into its components using catalysts, approximately 0.3 to 0.6 Gt of CO_2 could be utilized by 2050 to produce goods such as methanol, urea (as fertilizer), or polymers for building materials or vehicles.

Production of hydrocarbon fuels

Another strategy involves the use of CO_2 fuels. By combining hydrogen and CO_2, hydrocarbon fuels like methanol, synfuels, and syngas can be generated, serving a significant market. However, the current expenses associated with this method remain high, despite the existing transportation infrastructure.

Application for sustainable building materials

An alternative strategy lies in the realm of concrete building materials, whereby CO_2 is incorporated into aggregates for infrastructure or used in the cement curing process. This approach shows promise as it has the potential to replace traditional cement, which is a major source of pollutants, while also providing long-term CO_2 storage.

Bioenergy with carbon capture and storage (BECCS)

Bioenergy with carbon capture and storage (BECCS) is another approach to CO_2 sequestration. It involves utilizing bioenergy sources, such as biomass or biofuels, to generate power while capturing and storing the resulting emissions. The process includes growing trees or other biomass feedstocks that absorb CO_2 during their growth, utilizing the biomass for energy production, and then capturing and sequestering the CO_2 emissions generated in the process. By 2050, this strategy has the potential to capture and store approximately 0.5 to 5 $GtCO_2$ annually, contributing to significant reductions in greenhouse gas emissions and aiding in the mitigation of climate change (Fujii *et al*., 2005; Sunakorn and Kasemsap, 2010).

Enhanced weathering, forestry, and soil carbon sequestration

Enhanced weathering is a technique that utilizes rocks like basalt, crushed and spread on land, to rapidly convert atmospheric CO_2 into stable carbonate. This process not only helps mitigate climate change but also has the potential to increase agricultural yields. Furthermore, forestry presents an economically viable solution for carbon storage, including in buildings, with the potential to replace the use of cement. Both new and existing forests can contribute to this approach, with an estimated utilization of up to 1.5 $GtCO_2$ by 2050 (Smith, *et al*., 2019).

Soil carbon sequestration

Another effective method is soil carbon sequestration, which involves implementing land management techniques that enhance carbon storage in the soil. This not only boosts agricultural output but also serves as a significant carbon sink. By 2050, the increased agricultural output could result in the utilization of CO_2 ranging from 0.9 to 1.9 $GtCO_2$ annually (Kayla and Delerce, 2023).

Biochar

Biochar, considered one of alternative method limit CO_2 production. $_{It}$ produced by burning biomass at high temperatures with limited oxygen, has the potential to improve crop yields by 10% when added to agricultural soils. However, challenges persist in terms of consistent production and predicting soil reactions. It is projected that biochar could utilize between 0.2 and 1 $GtCO_2$ by 2050.

Enhanced oil recovery

Another approach is CO_2 enhanced oil recovery (EOR), which involves injecting CO_2 into oil wells to enhance oil production. The primary focus in EOR is to maximize oil and CO_2 recovery rather than injecting and storing more CO_2 than is generated through the consumption of the ultimate oil product. By 2050, an estimated 0.1 to 1.8 $GtCO_2$ could be used and stored annually through this method.

Microalgae Utilization

Microalgae have emerged as a promising solution for CO_2 fixation, offering a sustainable and efficient means to mitigate greenhouse gas emissions. These microscopic organisms have the remarkable ability to convert CO_2 into biomass through photosynthesis. The resulting biomass can then be processed to produce a wide range of valuable products, including biofuels, high-end chemicals, and even nutritional supplements. The utilization rates for microalgae in 2050 are projected to range from 0.2 to 0.9 $GtCO_2$ annually, highlighting their significant potential in carbon sequestration and utilization. The cultivation of microalgae can be done in various systems, such as open ponds or closed photobioreactors, making it flexible and adaptable to different geographical locations. Furthermore, the byproducts of microalgae cultivation, such as lipids and proteins, can be utilized in various industries, contributing to a circular and sustainable economy. Overall, microalgae represent a promising pathway for CO_2 utilization, offering both environmental and economic benefits in the journey towards a low-carbon future (Figure 3).

Ten Technologies for Zero Emission

These ten technologies, as highlighted by Hepburn *et al*. (2019), demonstrate promising avenues for achieving zero emissions and mitigating the impacts of climate change (Figure 4).

Renewable Energy Sources

Transitioning from fossil fuels to renewable energy sources such as solar, wind, hydro, and geothermal power can significantly reduce emissions.

Energy Storage Solutions

Advancements in battery technology and energy storage systems can help store excess renewable energy for later use, ensuring a consistent and reliable supply of clean energy.

Carbon Capture and Storage (CCS)

CCS technologies capture carbon dioxide emissions from power plants and industrial processes, preventing them from entering the atmosphere and storing them underground.

Advanced Nuclear Power

Next-generation nuclear reactors, such as small modular reactors (SMRs) and advanced fast reactors, have the potential to generate clean and reliable baseload power with minimal waste and safety concerns.

Electric Vehicles (EVs)

Widespread adoption of electric vehicles can reduce emissions from the transportation sector by replacing traditional internal combustion engines with zero-emission electric motors.

Hydrogen Economy

Utilizing hydrogen as a clean fuel source for transportation, power generation, and industrial processes can help decarbonize sectors that are difficult to electrify.

Smart Grids

Implementing smart grids that optimize energy transmission, distribution, and consumption can improve energy efficiency and integrate renewable energy sources more effectively.

Zero-Emission Buildings

Constructing energy-efficient buildings with sustainable materials and incorporating technologies like efficient insulation, LED lighting, and smart energy management systems can significantly reduce emissions from the buildings sector.

Circular Economy

Shifting towards a circular economy model, where waste is minimized, and materials are recycled or reused, can reduce the environmental impact of resource extraction and production processes.

Sustainable Agriculture

Implementing sustainable farming practices, such as precision agriculture, organic farming, and agro-forestry, can help reduce emissions from the agri-culture sector and enhance soil health.

CONCLUSION

The rise in CO_2 emissions from fossil fuels and industry, as observed in 2019, has significant implica-tions for global warming and climate change. The negative impact of these emissions is evident in various aspects, such as the potential decline in global food yields and the increased occurrence of catastrophic climatic events. Additionally, ecosystems and biodiversity are at risk of suffering losses due to these emissions. However, there is hope for mitigating CO_2 emissions through the utilization of innovative technologies and CO_2 utilization pathways. These approaches offer cost-effective solutions to reduce the overall emissions and combat the negative effects on the environment. By exploring and implementing these

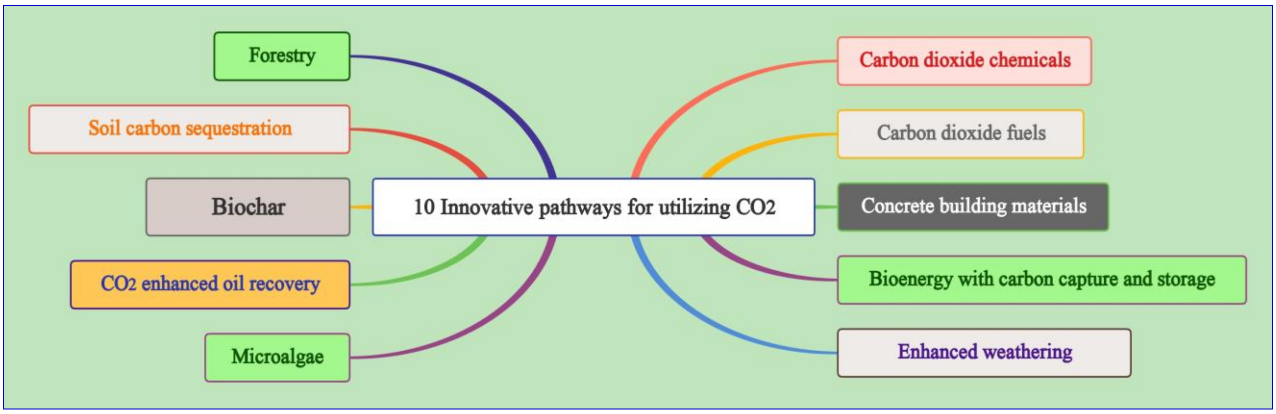

Figure (3): Ten innovative pathways for CO_2 utilization

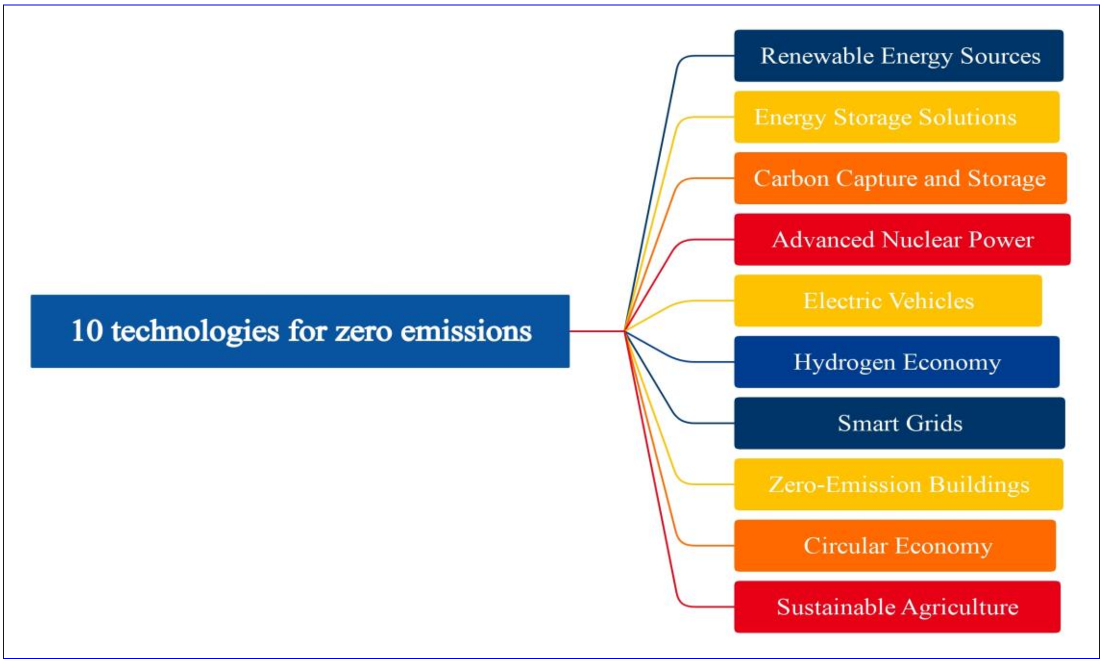

Figure (4) Ten technologies to capture CO_2 for achieving zero emissions.

technologies, we can take steps towards a more sustainable future and actively contribute to the mitigation of CO_2 emissions. It is crucial for governments, industries, and individuals to prioritize the adoption of these innovative technologies and support research and development efforts in this field. By taking these steps, we can strive towards a future where effective CO_2 sequestration is implemented, global warming is mitigated, and the adverse effects of climate change are minimized.

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استكشاف التخفيف من تغير المناخ: التقنيات المبتكرة والاستراتيجيات لإزالة ثاني أكسيد الكربون

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الملخص العربـــــي

خلال العقود السابقة، لوحظ ارتفاع مستمر وتدريجي في تركيز ثاني أكسيد الكربون (CO_2) في الغلاف الجوي. يسهم هذا الارتفاع في ظاهرة الاحتباس الحراري، مما يؤدي إلى احتباس المزيد من الحرارة على سطح الكوكب والاحتمال الناتج عنه لارتفاع درجة الحرارة العالمية. وبناءً على الاتجاهات الحالية، من المتوقع أن ترتفع درجة الحرارة العالمية بمقدار 1.5 درجة مئوية تقريبًا بين عامي 2030 و 2052. وبناءً على ذلك، يصبح من الضروري التخفيف من الاحتباس الحراري من خلال اتخاذ إجراءات جوهرية للحد من انبعاثات ثاني أكسيد الكربون. واحدة من الطرق للتعامل مع هذا التحدي هي تخزين ثاني أكسيد الكربون، حيث يتم التقاطه من الغلاف الجوي واستخدامه لإنتاج منتجات قيمة. وليس لهذا الأمر القدرة فقط على الحد من كمية ثاني أكسيد الكربون في الغلاف الجوي، ولكن أيضًا على خفض التكلفة المرتبطة بتقليل الانبعاثات. يمكن استخدام ثاني أكسيد الكربون، عندما يتواجد بمستويات أعلى من المستويات العامة، مباشرة في عمليات مثل استرجاع النفط المحسّن، حيث يتم حقنه في آبار النفط. بالإضافة إلى ذلك، يمكن تحويله كيميائيًا إلى مواد ومواد كيميائية ووقود مثل الميثانول والأسمنت والبيوكاربون وإنتاج الوقود. وبالرغم من أنه لا يوجد تكنولوجيا واحدة يمكن أن تعالج الاحتباس الحراري بشكل كامل، فقد تم تطوير العديد من النهج المبتكرة للمساعدة في تقليل مستويات ثاني أكسيد الكربون في الغلاف الجوي. وتشمل هذه النهج الاستيلاء المباشر على الهواء، ومعالجة السحب، والبناء القائم على الكتلة الحيوية، واستعادة المواطن الكربوني الأزرق، وتعزيز التعرية. يتم استكشاف هذه الأساليب والاستراتيجيات لتخزين ثاني أكسيد الكربون ووصفها من أجل مواجهة التأثيرات السلبية لثاني أكسيد الكربون وغازات الاحتباس الحراري الأخرى على تغير المناخ والاحتباس الحراري العالمي. من المهم أن ندرك أن العديد من الصناعات والشركات تلعب دورًا كبيرًا في إنتاج انبعاثات ثاني أكسيد الكربون. مع ذلك، من الممكن تقليل تركيز هذا الغاز من خلال تدابير مختلفة، سواء كانت قبل أو بعد الانبعاث، وبالتالي تقليل تأثيره على البيئة. لذلك، هدفت هذه الدراسة إلى استكشاف ووصف النهج والاستراتيجيات المبتكرة لتخزين ثاني أكسيد الكربون من أجل التخفيف من التأثيرات السلبية لثاني أكسيد الكربون وغازات الاحتباس الحراري الأخرى على تغير المناخ والاحتباس الحراري العالمي.