GLOBAL CLIMATE CHANGE: CARBON CAPTURE TECHNOLOGIES AND THEIR ROLES IN THE MITIGATION OF CLIMATE CHANGE.

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ABSTRACT

The escalating rates of carbon dioxide (CO_2) releases into the atmosphere due to industrial and anthropogenic activities need carbon capture technologies (CCTs) as critical partfor climate change mitigation. The elevated levels of CO_2 emissions into the biosphere have varying degrees of impacts on the climate of nations and biodiversity in general. These impacts include global warming, floods, greenhouse effect, acid rain, ozone layer depletion and other secondary effects on both aquatic and terrestrial natural habitats. There are

increasing concernsabout the fast-depleting populations of animal speciesat various stages of existential threats or even extinction. This unfortunate trend, if not adequately addressed could affect the food-chain adversely exposing humanity to grave dangers and threatening longevity of homo sapiens. In our current highly technologized global environment, scientists and engineers are working assiduously on promoting green technologies and evolving projects aimed at preserving the ecological profiles of communities in such manners that the health of our ecosystems is adequately protected legally and technologically through the application of eco-friendly engineering practices. This paper examines one of these engineered solutions known as CCTs, their current state, technological mechanisms, challenges, and ways they could effectively be integrated into broader climate policies by nations to ensure environmental sustainability.

This paper looks to illuminate the readers on the dangers of increasing CO_2 levels, their primary and secondary effects on the ecosystem and environmental sustainability. Despite past efforts directed at addressing environmental hazards by organs of the United Nations (UN) and non-governmental organizations (NGOs), the menace has not abated appreciably compared to the increasing threats to our ecological systems. It has become very necessary to develop technologies that could mitigate the effects of CO_2 releases into the biosphere and promote environmental sustainability for the benefits of both present and future generations, because life revolves around the environment for preservation.

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INTRODUCTION

Background:

Evidence of increasing global CO_2 emissions and their impact on climate change.

The evidence of the adverse impacts of increased CO_2 releasesto the atmosphere on global climate profile can be seen from reports released by renownedresearch bodies and institutions.According to the National Oceanic and Atmospheric Administration (NOAA) Global Monitoring Laboratory report (2023), discoveries from the Mauna Loa climate Observatory station in Hawaiishowed a rise in CO_2 levels in the atmosphere from 315 parts per million (ppm) in 1958 to over 420 ppm in year 2023. This finding asserts the contributive impacts of greenhouse emissions to global warming (Tans & Keeling, 2023). Climate measurements taken by the National Aeronautics and Space Administration (NASA) Earth Science Division in 2023 revealed heightened loss of ice mass in the colder Greenland and

Antarctica regions to the tune of approximately 280 gigatons per year contributing to rising sea levels altering surface reflectivity (albedo) further increasing global atmospheric temperatures (Shepherd, A., et al; 2018). According to Luthi (2008), astudy of ice core samples conducted by the European Project for Ice Coring in Antarctica (EPICA) revealed that human activities associated with industrial revolution are contributing immensely to the excessive release of CO_2 into the atmosphere today compared to the past 800,000 years.

Similarly, the Intergovernmental Panel on Climate Change (IPCC) report (2021) examined the average temperature rise of the earth between the later part of the 19th century (2013-2023) to be about $1.2^{O}C$ ($2.2^{O}F$) leading to heatwaves, droughts and changing weather patterns. Analysis conducted by both IPCC and NOAA in 2023 showed increases in the acidification of global ocean waters due to excessive CO_2 absorption by 30% resulting from proliferation of industrial activities across the globe. The absorption of elevated levels of CO_2 by ocean waters has lowered their pH level to 0.1 units threatening the existence of marine habitats.Furthermore, global sea levels arerising at an average rate of 3.7mm annually resulting in the displacement of global coastal communities due to flooding and altering trade and commerce activities in those settlements.(Doney, et al., 2019).

The World Meteorological Organization (WMO) report (2023) highlighted increasing global incidents and magnitudes of natural disasters such as hurricanes, floods, droughts, wildfires due to increasedatmospheric air moisture contents traceable to warmer global climates resulting in loss of lives, sensitive infrastructural damages and destabilization of the economies of many nations(Coumou, & Rahmstorf, 2012). The World Wildlife Fund (WWF) Living Planet Report cited changes in behaviors and the population distribution of plants and migration of animal species to cooler regions because ofadverse climate conditions caused by CO_2 emissions. This ecological imbalance has caused loss of biodiversity, disruptions ofthe natural balance inecosystems, and ecological degradation ofagriculturalhabitats leading to food shortages and forcing human populations to rely on genetically modified foods produced through biotechnology and its attendant health repercussions on healthy living.

The increasing use of fossil fuels like coal, oil and natural gas for energy supply contributes over 75% of global greenhouse gas (GHG) emissions into the atmosphere. The International Energy Agency (IEA)and BP Statistical Review of World Energy (2023)asserted that use of fossils for energy continues to acerbate CO_2 emissions thereby heightening climate changes. The United Nations Framework Convention on Climate Change (UNFCCC) highlighted the negative impacts of climate change arising from CO_2 emissions on developing nations. The environments of these developing nations are often subjected to environmental degradation through the exploitation of natural resources sometimes applying technologies that compromise environmental stability, increases the pollution of most aquatic habitats, affecting the sustainability of healthy food chains and global food security.

Significance:

There is an urgent needfor scalable and efficient carbon capture solutions to be developed to save our biodiversity and especially the biosphere from further environmental degradation emanating from excessive accumulation of CO_2 in the atmosphere cannot be overemphasized. Applicable carbon capture solutions must be capable of capturing and storing CO_2 from the atmosphere (Klaus, Hans-Joachim & Patrick, 2011). The solutions must be efficient, readily available, affordable, and capable of widerapplication on diverse environmental spectrums. While efforts are intensified to cut down on fossils and invest more into alternative energy sources for power and other industrial energy consumptions, CCTs must be capable of providing substantial reductions both in volumes and levels of concentrations of CO_2 in the air. Technologies that can capture CO_2 and recycle the gas into other safer products would be most beneficial in the effort to create a cleaner world for biodiversity sustainability. Scientists are exploring the use of special materials that could efficiently increase the capture of CO_2 in the atmosphere to help nations achieve global climate commitments (Tech Explore, 2024).The Rice University News (2024) published a research work that led to the creation of an electrochemical reactor capable of reducing energy consumption through direct capture of CO_2 in the air. This reactor provides one of the required solutions for scalable and efficient carbon capture. In addition to CCTs, the World Economic Forum (WEF) in her report published in 2023 said the importance of developing efficient carbon capture and storage (CCS) systems capable of reducing carbon releases and achieving the desired net-zero levels of CO_2 in the atmosphere.In 2024, the Pacific Northwest National Laboratory reported scientific breakthroughs in developing the most cost-effective carbon capture and conversion systems. This underscores the increased global efforts directed towards achieving cleaner environments for biodiversity sustainability.

Scope:

Following the discovery of the associated harmful impacts of excessive CO_2 deposition in the atmosphere and the increasing trend of global warming, scientists and engineers have been developing technologies to mitigate these effects on biodiversity and climate change. But carbon capture technology alone cannot curb the rising trend of ecological disequilibrium resulting to these harmful releases into the biosphere. To achieve a lasting and enduring solution, technology and administrative policies of Governments, regulatory bodies and NGOs must synergize and direct their energies towards the achievement of net-zero carbon emissions. This work examines the current CCTs in use, their applications, strengths, and shortcomings. The paper examines these technologies with the intent to guide the users on ways to maximize their application considering the peculiarity of the environments in question.

Carbon capture scientific and technological initiatives have been developed to mitigate the adverse effects of CO_2 emissions into the atmosphere. These are highlighted below and will be fully discussed in detail after:

- Direct Air Capture (DAC) technologies
- Membrane-Based Carbon Capture
- Cryogenic Carbon Capture
- Metal-Organic Frameworks (MOFs)
- Electrochemical Carbon Capture
- Algae-Based Carbon Capture
- Carbon Mineralization (sequestration)
- Solid Sorbent Technology
- Bioenergy with Carbon Capture and Storage (BECCS)
- Chemical Looping Combustion (CLC)

The detailed description of these CCTs, their advantages and disadvantages in the carbon capturing are provided in table 1 on page 8.

Carbon Capture SolutionsOverview.

Carbon capture technologies can broadly be classified under four major categoriesdepending on the nature of application in use. Carbon capture technologies solutions are effective in removing CO_2 directly from the air, while others are deployed to capture carbon emissions during post-combustion or pre-combustion of fossils. Another approach at managing carbon emissions is by storing them in large geological formations, this process is known as carbon sequestration. The table 1 below provides a summary of these solutions:

Table 1: Carbon capture technologies: Description, advantages & disadvantages

Carbon Capture Category	**Description**	**Advantages**	**Disadvantages**
Direct air capture (DAC)	Removes CO_2 directly from atmosphere using chemical processes	Can reduce atmospheric CO_2 levels, even from diffuse sources like vehicles and planes. Modular and scalable, can be installed anywhere. CO_2 can be reused (e.g., in fuels, beverages, or enhanced oil recovery).	High energy consumption, especially for heat and electricity. Expensive compared to other carbon capture methods. Requires renewable energy to ensure the process is sustainable.
Post-combustion technologies	Capture CO_2 from the exhaust gases of industrial processes or power plants.	Can be retrofitted to existing infrastructure (e.g., coal or gas power plants). Mature technology, widelydeployed in industries like natural gas processing.	High energy requirement for solvent regeneration. Large volumes of chemicals(e.g., amines) are needed,which can degrade over time. Potential environmental risks from chemical spills or waste.
Pre-combustion technologies	Removes CO_2 from fossil fuels before combustion, typically by converting fuel into hydrogen and CO_2 (e.g., gasification).	High CO_2 capture efficiency (up to 90%). Produces hydrogen, a clean fuel for energy or industry. Suitable for new power plants and industrial facilities.	Cannot be easily retrofitted to existing plants. Expensive at setup and maintenance. Complex processes requiring skilled operators.
Cryogenic carbon capture	Uses extremely low temperatures to condense and separate CO_2 from flue gases.	High capture rates (>95%). No use of chemicals, reducing waste and environmental risks. Can produce purified CO_2 for industrial use.	High energy requirement to achieve cryogenic temperatures. Expensive to run at scale. Limited applicability insmaller-scale facilities.
Carbon mineralization(carbon sequestration)	Converts CO_2 into stable minerals (e.g., carbonates) by reacting it with	Permanent CO_2 storage, preventing re-release into the atmosphere. Can be combined with	Limited to specific geological conditions. Slow reaction rates unless perfected.

	naturally occurring rocks.	renewable energy sources. Utilizes abundant natural resources like basalt rocks.	Transportation of CO_2 to mineralization sites can be costly.
Bioenergy with Carbon Capture and Storage (BECCS)	Combines biomass energy production with carbon capture, resulting in negative emissions.	Achieves negative emissions by removing CO_2 from the atmosphere through photosynthesis and storing it underground. Utilizes renewable biomass as a fuel source.	Competition for land use with agriculture and ecosystems. Transporting and processing biomass can produce added emissions. High implementation and operational costs.
Algae-Based Carbon Capture	Uses algae to absorb CO_2 through photosynthesis and convert it into biomass.	Produces biomass that can be used as biofuel, fertilizer, or animal feed. Compact systems suitable for urban areas. Low energy requirements compared to chemical methods.	Limited scalability compared to industrial carbon capture technologies. Requires sunlight and water, which may not be readily available. Sensitive to environmental conditions like temperature and light levels.
Chemical Looping Combustion (CLC)	Uses metal oxides to combust fuels while capturing CO_2 as a byproduct.	High thermal efficiency with near-complete CO_2 capture. Avoids mixing combustion gases, simplifying separation of CO_2.	Still at a pilot stage, with limited commercial deployment. Prohibitive costs associated with the production and recycling of metal oxides. Complex process requiring skilled operators.
Membrane-Based Carbon Capture	Uses membranes to selectively filter CO_2 from other gases.	Compact and easy to integrate into existing systems. Energy-efficient compared to chemical processes. No chemical solvents needed.	Limited to applications where gas streams have high CO_2 concentrations. Membrane fouling or degradation can increase maintenance costs. Requires high-pressure gas streams for best performance.
Ocean-Based Carbon Capture	Removes CO_2 from seawater, reducing its atmospheric exchange.	Potentially massive ability, as oceans are the largest natural CO_2 sink. Enhances natural carbon sequestration processes.	Environmental impacts on marine ecosystems are not fully understood. Limited by the availability of materials like olivine (for mineralization). Requires significant research and development to scale.

In designing an efficient and affordable carbon capture technology. It is germane that institutions and agencies consider the merits and demerits highlighted in the table above and juxtaposed these with other factors such as regulatory policies, economic considerations, traditional and religious values capable of affecting the implementation of decisions made by policy makers.

Benefits and Application of Carbon Capture Technologies in Climate Mitigation

The application of carbon capture technologies helps to reduce carbon emissions, creates enabling economic opportunities, fosters technological innovation, promotes environmental protection, economic growth, biodiversity preservation and sustainability. The benefits of the application of CCTs include:

Environmental benefits

Reduction of greenhouse gas emissions:CollectsCO_2 emissionsgenerated due to the combustion of fossils in industries thereby preventing harmful emissions from migrating freely into the atmosphere and contributing to climate change.

Support for carbon-neutral energy: Promotes the production of cleaner energy from fossil fuels while reducing emissions, this happens during the transition to renewable energy sources.

Mitigation of climate change impacts: Reduces the concentration of greenhouse gases like CO_2 in the atmosphere limiting global warming.

Protection of ecosystems: The lowering of CO_2 emissionsreduces ocean acidification, hence protects marine ecosystems and biodiversity.

Economic benefits:

Creation of New Markets:CO_2 is used in enhanced oil recovery (EOR), synthetic fuels production, and as a feedstock in chemical manufacturing, thus creating valuable economic opportunities.

Job creation: New jobs are created during the development, construction, maintenance, marketing, and operations of carbon capture facilities.

Support for hard-to-decarbonize industries: Useful in cement, steel, and petrochemical sectors during production in reducing emissions.

Carbon Credit Revenue: Companies earn carbon credits through capturing emissions, and trade it in carbon markets for revenue.

Policy and regulatory benefits

Alignment with Climate Goals: Helps nations to achieve their national and international targets on emission reduction, such as the Paris Agreement.

Flexibility for Policymakers: Provides near-term solution for reduction of emissions while nations scale up the use of renewable energy technologies.

Enhanced Energy Security: Does not inhibit the continued use of domestic fossils as fuel but reduces their environmental impact.

Social and global benefits

Improved air quality: Reduces the concentration carbon emissions in the air thereby improving public health.

Global climate leadership: Countries usingcarbon capture technologies prove leadership commitment on global climate control commitments.

Just Transition for Workers: Supports a gradual transition for workers in hydrocarbon industries through the infusion of carbon capture into their facilities.

Technological innovation

Circular economic advancement: Promotes innovation using captured CO_2 as a resource, especially in carbon-to-value technologies.

Scaling of negative emissions technologies: Together with bioenergy (BECCS) or direct air capture (DAC), it can achieve negative emissions, actively removing CO_2 from the atmosphere.

Long-term sustainability

Support for Net-zero goals: Contributes to achieving net-zero carbon emissions by complementing renewable energy deployment and energy efficiency initiatives.

Scalability and adaptability: Deployable at various scales and adaptablefor use invarying industrial processes.

Carbon Capture technologies, Regulatory Policies and Economics Factors

The interplay between technology, regulatory policy and economy is crucial in making the decision for the type of carbon capture system to develop. For instance, robust carbon pricing incentivizes investments, while infrastructural development policies can reduce logistical costs. The design of an effective carbon capture technology must consider these factors in mind and ensure that they are properly aligned with economic incentives and regulatory requirements, increasing their feasibility and adoption.

Policy Factors

Policies, regulations, and guidelines drive implementation. Innovation comes with a price and its success can either be achieved or deterred by the feelings of the end-users. Technology manufacturers must therefore include in their strategy the requirements for proper social integration and education to promote acceptability of new carbon capture technologies.

Regulatory Framework

Policy factors to be considered include existing local and international regulatory frameworks, and the need to align the desired technology with national or regional climate control targets such as the Paris agreement on emission reduction. The technology should receive helpfrom carbon pricing mechanisms such as carbon taxes or cap-and-trade systems. While considering carbon sequestration technologies, care should be taken to meet all permitting requirements for carbon transportation and storage in compliance with applicable environmental and safety regulations.

Incentivization and subsidization of Carbon capture technologies

Policies designed to provide financial incentives such as tax credits or direct subsidies to make carbon capture technology economically practical in the short term are good motivations for more research into new CCTs solutions. Researchers can explore the availability of special grants or low-interest loans for research and development (R&D) activities in carbon capture technologies.

International Cooperation and collaboration

Carbon capture technologies should be designed to accommodate varying international standards to ease cross-border collaboration, especially among multinational companies. International agreements should encourage technology transfer to increase the proliferation of environmentally friendly solutions that will mitigate the challenge of climate change.

Public Acceptance

Policies should be designed to build public trust in carbon capture technologies throughconsultation, campaigns, and outreach programs. There is global high level public awareness and bias about the safety and environmental impacts of modern technologies which must be adequately communicated. Public receptibility, acceptability and collaboration onmodern technology is fundamental to its success in application and can be achieved through good private-public partnerships or Government joint venture initiatives with entrepreneurs.

Infrastructure-related Policies

Enabling infrastructural facilities to efficiently transport CO_2 such as pipelines, storage tanks should be in place for proper scalability to be achieved. It is important to install systems that will be efficient, dependable, and safe to avoid loss of containment with potential of severe consequences on biodiversity. Policies designed formandatory retrofitting of existing industrial plants with carbon capture systems incorporated in their operations should be promoted.

Global Equity Considerations

Carbon emissions often present localized colorations but the long-term impacts could be widespread, profound, and devastating. Develop nations of the world can help developing countries to gain access to technology as part of the collective global effort to enhance carbon capture and mitigate against climate change.

RECOMMENDATIONS:

i. Research work into the development of hybrid and scalable carbon capture technologies for low-income earners should be intensified. This has become necessary because of the proliferation of small and medium scale enterprises (SMEs) in developing economies that depend solely on the burning of fossils fuels for their power requirement. The use of power generators arising from the shortage of power from the national grid increases CO_2 emissions into the atmosphere.

ii. Developing countries should investigate carbon capture technologies properly and ensure that they are environmentally friendly before buyingthem for their industrial development and economic needs. Policy makers should design laws that will prevent importers from bringing into the country obsolete technologies that worsen atmospheric pollution. Policies to deter countries from becoming dumping-grounds for environmentally unfriendly technologies should be enacted and enforced.

iii. There must be a balance between economic development and environmental considerations to promote biodiversity sustainability. The developed economies should eradicate or upgrade technologies that are not environmentally friendly beforetransferring them to developing nations. The standards organizations of countries should enforce sanctions against companies and organizations that import harmful technologies capable of causing environmental damages to their ecosystems.

iv. Governments and investors engaging in foreign direct investment (FDI) should conduct pre-investment surveys for the final destinations of their technology (recipient nations) to find the proper carbon capture solution or combination needed so that the global emissions targets could be achieved.

v. Governments should start policies and guidelines that would cut down on the use of fossils as energy sources to power their industrial hubs. More funding in research for alternative energy sources like renewable energy and hybrid gradual phasing out of carbon emissions into the air with its accompanying impacts on the environment.

vi. The industrializednationsshould put mechanisms in place to meet their commitments to eradicating carbon emissions. Commitments made during climate control conventions like the Paris agreement to eradicating global warming using green technology if fulfilled will reduce the adverse effects of excessive CO_2 releases into the atmosphere.

vii. Governments can reduce CO_2 concentration in the atmosphere through the implementation of deliberate policies designed to restore ecologically damaged habitats to their original states. One way to achieve CO_2 reduction would be to encourage afforestation, discourage deforestation, bush-burning and other human activities that are inimical to biodiversity sustainability.

viii. Over the years, perennial incidents of wildfires, tornadoes, hurricanes, earthquakes, and other natural disasters have shifted the ecological equilibrium in nations. Most habitats have lost their originality due to poor industrial waste management processes and procedures. There is therefore an overarching need for Governments to educate the citizenry about the dangers of such practices and promote policies designed to curb the proliferation of carbon emissions.

Conclusion

One of the most perturbing concerns of CO_2 releases into the atmosphere is that it becomes exceedingly difficult if not impossible to control the direction and final destinations these gases migrate to. Unfortunately, there is only one atmosphere covering the biosphere. The adverse impacts of increasing CO_2 emissions on biodiversity cannot be overemphasized.

Considerable progress can be made at reducing carbon emissions throughinternational collaboration in promoting green energy, cutting down on carbon emissions using CCTs and other political and administrative solutions. The environment has a way naturally restoring itself when not overstretched beyond threshold limits. The continuous degradation of the ecosystem portends great dangers to biodiversity sustainability. In the quest for a healthier environment, all stakeholders must prove commitment to promoting environmentally safe practices to guarantee a safer future for upcoming generations. Governments need to reappraise the funding for research and development (R&D) initiatives Universities, NGOs, and private-public partnerships to invest in carbon capture technology. In addition, an effective legal framework and political will to confront this challenge head-on should be encouraged. The institutionalization of a well-crafted energy transition policy that will ensure a gradual elimination of obsolete technologies contributing to CO_2 emissions into the atmosphere and replacing them with those friendly to biodiversity sustainability over time would be beneficial in curbingclimate change challenges. Efficient technologies designed for carbon capture should be scalable, affordable, and capable of being deployed widely.

In parts of the globe, there are cultural and religious biases that limit the implementation policies and programs designed to improve biodiversity preservation. The effort to achieve net-zero CO_2 emissions is collaborative requiring future evaluation of these cultural and religious biases and their impacts on achieving biodiversity protection and sustainable economic growth of nations. The environment sustains life, and the protection of biodiversity has multifarious benefits for future generations.

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