Climate Change: Mitigation Strategies and Need for Adaptation

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ABSTRACT

Life on Earth is under increasing threat of anthropogenic greenhouse gas (GHG) emissions. The anthropogenic activities have unequivocally caused about 1.0°C of global warming above the pre-industrial level, and it is expected to increase further and reach 1.5°C between 2030 and 2052 if the existing emission rates persist. This perilous change in the Earth's climate is causing uncontrollable wildfires, heatwaves, floods, droughts, storms, destruction of agricultural crops, biodiversity loss, and destruction of vulnerable ecosystems. If the current trend continues, Earth will become unhabitable and a hostile place to live. It becomes necessary to call for effective climate change mitigation strategies and adaptation mechanisms. In 2015, an internationally legally binding treaty called the Paris Agreement was adopted to tackle climate change and strengthen the global response to reduce GHG emissions. The agreement aims to hold the increase in global surface temperature to below 2°C above pre-industrial levels by 2100 and pursue efforts to limit the increase to 1.5°C. The aim of this study was to theoretically determine how erratic climate patterns are threatening and deteriorating the sustainability of diverse sectors worldwide. The article reviews some key climate change mitigation strategies such as conventional mitigation (reducing fossil-based CO_2 emissions), negative emissions (carbon dioxide removals), and radiative forcing geoengineering (altering the Earth's radiative energy budget to stabilize or reduce global temperatures). The significance of the synergy between climate change mitigation and climate change adaptation has also been discussed in this article.

Keywords: Climate change mitigation, Greenhouse gas emissions, Negative emissions technologies, Radiative forcing geoengineering, Climate adaptation strategies

Introduction

Earth's temperature has risen by an average of 0.11°F (0.06 Celsius) per decade since 1850, and this increased warming is taking place at a rate not witnessed in the past 10,000 years.[1]

Notably, 2023 was the warmest year since temperature records at a global level started in 1850 by a wide margin. It was 2.12°F (1.18°C) above the 20th-century average of 57.0°F (13.9°C) and was 2.43°F (1.35°C) above the pre-industrial average (1850–1900).[1]

These rising temperatures result from increased greenhouse gas (GHG) emissions due to natural systems, human activities, and industrialization causing erratic weather patterns or climate change.

GHG emissions prevent heat trapped by the Earth's atmosphere be reflected to space, and this has been the main driving force behind global warming. Natural systems that increase GHG emissions include forest fires (change in global carbon budget), permafrost, wetlands, earthquakes (Rn, CO_2, CH_4, and CO are emitted from active fault zones), oceans, mud volcanoes, and volcanoes,[2] while anthropogenic activities are predominantly related to energy production (burning of fossil fuels), industrial activities, and those related to forestry, land use, and land use change (e.g., conversion of forest into agricultural land).[3]

The evidence for rapid climate change is compelling:

- Sea level rise: Sea level is rising and will continue to rise this century at increasing rates. Global sea level rose about 6.7 inches/17 cm in the last century.[4]
- Global temperature rise: Global temperatures are already up 1.1°C and most of this warming has been happening since the 1970s. The United Nations Environment Programme's (UNEP) 2021 Emissions Gap Report shows that with the present nationally determined contributions and other firm commitments globally, we are on track for a calamitous global temperature rise of around 2.7°C by the end of the century.[5]
- Warming oceans: Warming ocean temperatures now account for 40% of the global rise in sea levels. The oceans have absorbed much of this increased heat (90% of the excess heat generated as a result of climate change has ended up in the sea), with the top 700 m of ocean showing warming of 0.302°F since 1969.[6]
- Shrinking ice sheets: The Greenland and Antarctic ice sheets have thinned. NASA's Gravity Recovery and Climate Experiment recorded a rate of 150–250 km^3 (36–60 cubic miles) loss of ice for the period between 2002 and 2006 while Antarctica for the period between 2002 and 2005 recorded a loss of 152 km^3 (36 cubic miles) of ice.[7]
- Declining Arctic Sea ice: The area as well as the thickness of the Arctic Sea ice has significantly reduced in the last few decades only due to rising temperatures.[8]
- Glacial retreat: Due to the rise in global temperatures, glaciers are retreating at a very fast speed almost everywhere across the globe, including in the Alps (central Europe and tropical and subtropical regions of South America and Africa), Himalayas (Asia's Hindu Kush), Andes (found along the border between Chile and Argentina), Rockies (below Taylor and Tyndall glaciers), Alaska, and Africa.[9]

- Ocean acidification or osteoporosis of sea: Since the beginning of the Industrial Revolution, the acidity of surface ocean waters has increased by about 30%. The amount of carbon dioxide absorbed by the upper layer of the oceans is increasing by about 2 billion tons per year.[10]

GHG Emissions Overview

The gases that are termed "greenhouse gases" according to the Kyoto Protocol including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases such as perfluorocarbons, hydrofluorocarbons, and sulfur hexafluoride (SF_6) are widely discussed in the article.[11]

As per the emissions gap report by UNEP in 2019, total GHG emissions in 2018 were around 55.3 $GtCO_2e$, out of which 37.5 $GtCO_2$ have been contributed by fossil fuel burning and industrial activities. Evidence suggests an increase of 2% in both total global GHG and fossil CO_2 emissions in 2018, as compared to a yearly increase of 1.5% over the past 10 years. CO_2 emissions generated from fossil fuel burning have increased in recent years and the key reason is an increase in energy demand due to the growing population.[12]

Furthermore, emissions related to land use change amounted to 3.5 $GtCO_2$ in 2018. Combined emissions from both land use and fossil fuel burning accounted for approximately 74% of the total global GHG emissions. According to scientists, another GHG, methane (CH_4), concentration in the atmosphere has almost doubled over the past 200 years. The emission rate of CH_4 recorded in 2018 was an increase of 1.7% as compared to an annual increase of 1.3% over the past 10 years. Another significant GHG, nitrous oxide (N_2O) emissions (the third most important human-made GHG), mainly contributed by agricultural and industrial activities, recorded a surge of 0.8% in 2018 as compared to a 1% annual increase over the past decade.[12]

In 2018, a significant increase in the percentage of fluorinated gases was observed, rising from 4.6% to 6.1% annually over the last decade.

For reference, a study published in the Intergovernmental Panel on Climate Change (IPCC) earlier this year indicated that due to human activities, there is an estimated 1.0°C of global warming above the pre-industrial level.[12]

It is stated that global warming can reach 1.5°C if the emission rates remain the same in the future period between 2030 and 2052 according to IPCC.[13]

Drivers of Climate Change

Here are the primary drivers of climate change.[14]

1. Human Activities

a. *Burning of Fossil Fuels:*
Coal, oil, and natural gas: Burning of these fuels for the generation of electricity, heating, and transport emits high quantities of carbon dioxide (CO_2) and other GHGs.

b. *Deforestation and Land Use Changes:*
Clearing forests for agriculture or urban development: Trees sequester CO_2 and deforestation reduces this ability, and emission space of trees is also eliminated by felling the trees.

c. *Agriculture:*
Methane from livestock: GHGs like CH_4 released by ruminant animals such as cows and cattle during digestion.
Rice paddies: Floated rice fields also release methane.
Nitrous oxide: Current practices of using fertilizers and other common agricultural practices emit nitrous oxide (N_2O), which is one of the most effective GHGs.

d. *Industrial Processes:*
Cement production: This process, which binds together sand and rock to form concrete, releases CO_2 when calcium carbonate is thermally decomposed producing lime and carbon dioxide.
Chemical and manufacturing industries: Discharge different GHGs in the production processes.

e. *Waste Management:*
Landfills: Organic waste undergoes the anaerobic process without air in the landfill to generate methane.
Wastewater treatment: Releases GHGs like methane and nitrous oxide and a small amount of carbon dioxide.

2. Natural Processes

a. *Solar Radiation:*
Variations in solar output: Fluctuations in the volume of solar irradiance may alter world climate temperatures. Still, this has a considerably lesser effect as compared to the role played by humans.

b. *Volcanic Activity:*
Eruptions: A huge amount of CO_2, ash, and aerosols are released from the eruptions.

c. *Natural Carbon Cycle Variations:*
Ocean–atmosphere exchanges: Oceans regulate CO_2 in the atmosphere (oceans absorb and release CO_2) by both natural cycles and human activity.
Biological activity: Plant growth and decay also prove to play a crucial role in relation to carbon.

3. Feedback Mechanisms

a. *Albedo Effect:*
Melting ice: It lessens the Earth's albedo or reflectivity, thereby increasing the amount of energy trapped by the planet, and thus, the increase in temperature.

b. *Permafrost Thawing:*
Release of methane: The permafrost in the Arctic region is caused to thaw, and when it does it releases stored methane, a potent GHG into the atmosphere.

c. *Water Vapor:*
Increased evaporation: Increase in temperatures increases the amount of water vapor in the

atmosphere. Water vapor is another potent GHG that increases the rates of warming.

Climate Change Impacts, Risks, and Vulnerabilities

A proper understanding of the extremity of damage that climate change inflicts on both natural and human systems, and the related threats and risks, is the key to grasping the current state of the climate crisis. The secretary of the United Nations Climate Change Secretariat has published a report on the changes in the indicators of climate; this comprises the temperature, precipitation, sea level rise, ocean acidification, and extreme events. Some of the climate affectations that were reported included droughts, floods, hurricanes, severe storms, heat waves, wildfires, cold waves, and landslides.[15]

A review of sources such as the Centre for Research on the Epidemiology of Disasters similarly reveals that in 2018 the world faced climatological/meteorological disasters including 315 events. These related to 16 instances of drought, 26 of heat or cold, 127 of flooding, 13 of landslides, 95 of storms, and 10 of wildfire.

In 2018, natural disasters had a significant impact, resulting in the loss of approximately 68 human lives due to floods and storms. The financial toll was staggering, with total losses amounting to $131.7 billion. The breakdown of these losses includes $70.8 billion from storms, $19.7 billion from floods, $22.8 from wildfires, and $9.7 billion from droughts, which together accounted for 93% of total losses.[16]

Furthermore, several climatic hazards contribute to the vulnerability of many sectors in most countries. These include rising temperatures, fluctuations in rainfall, alterations in seasonal patterns, changes in disease patterns, desertification, oceanic effects, and the deterioration of soil and coastal areas. The sectors most at risk from climate change are food, water, health, ecosystem, human habitats, and infrastructure. It is important to note that Africa is the region most vulnerable to climate variability.[17]

It is also necessary to stress that such sectors are interrelated, and so are the consequences.

The World Economic Forum's Global Risks Report 2020, which is its 15th edition, highlighted numerous climate realities and established regions that are gravely impacted.

Critical issues such as food and water security are significantly affected by climate change. Frequent relocations are anticipated due to harsh weather and disasters resulting from rising sea levels. This situation is likely to intensify geopolitical rivalries as nations seek to exploit resources, particularly in coastal areas and border regions.[18]

An assessment included in the special report from the IPCC highlighted the effects and expected vulnerabilities associated with temperature increases of 1.5°C and 2°C.

We are likely to reach a temperature increase of 1.5°C within the next three decades. A rise in warming levels beyond this point would significantly increase risk effects. For instance, water stress would pose double the risk under a 2°C increase compared to a 1.5°C rise. Under the 2°C scenario, it is projected that the number of people affected by fluvial floods will increase by 70% compared to the 1.5°C scenario, especially impacting regions in the United States, Europe, and Asia. Additionally, species extinction in terrestrial ecosystems would rise dramatically under the 2°C level compared to a 1.5°C increase.[19]

We can conclude that the world is in a current state of climate emergency.

Are There Any Technologies that Could Be Utilized to, for example, Predict Climate Changes/Progression?

The scientific community has at its disposal a number of postmodern technologies, with which climate changes are predicted and their further evolution is tracked, in greater detail and with greater precision. Some of these include:

1. Machine Learning and Artificial Intelligence: Climate change is being forecast based on data gathered from automated weather stations, satellites, and other devices using machine learning algorithms. It is capable of analyzing past records and provides estimates of future temperatures or rainfall, abundance, and possibility of storms or droughts, among others.
2. Climate Modeling Supercomputers: Advanced computation enables the modeling of climate processes within Earth's climate framework due to its ability to allow for complex calculations. These supercomputers process the data of such models through the system and provide estimates of climate conditions for seasons, centuries, and any time in between.
3. Remote Sensing via Satellites: Communication satellites equipped with sensors measure global climate aspects such as sea surface temperatures, ice conditions, GHG levels, and vegetation health. These measurements are essential for observing and analyzing climate patterns and predicting current weather conditions.

Internet of Things (IoT) Sensors and Environmental Monitoring Networks: The IoT involves a network of sensors that collect environmental data from the local environment including temperature, moisture, humidity, air, and soil quality. This detailed information is invaluable for observing microclimates and comparing regional climate changes.

1. Geographic Information Systems (GIS): Technological innovation in GIS mapping and analyzing climatic information at the geographical reference to indicate how climate changes affect specific locations. Geo-informatics can be employed to assess elements of climate change such as deforestation, urban sprawl, rising sea levels, and many others.

2. Quantum Computing (Emerging): Though it is still in the embryonic state, quantum computing surpasses the possibilities of classical computing profoundly. It is suggested that the quantum models may help broaden our knowledge of chaotic climate occurrences that currently make it challenging to make a precise and elaborate climate forecast.

These technologies are critically important to generate accurate climate predictions and feed information to decision-makers, climate-related researchers, and scientists who work on adaptation and mitigation.

Global Climate Action

The United Nations Framework Convention on Climate Change, or UNFCCC, was signed in 1992. It came into force in 1994. Since then, UNFCCC has been the leading actor, and a much-needed enabler, of climate action in the world. The major goal of the convention is the prevention of any adverse effects on the climate system through the enhancement of the stability of GHG concentrations in the atmosphere. The basic obligations to all the participants were described by the convention, although the main tasks such as national measures, controlling anthropogenic emissions by sources, and improving the sinks for GHG were assigned to developed countries. It is presently signed by 197 nations.[20]

The UNFCCC meeting of the parties, COP-21, was held in Paris in 2015 with the adoption of the Paris Agreement, which came into force in 2016. The Paris Agreement further integrated other objectives, actions, stronger conformity, and disclosure necessities together with support structures to the climate change-fighting framework that was already in place. The purpose of the agreement is to reduce the average global temperature to 2°C above the pre-industrial level by the year 2100 and pursue efforts to limit the increase to 1.5°C.[21]

At COP-3 in 1997, held in Japan, the Kyoto Protocol was adopted, which came into operation in 2005. The Kyoto Protocol made provisions for the emission reduction commitments for the developed countries where the commitment period schedule was made for 5 years between 2008 and 2012. It presented all related policies, monitoring and reporting systems, and the framework established three market-based mechanisms for those purposeful targets. It proposed two project-based instruments: the clean development mechanism and the joint implementation mechanism.

The UNFCCC COP-21 was carried out in Paris in 2015, where Paris Agreement was adopted, which came into force in 2016. The Paris Agreement introduced more goals, commitments, stronger compliance, and reporting requirements into the existing structure to combat climate change. The key objective of the Paris Agreement is to strengthen the global climate response by ensuring the global temperature rise well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C.

Economic Implications of Climate Change

Climate change is already impacting us, and its physical effects are evident. If we do not come together to address this issue, the damage to human well-being and the economy will worsen and become increasingly expensive to repair.

Human activities are contributing to more frequent and intense hurricanes, heatwaves, and other extreme weather events that are causing loss of life and making life difficult for people around the world. The latest IPCC report, published in 2021 urges us to take action.

In 2021, a severe heatwave lasting 4 days caused temperatures in the Pacific Northwest to reach an unprecedented high of 46.6°C, resulting in the deaths of more than 200 people. Additionally, Western Europe, Ghana, Niger, India, Afghanistan, and South Sudan experienced extreme floods, while Central Asia faced drought and heatwaves.

The following is the breakdown of how climate change is impacting economies on multiple levels:

1. Physical infrastructure destruction—Extreme weather events such as floods, hurricanes, droughts, and wildfires are causing significant damage. These will put tremendous pressure on insurance premiums for consumers and businesses. Increasing sea levels are increasing the risk of damaging coastal infrastructure.
2. Impact on agriculture and food security—Increasing temperatures and erratic weather patterns are damaging crops and resulting in increased food prices and volatility.
3. Supply chain disruptions—Adverse events like floods and droughts are disrupting food supply chains and impacting global markets for rice, corn, and the like.
4. Health costs—Increasing temperatures and climate change also increase the spread of diseases like malaria and dengue, particularly among vulnerable populations. This puts a strain on healthcare systems.
5. Energy and utility costs—This includes increasing demand for cooling, load shedding, power outages, energy supply disruptions, and increasing energy costs.
6. Labor productivity and economic output—This causes reduced productivity leading to lower economic output. There are disproportionate economic challenges from climate change for developing nations. This heightens global inequality and puts extra burden on these economies.
7. Market instability and investment risks—Climate change is increasing financial risks affecting asset values and uncertainty in global markets, especially for enterprises that are reliant on fossil fuels or those in vulnerable geographic areas. Globally, investors prefer and are interested in green investments, which places strain on industries with high carbon footprints.

8. Insurance industry impact—This includes higher payouts and premiums due to climate-related disasters.
9. Adaptation and mitigation costs—There continues to be limited investment in resilient infrastructure, mitigation, and adaptation technologies, which is increasing costs to address recovery efforts in the advent of any adverse weather event.

Climate change has a very broad and direct impact on the economy through a range of sectors including the built environment that includes structures and roads and agriculture that determines our supplies of food, health, and energy, among other sectors. The opportunity costs of inaction may well outweigh the costs oftentimes linked to active climate change policies and investment. Being comprehensive about climate change has potential gross long-run economic opportunities and enhanced robustness that could form the foundation of strengthening a superior future.

Climate Change Mitigation Strategies

Some of the climate change mitigation strategies include conventional mitigation (reducing fossil-based CO_2 emissions), negative emissions (CO_2 removals), and radiative forcing geoengineering.

Conventional Mitigation Technologies

Conventional mitigation technologies play a crucial role in reducing GHG emissions and mitigating climate change. Here's a brief overview of each technology and its application in different sectors:

1. **Renewable Energy**
   - Power Sector: This sector is usually known and classified as wind energy, solar energy, hydro energy, and biomass energy. These sources of electricity production do not produce GHGs during the electricity generation process.
   - Transportation Sector: Renewable energy can be used in an indirect or direct manner, whereby the former can be derived from renewable electricity sources apart from hydrogen fuel and the latter is evident from electric cars.[22]

   In 2022, renewable energy supply from hydro, ocean, geothermal, solar, and wind rose by close to 8%, meaning that the share of these renewable energy technologies in total global energy supply increased by close to 0.4 percentage points, reaching 5.5%.[23]
2. **Nuclear Power**
   - Power Sector: Nuclear power stations do produce consistent and large amounts of electricity with a comparatively very small percentage of GHGs.

   Today there are about 440 nuclear power reactors operating in 32 countries, with a combined capacity of about 390 GWe. In 2023, these nuclear power reactors generated about 2602 TWh, about 9% of the global electricity. Many nations are expanding or developing their nuclear power programs.[24]
3. **Carbon Capture and Storage and Carbon Capture and Utilization**
   - Industrial Sector: Carbon capture and storage (CCS) technology captures carbon dioxide emissions from industrial processes (like chemical reactors, cement, and steel manufacturing) and stores it beneath the Earth. CCS involves using captured carbon dioxide in several applications like making synthetic fuels or materials.

   In 2023, the announced capture capacity for 2030 increased by 35%, while the announced storage capacity rose by 70%. This brings the total amount of CO_2 that could be captured in 2030 to around 435 million tons (Mt) per year and announced storage capacity to around 615 Mt of CO_2 per year.[25]
4. **Fuel Switching**
   - Power Sector: Replacing "intense" sources of fuel such as coal with "less-intense" ones such as natural gas as the latter releases more unit CO_2 emissions per produced energy.
   - Industrial Sector: Switching to lesser carbon-emitting fuels such as natural gas or hydrogen as opposed to heavy carbon-emitting fuels such as coal or oil.
5. **Efficiency Gains**
   - Building Sector: Adoption of proper designs, appliances, and heating/cooling systems with the view of using minimal energy.
   - Transportation Sector: Reducing automobile usage efficiency, supporting available means of transportation, and non-mechanized means of transport—cycling and walking.
   - Industrial Sector: Increasing the effectiveness of the processes of production and eliminating unnecessary energy consumption in manufacturing processes.

These technologies, as well as techniques, are compulsory to ensure sustainable development and minimize the effect of human activities on the environment (Figures 1–3).

Negative Emissions Technologies

Negative emissions technologies stand for the treatments for the removal of carbon dioxide or other GHGs from the environment and decrease the quantity of GHGs available in the atmosphere with the primary intent of partly or fully undoing the effects of climate change. The following are some of the primary negative emissions technologies currently being researched and implemented.[26]

1. **Afforestation and Reforestation**

   Afforestation: Sowing trees on the land that has provision of trees for a small amount of time. Reforestation: Sowing of new trees on land that

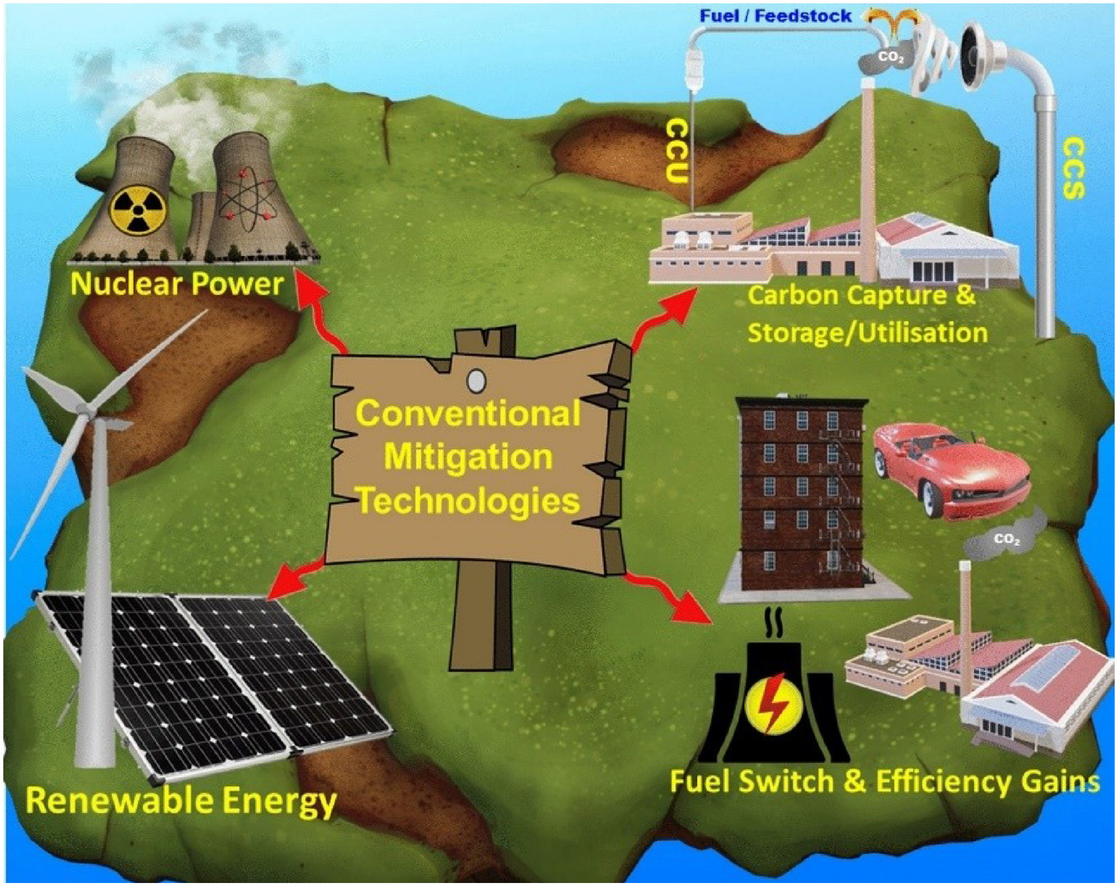

Fig 1 | Major decarbonization technologies like renewable energy, nuclear power, carbon capture and storage (CCS) as well as utilization (CCU), fuel switching and efficiency gains which focus on the reduction of CO_2 emissions related to the supply and demand sides of energy.

Source: Fawzy, S., Osman, A.I., Doran, J. et al.[18]

has been recently converted to barren land after deforestation.

Afforestation is a biogenic negative emissions technology that has a significant contribution to the practices of climate change abatement. Afforestation can be applied either in the creation of new slopes that were, hitherto, without trees or in the restoration of previous forest areas that have been degraded through factors such as deforestation or other related factors and is known as reforestation.

Regarding technology readiness, afforestation and reforestation activities have been practiced globally and included in the climate change policies as a part of the Kyoto Protocol's clean development mechanism program since the 1990s.

2. **Bioenergy with CCS**

This includes the cultivation of plants and crops, their conversion into energy, trapping the released CO_2, and its sequestration.

Bioenergy with CCS, abbreviated as BECCS, is among the most debated NETs in the literature. The IPCC, within the various assessments for climate change, heavily leaned on bioenergy CCS as one of the pathways toward reaching temperature targets. The technology is in fact a combination of biopower and CCS technologies that were posted earlier. Regarding the idea of the technology, thus, it should be said that the mechanism is rather simple. Carbon dioxide is sequestrated through photosynthesis during the growth of the biomass feedstock but the carbon in biomass is released through combustion for energy production. The emitted CO_2 during burning is captured and sequestrated in appropriate geological structures.

This technology can also help in lowering the concentrating capacity of GHGs especially CO_2 out of the atmosphere. In the aspect of technology maturity, those detailed bioenergy technologies are known to be more or less ready; on the other hand, CCS is relatively less ready.

Hardcopy storage integrity and leakage are the main areas of technology risk.[27]

3. **Direct Air Capture**

Direct air capture ((DAC) technologies extract carbon dioxide directly from the atmosphere for storage or utilization. To date, 27 DAC plants have been commissioned worldwide, capturing almost 0.01 Mt CO_2/year.[28]

4. **Soil Carbon Sequestration**

Soil CCS is defined as the storage of atmospheric carbon dioxide through the modification of the existing land use practices in order to enhance the levels of carbon present in the soil. This in turn depends on the number of inputs such as residues, litter, roots, and manure, and the carbon losses through respiration, which are affected by soil disturbance. Management practices insert more carbon into the soil and/or decrease the amount of carbon that is released back into the atmosphere. Literature shows that the sequestration of carbon within the soil increases the fertility and health of the soil as well as the productivity of the crops since it boosts the accumulation of organic carbon. The literature looked at various land management practices that enhance soil carbon storage, which include cropping systems intensification and rotation, zero tillage and conservation tillage, nutrient placement, mulching and crop residues and manure incorporation, biochar and organic fertilizers, and water management.

5. **Ocean-Based Carbon Removal**
   Ocean fertilization as a means for removing carbon dioxide from the atmosphere involves the dropping of nutrients, the macro including phosphorus and nitrates and the micro which includes iron on the upper surface of the ocean in order to stimulate biological activity. Phytoplankton is another topic related to the idea of sequestration in oceans; these are microscopic organisms that are present in the surface layer of the ocean. The isolated CO_2 in the form of organic marine biomass floats to deep waters naturally; this process is called the biological pump. Nevertheless, it must be understood that this flow downward is to some extent compensated along the vertical by the carbon respiration of oceanic life. Like plants do on the solid land, phytoplankton harnesses light, carbon dioxide, and nutrients to produce food matter. In the natural system, nutrients would be in the ocean in many forms via death and decomposition of marine animals. Therefore, the level of marine production depends solely on the availability of recycled nutrients in the sea. The concept of ocean fertilization lies in the replenishment of nutrients to enhance the extent of biological processes whose outcome adds up to the CO_2 uptake ratio as regards the natural rate of carbon dioxide consumption through respiration in the atmosphere, thus creating a carbon-negative status of the atmosphere.
6. **Enhanced Terrestrial Weathering**
   In the natural system silicate rocks disintegrate through a process known as weathering. This chemical reaction reduces the availability of CO_2 in the atmosphere while giving out metal ions as well as carbonate and/or bicarbonate ions. The dissolved ions are transported in streams of groundwater, through rivers, and accumulate in the oceans, where they are locked as alkalinities or are formed in the land system as carbonates. Accelerating this weathering process is thus a technique that can be used to increase the drawdown of CO_2 in a much shorter time span. This is attained through milling of silicate rocks to enlarge their surface reactivity and their rate of dissolution of minerals. The ground material is then applied to croplands that offer a wide range of co-benefits in the mentioned publications.
7. **Wetlands Restoration and Construction**
   Wetlands are concentrations of carbon-rich environments that enable the removal of atmospheric carbon and storage in vegetation and soil matters. An example of wetlands is peatlands and coastal systems including mangroves, tidal wetlands, and seagrass beds, which are also known as blue carbon habitats.

Challenges and Considerations

- Scalability: Almost all NETs require deployment at a massive scale in order to affect the global levels of CO_2 substantively.
- Cost: Some of the technologies may be expensive to implement and maintain over time, and this is usually a financial cost in the overall process.
- Energy Requirements: While some NETs, especially the DAC, demand a lot of energy, this can reduce their effectiveness if the energy is not renewable.
- Environmental Impact: Some NETs pose long-term environmental risks that may not be conclusively evident, more so, the marine-based methods.

Radiative Forcing Geoengineering Technologies

Radiative forcing geoengineering methodologies constitute a group of technologies whose purpose is to change the Earth's radiation energy balance to reduce global temperatures. It is performed by either raising the albedo of the Earth and making more shortwave radiation from the sun to be reflected back to space, usually called solar radiation management, or by increasing the emission to space of longwave radiation from the Earth's surface, termed "terrestrial radiation management."[29]

Need for Climate Adaptation

Today, the management and adaptation works are divided since there is a dissimilar priority to the measures and separate planning and policies for the implementation of measures at the international and national levels. The idea that strategic and tactical integration and synergism of adaptation and mitigation could yield considerable and multiple scale gains in the land use sector is emerging. However, attempts to apply synergies of adaptation and mitigation actions remain limited due to the insufficient qualitative basis of the concept and policy-limited concerns.

Risk reduction and adaptation are the main mechanisms of the intended climate change convention to avoid disastrous consequences for people and the biosphere. The lower global mitigation effectiveness means that little is done to limit the anthropogenic

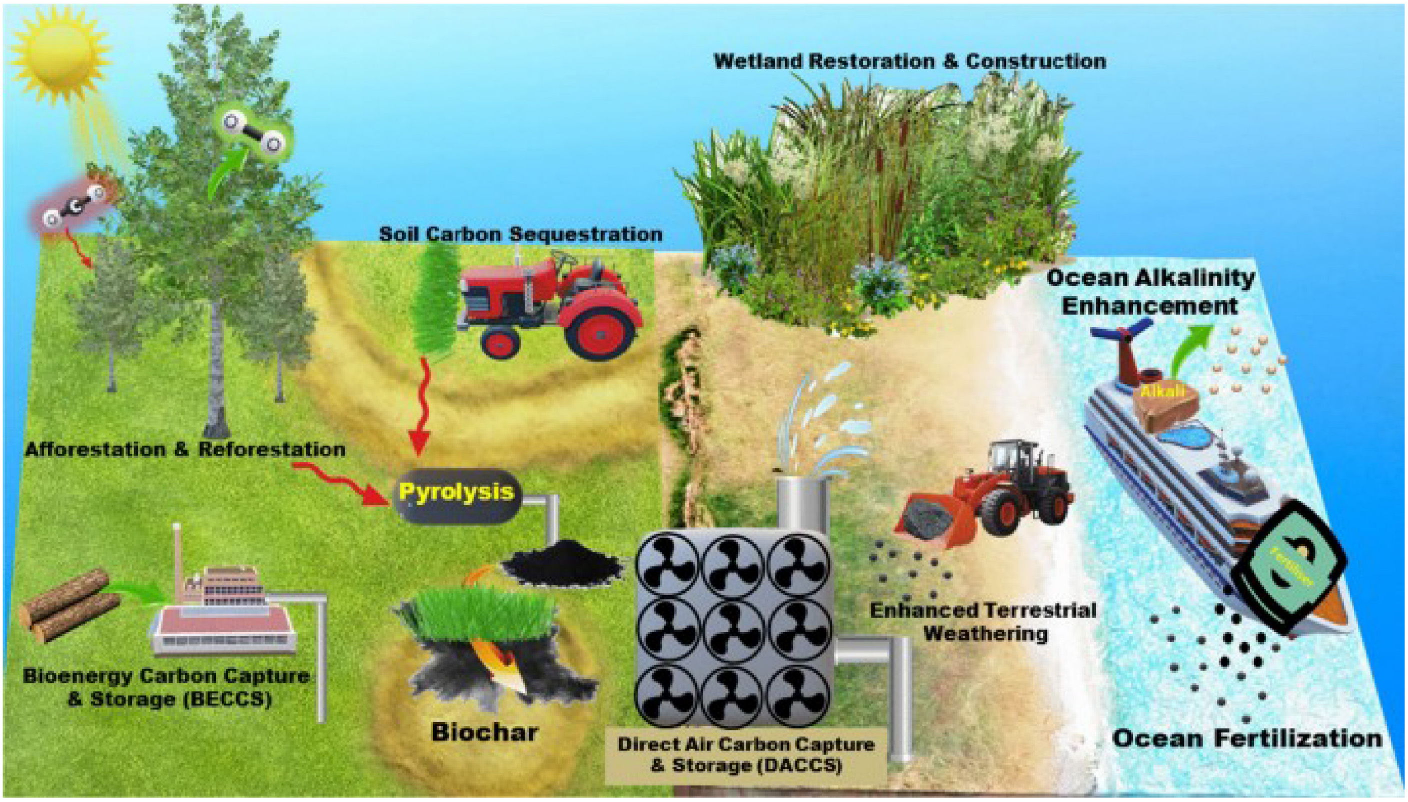

Fig 2 | Major negative emissions technologies and techniques like bioenergy carbon capture and storage, afforestation and reforestation, biochar, soil carbon sequestration, enhanced terrestrial weathering, wetland restoration and construction, direct air carbon capture and storage, ocean alkalinity enhancement and ocean fertilization which are deployed to capture and sequester carbon from the atmosphere.

Source: Fawzy, S., Osman, A.I., Doran, J. et al.[18]

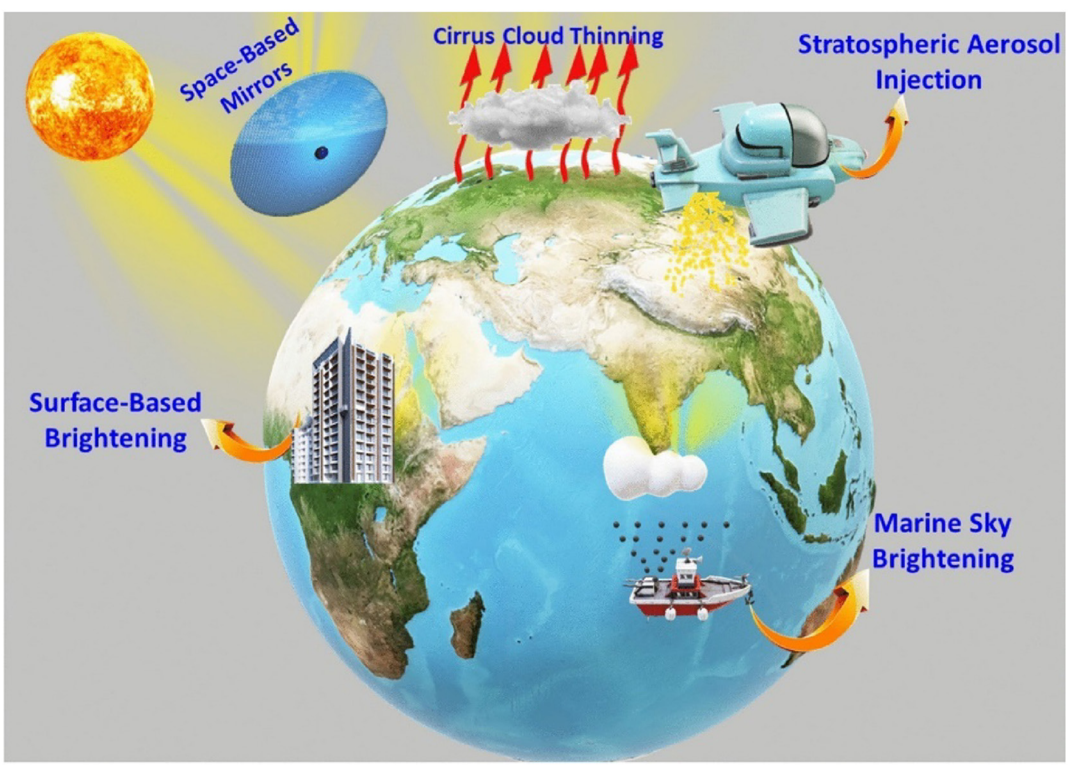

Fig 3 | Major radiative forcing geoengineering technologies like stratospheric aerosol injection, marine sky brightening, cirrus cloud thinning, space-based mirrors and surface-based brightening that aim to alter the earth's radiative energy budget to stabilize or reduce global temperatures.

Source: Fawzy, S., Osman, A.I., Doran, J. et al.[18]

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GHG emissions or enhance the GHG sinks, and the higher adaptation is required not to feel the negative impacts.

Applicable measures refer to measures that focus on either increasing the capability of a system to build up resistance to climate change effects or/and searching and exploiting the benefits offered by climate change. Even though both measures are designed to minimize climate change's adverse effects on people and ecosystems, they are different based on objectives, coverage, the temporal perspective, and level of integration.[30]

Adaptation projects may have a direct impact on mitigation by influencing ecosystems and carbon stocks. Projects under the ecosystem-based adaptation accord can by themselves enhance climate change mitigation, either by enhancing or conserving carbon reserves. The interdependencies between the services provided by the ecosystem give an understanding of the extent to which an adaptation project reduces the effects or, in other words, offsets the effects of climate change; for example, mangrove plantations act as both a shield to the coastal structures and a carbon sink.

However, there are possibilities to sacrifice a part of carbon to achieve a higher local than those provided by taking into account the specific ecosystem services prioritized in an adaptation project. It is also worth underlining that ecosystem services and carbon might exist in different forms. Apart from these gross effects of adaptation projects, there are other effects that can be experienced if an adaptation project eliminates displacement effects and induced deforestation.

How Does This Review Differ from What Is Already Published in the Literature? What Does It Contribute That Is New?

Previous reviews of the climate change literature are mainly concerned with the mature fields that are GHG emissions, impacts of climate change on distinct sectors such as agriculture or energy, or geographical zones. This article focuses on innovative methodologies to tackle climate change. It also captures some of the latest examples of impacts of climate change. The article presents scientific information as well as practical strategies.

The information presented in this review is relevant as it presents workable solutions and prescriptions and policy-based implications.

Also, as climate science changes every few years, it is likely that this review containing usual IPCC findings, advanced climate models, or cumulative emissions might get updated. Making it current by underlining present climate fluctuations, outstanding technological changes in climate change mitigation, or newly experienced impacts might make the information it contains valuable.

Conclusion

Considering the current state of climate emergency, it is critically urgent to start designing and building effective and efficient mechanisms of climate change mitigation and adaptation. It is stressed that there is no single strategy available to combat climate change, and all the technologies and techniques discussed above must be made feasible to use. Many governments have realized that decarbonization strategies are needed to deliver on the goals set in the Paris Agreement and are working tirelessly to develop solutions to decarbonize and address the issue of climate change.

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