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REVIEW ARTICLE

Zero carbon agriculture: Sustainable practices and technologies for carbon-neutral food production

S Indhu Pavithra[1], D Leninraja[1]*, K Sathiya Bama[2], P Dhevagi[3], A Beaulah[4] & Kavitha M P[5]

[1]Department of Natural Resource Management, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam, Theni 625 604, India

[2]Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[3]Department of Environmental Science, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[4]Post -Harvest Technology, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam, Theni 625 604, India

[5]Agricultural Research Station, Tamil Nadu Agricultural University, Vaigai Dam 625 562, India

*Email: leninraja@tnau.ac.in

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Abstract

Since the Industrial Revolution, global expansion has primarily depended on the extraction of natural resources. Anthropogenic activities, such as the widespread use of fossil fuels, deforestation and other types of land-use change, have increased levels of greenhouse gases (GHGs) in the atmosphere, contributing to global climate change. The most essential task in the world is to become carbon neutral by 2050 to counteract the deteriorating global climate change. To achieve this goal, it is required and challenging to modify present industrial processes to minimise GHG emissions and enhance CO_2 removal from the atmosphere. The study suggested technologies to accelerate our race to C neutrality in a variety of areas, including renewable energy, sustainable food systems (increasing soil C sequestration and lowering C emissions), preserving the health of earth's largest C stores (restoring and protecting marine and forest ecosystems) and C-neutral chemical industrial production. The wealth of information offered in this study has the potential to enthral the global population and encourage the creation of innovative solutions to avert climate change while also supporting human activities. It also includes carbon sequestration solutions to facilitate the energy sector's net zero.

Keywords

carbon capture; carbon neutrality; carbon sequestration; renewable energy

Introduction

Industrialization, the driving force behind economic growth and urbanisation, has hastened the development of numerous industries in line with the global population and resource boom. The world's population is anticipated to increase from 7.8 billion in 2020 to 9.9 billion in 2050, requiring 80% more energy and 70% more food, assuming rising living standards. Over the last two centuries, the global economy has become largely reliant on the overexploitation of natural resources, as well as the disruption of life-sustaining biogeochemical cycles and processes in nature (1). The present growth in the use of petroleum resources and deforestation stems from the need to fulfil the rising demand for energy, food and other goods. These environmentally harmful activities are the core cause of increased anthropogenic emissions of global greenhouse gases (GHGs), which are the principal drivers of climate change. In 2016, energy and food systems accounted for more than 90% of total world GHG emissions (mostly in the form of CO_2) (2).

GHG emissions are expected to climb by 50% by 2050, due mostly to a predicted 70% increase in energy-related CO_2 emissions (3). These emissions will continue to climb at their current rate, pushing the carbon cycle out of dynamic equilibrium and causing lasting changes to the climate system. As a result, targeted initiatives to reduce carbon emissions and enhance carbon sequestration must start with a combination of socioeconomic and technological approaches. In response to the ever-increasing global greenhouse effect, on December 12, 2015, all countries signed a historic United Nations climate agreement in Paris to address GHG emissions and climate change. Under the 2015 Paris Agreement, all countries promised to keep temperatures below 2.0°C and aim to limit global warming to less than 1.5°C by 2050 (4, 5).

In 2020, the average global temperature was 1.2°C higher than it was prior to the Industrial Revolution and the effects of this increase are evident around the world. Given the current climate data, it is imperative that we urgently enhance our efforts to lower GHG concentrations in the atmosphere to combat global climate change. To attain carbon neutrality and support human activities, it is crucial to decrease carbon emissions from fossil fuels and food while also enhancing carbon absorption in both terrestrial and marine ecosystems. Governments have implemented numerous strategic measures to reach carbon neutrality. Nonetheless, due to the magnitude of the emissions involved, achieving net-zero carbon emissions is a difficult endeavor. Despite advancements in renewable energy consumption, the shift from conventional to renewable energy is slow and the world is not on schedule to reach carbon neutrality and sustainable development by 2050. As a result, greater work is required to turn the energy industry into a carbon-neutral centre. This can be accomplished by collaborating with various multidisciplinary research teams and applying integrated approaches developed in response to recent scientific and technological advances in civil and environmental engineering, biotechnology, nanotechnology and other fields. In addition to developing renewable energy, food system management must be optimised to boost production efficiency and minimise carbon emissions (6).

Advancements in renewable energy use and the shift from traditional to renewable sources are happening slowly and the global community is not making sufficient progress toward achieving carbon neutrality and sustainable development by 2050. Consequently, greater efforts are essential to convert the energy sector into a carbon-neutral ecosystem. This can be accomplished by collaborating with various interdisciplinary research teams and applying integrated approaches that leverage contemporary scientific and technological innovations in fields like civil and environmental engineering, biotechnology, nanotechnology and others. Besides increasing the use of renewable energy, optimizing food system management is crucial for enhancing production efficiency and minimizing carbon emissions (7).

Numerous assessments have been carried out to explore ways to achieve carbon neutrality, focusing on renewable energy options, carbon capture and storage in both land and ocean environments, as well as reforms in food production systems. Nevertheless, as far as we know, there has been no comprehensive review that examines the advantages and drawbacks of all emerging technologies aimed at carbon neutrality, nor has there been an analysis of the uncertainties tied to these new technologies regarding climate change mitigation. This review centers on innovative technologies designed to hasten our journey towards carbon neutrality across several domains, including renewable energy, sustainable food systems (enhancing soil carbon storage and reducing carbon emissions), safeguarding the Earth's major carbon reservoirs (by restoring and protecting marine and forest ecosystems) and environmentally friendly chemical industrial production. The findings presented in this paper are meant to inspire the global scientific community and stimulate interest in future investigations into inventive strategies for achieving carbon neutrality as well as the United Nations Sustainable Development Goals (8).

Technologies for renewable energy

The excessive use of energy derived from finite resources results in energy deficits, increases GHG emissions, accelerates climate change and harms the environment, thereby threatening humanity's well-being. Consequently, the awareness of ecological issues and the shift towards low-carbon or carbon-free energy solutions have become increasingly crucial. To tackle these pressing issues, various international policies have been established. Renewable energy types, such as solar, wind and marine energy, are often seen as vital and effective strategies for achieving carbon neutrality. Alongside nuclear and hydrogen energy-both of which minimize resource consumption and pollution risks and are deemed essential for ensuring national energy stability and attaining carbon neutrality-bioenergy also plays a significant role in reshaping the framework of energy production and usage. The following sections will explore important renewable energy technologies and their roles in achieving carbon neutrality (Fig. 1) (9, 10).

Solar energy

The sun offers a limitless source of energy. As a clean, renewable and ubiquitous resource, solar energy could have a crucial role in the global renewable energy landscape. At present, fossil fuels such as oil, coal and natural gas dominate the majority of worldwide energy consumption. In contrast, renewable sources like solar power, hydropower, wind energy and tidal energy, which do not generate carbon dioxide, make up only a small fraction of overall energy usage. To achieve carbon neutrality, it is essential to boost the adoption of renewable energy. Therefore, transitioning from traditional fossil fuels to solar energy is not only highly beneficial but also critical for reducing carbon dioxide emissions and moving towards decarbonized energy systems necessary for achieving carbon neutrality (11, 12).

The growth of photovoltaic technology is rapid and it has gained acknowledgement as an effective method for capturing solar energy. Conventional thin-film solar cells, which utilize inorganic semiconductors like silicon, gallium arsenide, copper indium gallium selenide and cadmium telluride, have been extensively commercialized due to their impressive power conversion efficiency and reliable

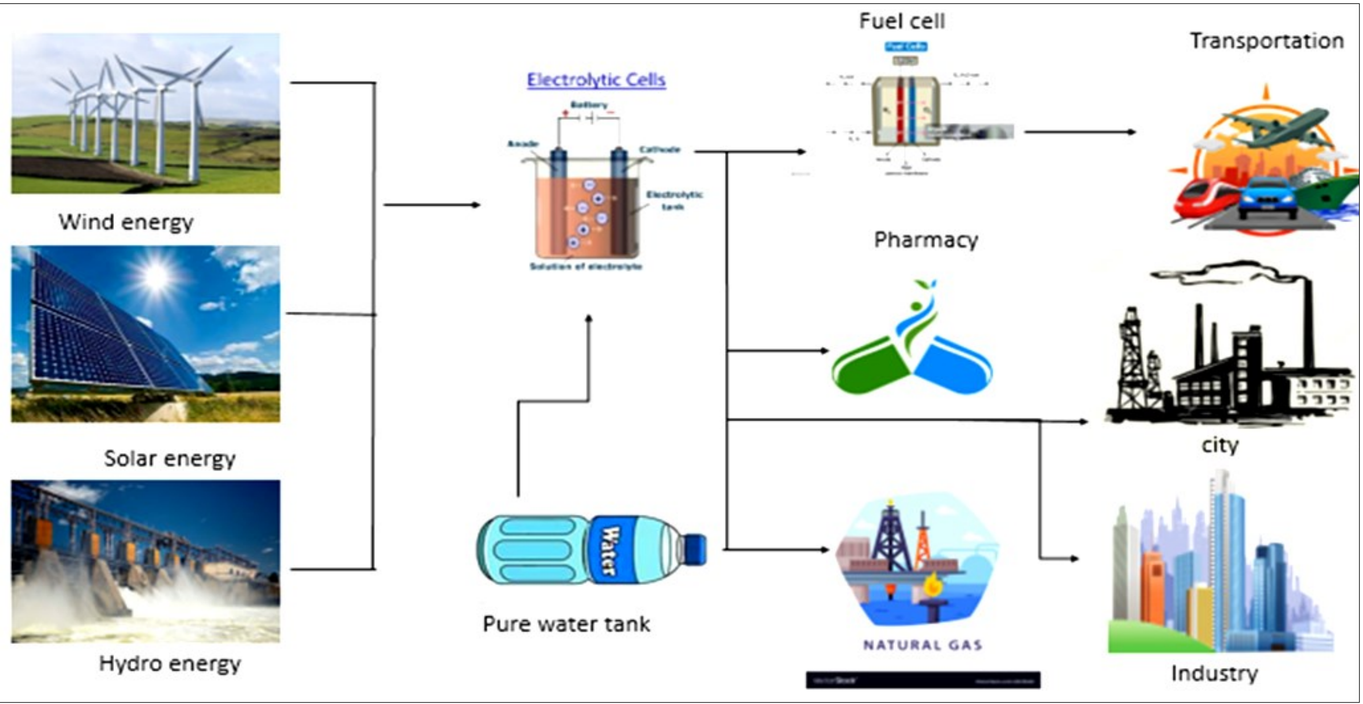

Fig. 1. Core technologies for renewable energy production.

performance (13).

In recent years, advancements in photovoltaic technology have led to the development of various innovative types of solar cells, including organic solar cells, perovskite solar cells, quantum dot solar cells and additional integrated solutions. This new generation of solar technology has the potential to complement conventional solar cells and act as a cost-effective substitute for photovoltaic systems across numerous applications. These technologies not only produce energy but also play a significant role in reducing carbon emissions. While their power conversion efficiency has exceeded 18%, there remains an opportunity to enhance the efficiency and durability of large-area solar cells, as well as to lower production and decarbonisation expenses. Moreover, solar panel systems and photovoltaic systems connected to the grid are essential for electricity production and could accelerate our progress toward achieving carbon neutrality (14-16).

A groundbreaking concept known as liquid sunshine has been developed, which involves combining solar energy with captured CO_2 and water to produce sustainable liquid fuels like methanol and alcohol. This innovation could facilitate an environmentally harmonious cycle that integrates CO_2 generation and use within international industrial frameworks (17, 18).

A revolutionary idea termed liquid sunshine has been introduced, which entails the integration of solar power with collected CO_2 and water to generate sustainable liquid fuels such as methanol and alcohol. This advancement has the potential to create an eco-friendly cycle that incorporates the production and utilization of CO_2 into global industrial systems (19, 20).

Wind energy

The movement of air, influenced by the uneven heating of the Earth's surface by the Sun, generates wind. Consequently, this indicates that wind energy can be viewed as a form of indirect solar energy. Similar to solar energy, wind energy is expected to be pivotal in achieving peak carbon emissions and environmental neutrality. The planet is rich in wind resources, predominantly located in regions such as grasslands, deserts, coastal areas and islands. The specific location greatly affects the economic viability, technology and application of wind energy. Globally, wind power is highly esteemed and its advancement is actively encouraged. Nonetheless, a significant challenge associated with harnessing wind energy is the noise produced by wind turbines.

There is a critical need for strategies that lower or eliminate the noise generated by wind turbines while ensuring responsible usage of wind sources. Additionally, improper placement of wind turbines can pose threats to avian populations, leading to collisions, disturbances, or destruction of habitats (21, 22).

The expense associated with the installation of wind turbines is currently quite high, which hinders the widespread use of this technology. In order to satisfy energy consumer demands, it is essential to allocate additional resources towards enhancing and advancing wind energy solutions.

Ocean energy

Ocean energy refers to the power inherent in bodies of water within the ocean and it stands out as a renewable and environmentally friendly resource. The potential energy housed within oceans is immense, with the capability to supply energy for the entire world. There are five primary forms of ocean energy: tidal, wave, ocean current, thermal and osmotic energy. Mechanical energy can manifest as tides, waves, or currents. Research into harnessing ocean energy began several decades ago. The distribution of various energy types across different geographical locations, along with the technologies employed to capture them, shows significant variation.

One advanced technology for capturing tidal energy is the tidal barrage system. Wave energy, which encompasses both kinetic and potential energy generated by water waves, is more widely dispersed. This phenomenon is primarily driven by wind, which transfers a part of its kinetic energy to the water at the ocean's surface. The methods for capturing wave energy are still in development and do not yet match the maturity of tidal energy technologies; numerous devices are currently undergoing small-scale testing in anticipation of their future commercialization.

Osmotic energy, or salinity gradient energy, involves the energy generated by the interaction between water bodies of differing salt concentrations. The uniformity of seawater salinity varies globally; for instance, salinity gradients occur in estuaries where freshwater converges with salt water. To effectively harness this type of energy, specialized high-performance membranes capable of withstanding saltwater conditions are essential. Presently, two key technologies under exploration include pressure-retarded osmosis and reversed electrodialysis. Osmotic energy is still conceptual and has not yet proven to be economically viable. There is a rich potential for ocean energy reserves to serve as a power source for the entire planet. Technologies focused on capturing tidal and wave energy are evolving toward commercial feasibility. In contrast, the extraction technologies for ocean current energy, thermal energy and osmotic energy remain in the initial stages of development. The predominant obstacles to utilizing ocean energy effectively include the need for economic cost-competitiveness and the reliability of technologies when faced with the challenges of severe oceanic conditions (23).

Bioenergy

Biomass serves as a renewable energy source derived from plants. Key contributors to biomass energy include leftover materials from agriculture and forestry, organic components in municipal solid waste, livestock waste, human sewage and industrial byproducts. Biomass contributes approximately 13% to 14% of the global energy use each year. Several techniques exist for transforming biomass into energy, including those detailed below. One method, known as chemical conversion, encompasses processes like esterification and transesterification, which convert vegetable oils and animal fats into fatty acid esters, yielding biodiesel. Transesterification is essential since raw materials consist of triglycerides that cannot be used directly as fuel.

In the presence of methyl or ethyl alcohol and predominantly an alkaline catalyst, triglycerides are converted into either methyl or ethyl esters (biodiesel). The vegetable oils most commonly used in biodiesel production include rapeseed oil (making up 80%-85%) and sunflower oil (comprising 10%-15%). Lignocellulosic biomass, which consists of agricultural and forestry residues, is the primary biomass feedstock for biological conversion. This type of biomass is the most plentiful and readily available renewable resource globally, primarily composed of three complex biopolymers: cellulose, hemicellulose and lignin. The production of cellulosic bioethanol occurs through three phases: pretreatment, enzymatic hydrolysis and fermentation. Pretreatment includes various physical, chemical, or physicochemical methods to enhance enzyme access to the biomass. Several challenges need to be tackled, such as the significant costs associated with transporting biomass to bioenergy production sites utilizing different conversion methods, along with ensuring the sustainability of bioenergy feedstock production (24, 25).

H_2 energy

For the past two centuries, the industrial sector has relied on hydrogen. Since the year 1975, the demand for this element has increased more than fourfold and continues to rise. Until recently, hydrogen production was primarily obtained from fossil fuels, which contributed approximately 6% of the global natural gas market and about 2% of global coal, leading to annual carbon dioxide emissions of around 830 million tons (26). In recent times, hydrogen energy has garnered significant interest due to its potential to create a renewable energy infrastructure akin to an electrical grid. This integration is crucial for transitioning energy systems and reducing carbon emissions across various energy applications. Moreover, hydrogen represents the most economical solution for long-term energy storage, particularly for inter-seasonal needs. However, the challenge lies in storing large quantities of hydrogen safely and cost-effectively. Implementing underground storage in large salt caverns and utilizing existing or upgraded gas pipelines for hydrogen transport could affordably facilitate long-term energy storage and sector interconnection. Nonetheless, the requirements for equipment modifications depend on the specific conditions of each location (27, 28).

Nuclear energy

Nuclear energy plays a significant role in the realm of clean energy, representing 40% of global low-carbon electricity generation and preventing approximately 1.7 gigatons of carbon dioxide emissions each year. This positions nuclear energy as a vital strategy for enhancing national energy security and achieving carbon neutrality. The predominant method of generating nuclear energy is through nuclear fission, while nuclear fusion technology remains in development. Nonetheless, the future of nuclear fission energy faces uncertainty due to various factors, such as increasing costs, difficulties in managing radioactive waste, concerns surrounding plant safety and the potential for nuclear weapons proliferation.

To address these challenges, Generation IV reactor systems are being proposed based on certain criteria: safety, reliability, security, cost-effectiveness, sustainability and resistance to proliferation. Additionally, these reactors are critical elements in creating a sustainable and low-carbon energy system, fostering responsible environmental practices in both electricity and non-electric sectors. The Generation IV International Forum has included molten salt reactors (MSRs) for their safety and sustainability attributes. In 2011, the Chinese Academy of Sciences initiated the "Thorium molten salt reactor nuclear energy system" project, aiming for effective thorium energy use and comprehensive nuclear energy deployment within the next two to three decades.

The compact modular design of MSRs can mitigate the research and development difficulties associated with larger commercial variants while enhancing their economic viability and safety. MSRs that can be deployed in the near term will boast safety levels comparable to, or exceeding, those of evolutionary reactor designs. Moreover, by utilizing high-temperature molten salt as a coolant, MSRs can integrate with molten salt energy storage technologies found in concentrated solar power facilities, enabling the creation of extensive, high-capacity heat storage systems. In this context, MSRs serve as a reliable baseload energy source, helping to stabilize and support variable and intermittent sources of renewable energy. Even during prolonged periods of extreme weather, they can ensure a constant supply of energy (29, 30).

Geothermal energy

Geothermal energy refers to the heat that is stored beneath the Earth's surface, characterized by its non-carbon nature, stability, sustainability and considerable capacity. In the future energy landscape, it is poised to be crucial for providing a reliable and consistent foundational energy supply. The main use of geothermal energy lies in the generation of power, where natural geothermal steam or steam from a low-boiling working fluid, warmed by geothermal resources, is harnessed to drive turbines for electricity production. At present, technologies for generating geothermal power primarily consist of dry steam, flash power and binary cycle systems. Additionally, geothermal energy can be utilized directly as thermal energy, which is most effective for resources with medium to low temperatures. Current technologies for direct geothermal applications encompass ground source heat pumps, geothermal heating, geothermal cooling, geothermal greenhouses and geothermal drying methods (31, 32).

Technologies for enhanced carbon sink in global ecosystems

In the past five decades, land ecosystems have successfully captured about one-third of human-caused GHG emissions. Within this context, agricultural practices related to crops and livestock, along with activities linked to land use changes, are responsible for 71% of these emissions. Forest ecosystems stand out as vital carbon sinks, absorbing 45% of human-induced GHG emissions and supplying 85% to 90% of the biomass found on land. Occupying more than 70% of the Earth's surface, the oceans also play a significant role in capturing CO_2 from the atmosphere (33).

At present, the ocean's ecosystem captures 22.7% of the carbon dioxide emitted by humans annually. Our focus is on improving crop and livestock production systems, bolstering the health of forest ecosystems through soil carbon storage and utilizing both soils and marine environments as natural reservoirs for carbon (33, 34).

Carbon emission reduction in agricultural food production systems

Over the last two decades, GHG emissions resulting from agricultural food production have surged by approximately one-third. The main contributors to these emissions are both crop and animal production. Specifically, enteric fermentation, manure and pasture management and fuel consumption in livestock farming are responsible for 4.2 Gt CO_2-eq per year. Additionally, the application of synthetic nitrogen fertilizers and crop production for both human and animal consumption contributes 3.6 Gt CO_2-eq annually. Furthermore, crop-livestock production systems account for another 3.3 Gt CO_2-eq yearly (Fig. 2). Despite this understanding, there remains uncertainty regarding the widespread implementation of carbon capture and storage technologies within food production systems. To significantly reduce agricultural GHG emissions, other technologies or strategies will be necessary

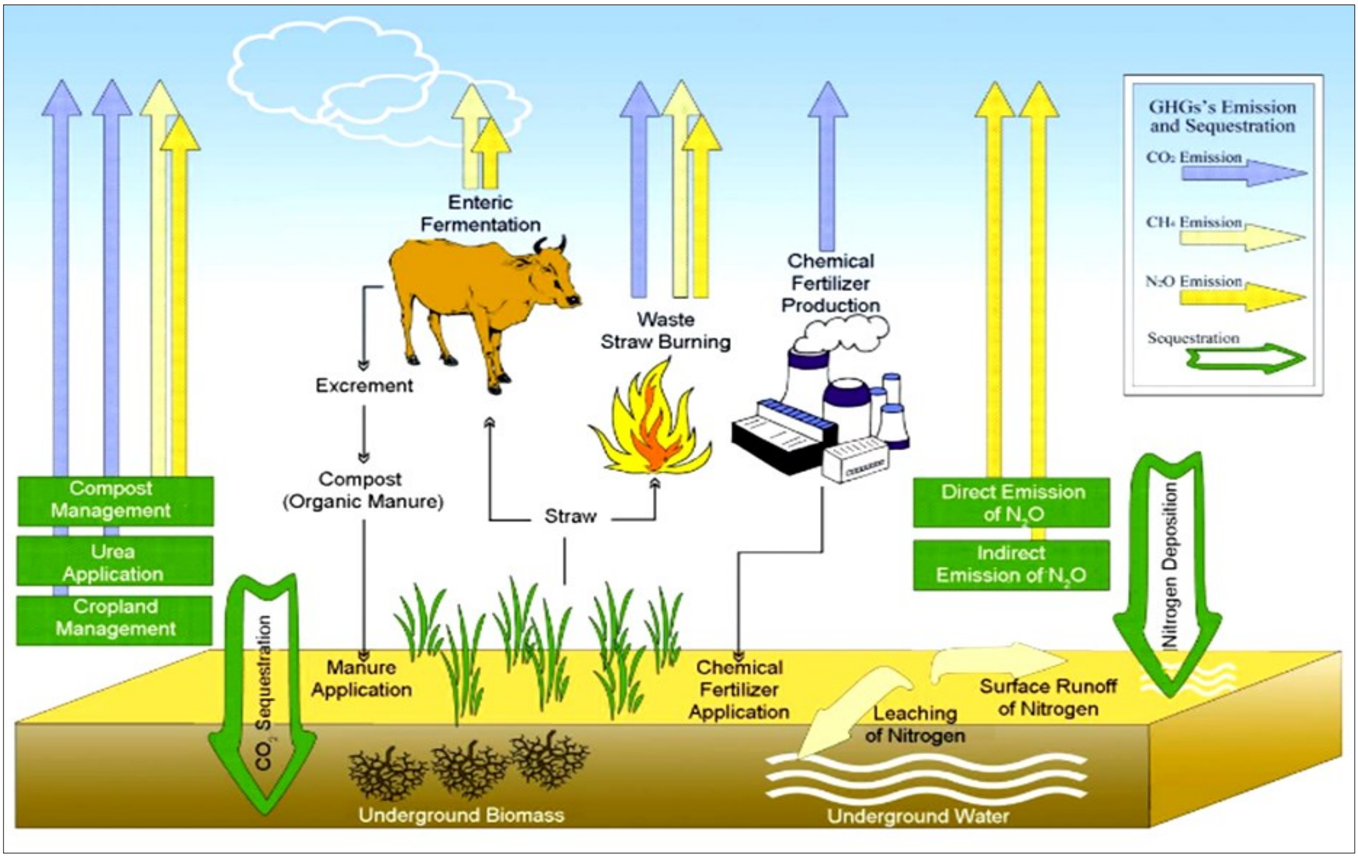

Fig. 2. A summary of worldwide greenhouse gas emissions (Gt CO_2-eq per year) and approaches to enhance GHG mitigation.

(35, 36). For instance, it is essential for us to modify our dietary practices by including a greater variety of plant-based dishes rather than relying on animal products.

Revolutionary technologies for agricultural food production

Biotechnology, autonomous control systems and artificial intelligence have enabled the large-scale manufacturing of vegetables, fruits and meat products. Meats derived from plants and cultured cells can now be artificially generated from sources that do not involve animals. Traditional examples of plant-based meats include tempeh and tofu, while modern alternatives are crafted from proteins obtained from plants or fungi, which are then synthesized and transformed into meat alternatives. Advanced technologies like shear cells and 3D printing are utilized to enhance the flavor and texture of plant-based meat options (37, 38).

Factors driving the terrestrial carbon sink

The primary climatic elements that affect plant photosynthesis and consequently, the extent of carbon sinks in land-based ecosystems, are temperature, precipitation and solar radiation. Significant reductions in soil carbon within natural ecosystems have occurred due to climate change and human activities (39). A conducive climate, particularly one characterized by substantial rainfall, is closely linked to increased biomass production and greater diversity of species. This relationship has the potential to enhance soil organic carbon (SOC) reserves while counterbalancing any adverse effects that a favorable climate might have on SOC levels. Conversely, in shrublands and forested areas, the storage of SOC and favorable conditions-such as elevated temperatures and rainfall-show a persistent negative correlation, unlike in grasslands. Additionally, other elements that affect the uptake of CO_2 by land-based ecosystems encompass the concentrations of atmospheric CO_2 and the duration of the growing season (40, 41).

Carbon sink in marine ecosystems

The quantity of carbon held in the ocean is roughly 44 times greater than the amount found in the atmosphere and this carbon typically remains in the ocean for several hundred years. Blue C refers to the carbon from the atmosphere that has been captured and retained within marine ecosystems.

Ocean carbon sinks and coastal blue carbon

Numerous physical and biological phenomena impact the capacity of the ocean to act as a carbon sink. The process known as the "solubility C pump" plays a role in extracting atmospheric CO_2, leading to its reaction and dissolution in the upper layers of the ocean. Conversely, the "biological C pump" refers to the uptake of atmospheric CO_2 by marine microorganisms through photosynthesis, which then moves to the deep ocean in the form of sinking biogenic particles or dissolved organic substances, facilitating long-term carbon storage. Nonetheless, most of the material that is exported undergoes remineralization back into CO_2 (42, 43).

Throughout this process, some of the fixed carbon remains as persistent dissolved organic matter rather than fully mineralizing, enduring for thousands of years. Although the initial idea of blue carbon was introduced in 2009, it pertains to the carbon sequestered by marine ecosystems, which include both nearshore and open ocean environments. Recent advancements and research in blue carbon have primarily focused on coastal wetlands, such as mangroves, seagrasses and salt marshes. These coastal ecosystems play a significant role in capturing atmospheric CO_2 through photosynthesis. A varying amount of carbon becomes buried in sediments that are periodically flooded and characterized by low oxygen levels, which helps prevent its release back into the atmosphere (44, 45).

Mangroves and tidal marshes capture 196.72 Tg of CO_2 each year, representing 30% of the total organic carbon settled on the ocean bottom. Seagrass ecosystems are projected to sequester between 176 and 411 Tg of CO_2 equivalents annually. The carbon retained in these coastal environments, known as blue carbon, has the potential to be preserved for thousands of years. Furthermore, when this carbon storage is combined with the ongoing accumulation of organic carbon in soil and sediment due to rising sea levels, marine ecosystems demonstrate a significantly higher capacity for carbon sequestration compared to land-based ecosystems (46, 47).

Practice for blue carbon management

Sustaining, conserving and restoring these marine ecosystems over the long term is essential for maintaining the carbon sequestration capabilities and various ecosystem services that humanity depends upon. A key approach to improving blue carbon involves encouraging microbial carbon storage in coastal environments, which can be achieved by decreasing the application of chemical fertilizers on land. This highlights the necessity of integrating policies that address both land and sea to facilitate carbon storage and promote sustainable development. Furthermore, preventing untreated sewage from flowing into rivers along with limiting chemical fertilization in agricultural practices may significantly reduce human-induced nutrient runoff into marine ecosystems, thereby decreasing the release of dissolved organic carbon that can lead to breakdown and respiration (45, 48). To sum up, oceanic ecosystems, comprising coastal wetlands and expansive waterways, are recognized as the largest natural carbon sinks on the planet. Coastal environments that generate blue carbon rank among the most effective ecosystems for sequestering carbon in sediment. Enhancing the capacity of these marine ecosystems for carbon capture or reducing carbon emissions is crucial for achieving carbon neutrality. Safeguarding and rehabilitating oceanic ecosystems represents the most immediate and effective method for boosting carbon sequestration. Additionally, implementing eco-engineering techniques and practices is essential for improving carbon capture in these marine environments. Such efforts include integrated carbon sequestration strategies that connect land and sea, sustainable aquaculture practices and the creation of artificial upwellings in marine settings (49, 50).

Tackling the carbon footprint of global waste

***Zero waste biochar as a carbon-neutral tool*:** Biochar, though a modern term, refers to an ancient practice involving a porous solid material produced by subjecting feedstocks to elevated temperatures ranging from 300°C to 900°C in environments with limited or no oxygen. There are multiple techniques for the thermochemical conversion of feedstocks into biochar, such as pyrolysis, hydrothermal carbonization, torrefaction, gasification and traditional carbonization. Among these methods, pyrolysis is particularly prevalent as it transforms approximately one-third of the feedstocks into stable biochar products, in addition to yielding bio-oils and non-condensable gases. Various organic materials can be utilized to produce biochar for diverse applications, including agricultural leftovers, forestry byproducts, manure from livestock, leftover food, industrial organic waste, municipal waste and animal remains (51).

Several researchers have made significant progress by examining the pyrolysis of plastic waste to generate char, while others have explored the co-pyrolysis processes involving organic materials and polymers. The char derived from materials originating from fossil fuels does not serve as a method for removing carbon dioxide from the environment, nor is it utilized as a soil enhancement (hence not termed biochar); instead, it functions as a construction material. Notably, biochar can be produced on a variety of scales, ranging from large-scale industrial operations to small residential projects, including agricultural settings. Consequently, the production of biochar from widely available waste carries substantial social and environmental implications in the pursuit of carbon neutrality. The ability to generate biochar for diverse uses sustainably positions the biochar sector as a promising avenue for achieving a more sustainable and thriving future for both people and the planet (52).

Biochar for sustainable development **:** Apart from its role in waste management, biochar is implemented in various human endeavors aimed at fostering a circular economy and supporting sustainable development. This material is gaining recognition as a potent and safe natural adsorbent, capable of capturing carbon dioxide and eliminating a range of organic and inorganic pollutants from solids, liquids and gases (53).

When utilized as a soil enhancement, biochar can boost plant growth and increase photosynthesis by improving the physical, chemical and biological attributes of soil. This contributes to carbon storage in land ecosystems and helps alleviate climate change effects. The incorporation of biochar into farming soils has been linked to improved availability of soil moisture, enhanced water retention and better nutrient accessibility. It also leads to increased microbial biomass and activity in the soil, diminishes the chances of surface crusting and erosion, enhances antibacterial properties and decreases both the movement and toxicity of environmental contaminants. When combined with nutrients and microorganisms, biochar serves as an effective carrier for agricultural inputs, enhancing the effectiveness, viability and functionality of microbial agents introduced into the soil (54, 55). In addition, biochar can provide essential nutrients for plant development while suppressing diseases caused by soil-dwelling pathogens, thereby altering the agricultural setting. It also has the potential to reduce emissions of methane, nitrous oxide and other pollutants during the decomposition of biomass in soil by adsorbing free carbon and nitrogen molecules on its surface, thus modifying system characteristics. Research indicates that using biochar as a soil additive can lead to a reduction in soil methane emissions by 39.5% and nitrous oxide emissions by 30.92%. Moreover, studies have demonstrated that biochar can decrease GHG emissions (including methane, nitrous oxide and carbon dioxide) during the composting process. Its application is highly recommended to enhance the composting procedure and conserve carbon, nitrogen and other essential compost

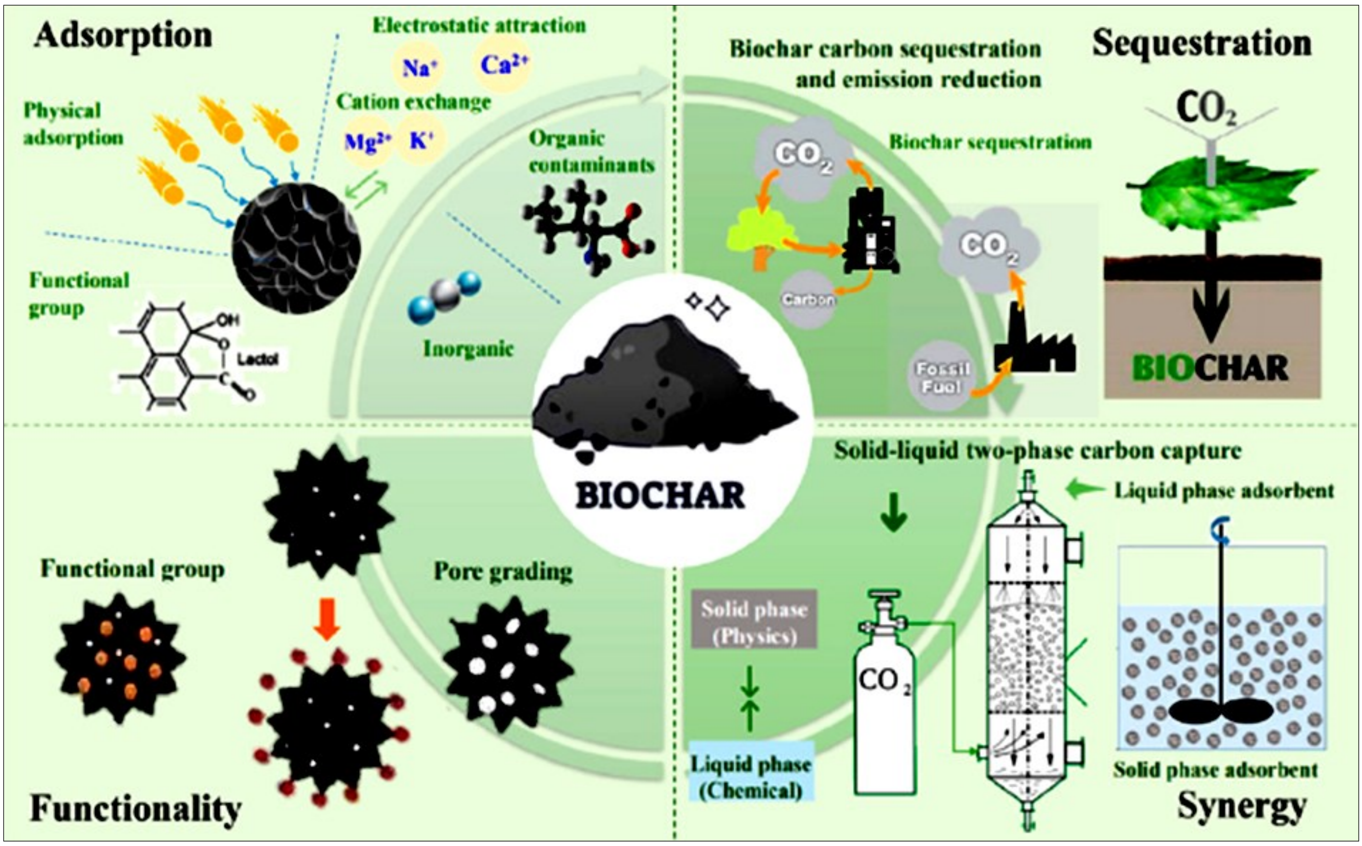

Fig. 3. Zero waste biochar as a carbon-neutral tool for sustainable development.

minerals. Therefore, the conversion of agricultural waste into biochar is viewed as a promising approach for enhancing soil fertility while concurrently reducing GHG emissions (Fig. 3) (56, 57).

In order to attain sustainable development within a carbon-neutral framework, it is essential not only to decentralize the production of biochar and increase public understanding of its various benefits, but also to pinpoint key elements crucial for enhancing the biochar system's effectiveness in reducing GHGs, removing carbon dioxide and safeguarding the environment. Given that the characteristics and applications of biochar can vary significantly based on the conditions of pyrolysis and the type of raw materials used, future research aimed at optimizing biochar should prioritize the pre-treatment of feedstocks, the pyrolysis process itself, operational conditions and the resulting yield. Lastly, incorporating ecological approaches to refine the production of biochar, its characterization and life-cycle analysis, along with establishing standards guided by both experimental data and theoretical models, will facilitate collaboration among policymakers, biochar manufacturers, users and other key stakeholders, driving efforts toward achieving carbon neutrality (58, 59).

Bio-based products for carbon sequestration

Utilizing biomass for the conversion, repurposing and recycling of CO_2 presents an environmentally sustainable approach to address climate issues while fostering a circular bioeconomy. Biomass possesses the capability to produce all forms of fossil fuels. Beyond generating bioenergy, non-edible biomass can serve as a substitute for finite fossil fuel supplies in the industrial manufacturing of essential items such as plastics, lubricants, medical devices, paints and other pivotal products. This is grounded in reality, as recent advancements in various fields, including biotechnology, nanotechnology and nanobiotechnology, have paved the way for biomass to play a crucial role in truly sustainable production systems worldwide (60, 61).

Technologies for CO_2 capture, utilization and storage

The process of capturing, using and storing carbon dioxide (CCUS) involves three distinct steps: the extraction of CO_2 from emission sources, the conversion and use of CO_2 and its transportation and deep underground storage with long-term separation from the atmosphere. CCUS represents an essential technology for meeting goals related to lowering CO_2 emissions. The International Energy Agency (IEA) asserts that in order to curb emissions, it is necessary to go beyond merely enhancing energy efficiency and modifying the energy system; to limit the rise in global temperatures to below 2°C by 2050, 19% of CO_2 emissions need to be captured and stored. Failing to implement CCUS will result in a 70% increase in the overall expenses of CO_2 reduction efforts by the year 2050 (62, 63).

Capturing and storage of CO_2

Carbon dioxide capture and storage (CCS) was initially suggested in 1977 and has progressed through three distinct phases up to now. The initial phase lasted from 1977 until 1996 and focused on improving technology. The first initiative for CCS technology began in 1989 at the Massachusetts Institute of Technology. To support CCS initiatives, the Norwegian government introduced a carbon dioxide tax in 1991 to help the nation achieve its environmental objectives. Consequently, this carbon tax allowed for the establishment of the first plant dedicated to collecting carbon dioxide from a platform at the Sleipner gas field. The second phase, which spanned from 1997 to 2018, involved demonstrating the technology on a larger scale (64, 65).

Carbon capture technology status

At present, the main methods for gathering CO_2 include capturing it after combustion, capturing it before combustion and using oxygen-fuel combustion (Fig. 4). Post-combustion involves extracting CO_2 from the flue gases and is considered one of the simpler techniques for retrieving CO_2 in energy systems (66).

The post-combustion capture method employs gas separation methods like physical absorption, chemical absorption, membrane separation and others. Due to the thorough treatment of flue gas after combustion and the low levels of CO_2, the chemical absorption method is the most appropriate technology for separating CO_2 after combustion (67).

The advantage of post-combustion capture lies in its ease of implementation and the minimal alterations required for the power generation system. Due to the dilution by nitrogen, the level of CO_2 in the exhaust of an energy system is usually quite minimal (with coal-fired power plants typically showing CO_2 levels around 10%-15% and natural gas power plants having even lower levels, about 3%-5%), necessitating extensive processing of the exhaust gases.

When applying the chemical absorption technique to extract CO_2 from the exhaust gases of coal-fired plants, the energy demand is roughly 0.37-0.51 MWh per ton of CO_2. This suggests that achieving a 90% reduction in CO_2 concentration can lead to a drop in energy system efficiency of 11.0-15.0 percentage points while escalating the capital investment in power plants by 50%-80%. The current research in post-combustion separation aims to create more efficient absorbents and enhance the separation technique to lower the energy costs associated with CO_2 extraction. Nonetheless, the significant energy requirement for post-combustion separation primarily stems from the low concentration of CO_2 present in the exhaust gases. Merely improving the absorbents and refining the process may not sufficiently decrease energy usage related to separation (68, 69).

Pre-combustion refers to the method of extracting CO_2 before the fuel undergoes combustion. The process involves transforming fuel into syngas, which mainly consist of carbon monoxide and hydrogen. Following this, the carbon monoxide in the syngas is converted to carbon dioxide and hydrogen and ultimately, carbon dioxide is extracted from the hydrogen. As CO_2 extraction is carried out before the fuel is burned and because the fuel gas does not contain nitrogen, the concentration of CO_2 in the syngas can reach up to 30%. The findings indicate that a 90% capture of CO_2 before the combustion in IGCC impacts net power efficiency by a range of 8.0 to 10.0 percentage points, which is lower than the impact of capturing CO_2 after

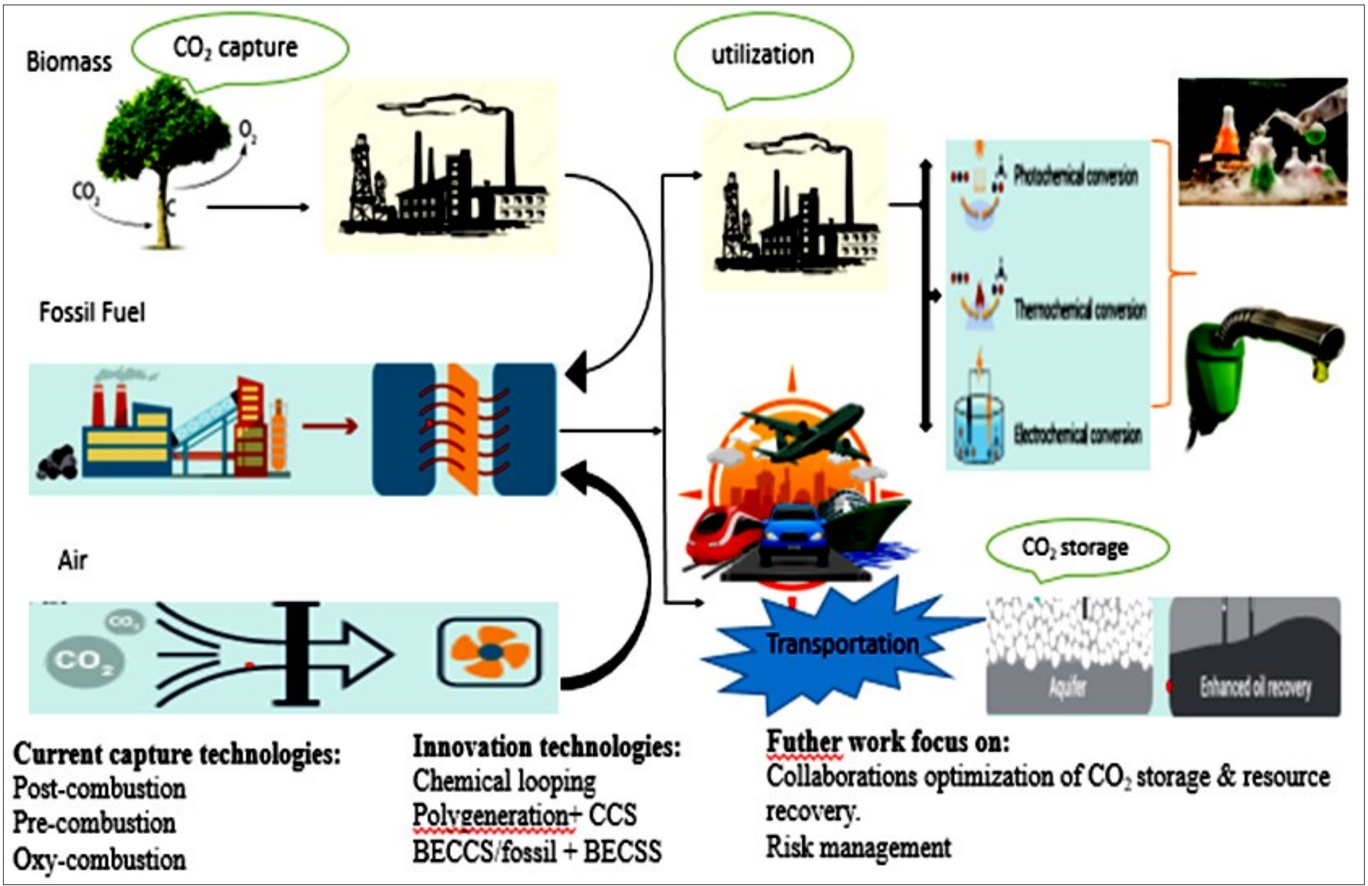

Fig. 4. The roadmap for CO_2 capture technology development in the industry.

combustion. However, advancements in coal gasification technology and gas turbines that utilize hydrogen-rich gas are necessary for improving IGCC pre-combustion processes (70, 71).

CO_2 transportation status

The movement of captured CO_2 to either a utilization or a storage site is known as CO_2 transportation. This process shares similarities with the transportation of oil and gas, utilizing various methods such as pipelines, ships, railways and roads, with pipeline transportation presenting the greatest promise for implementation. In recent times, a variety of CO_2 pipeline transportation methods have developed globally. For instance, in the United States, a main pipeline system has been built that stretches over 5000 km. At present, CO_2 transportation in China primarily involves low-temperature storage vessels that are moved by road.

In the area of transporting low-pressure CO_2, we can learn from the expertise gained in the established methods of oil and gas pipeline transport; concurrently, exploration into transporting high-pressure, low-temperature and supercritical CO_2 is just beginning (72, 73).

CO_2 storage status

CO_2 storage involves the collection of carbon dioxide and its confinement in geological formations through engineering and technological methods. This method may effectively sequester CO_2 from the environment over an extended period. The geological storage sites mainly include land-based saline aquifers, seabed saline aquifers, abandoned oil and gas fields, along with various other technologies. Currently, the main hurdles to advancing CO_2 geological storage technology are long-term safety and reliability (74).

Challenges and future technology development directions

The systems for capturing CO_2 that are being validated and developed globally primarily utilize post-combustion separation methods. Nonetheless, these approaches require substantial energy and are expensive, offering limited potential for reduction. During the initial phases of promoting CCS technology, post-combustion techniques are relatively straightforward and involve low levels of technical complexity (74).

This technology is frequently employed in CCS demonstration initiatives. It has the potential to lower CO_2 emissions in the near term. Nonetheless, due to the fundamental nature of this technology requiring higher energy consumption to achieve CO_2 reductions, relying on it as the main approach for long-term CO_2 emission cuts will lead to unsustainable energy and financial costs for governments. Therefore, for the widespread adoption of CCS technology, countries need to create energy-efficient, cost-effective CCS solutions suitable for developing nations, aimed at the clean use of coal. Examples include new poly-generation techniques, chemical chain approaches and NET integrated with multi-energy CO_2 capture technologies (75, 76).

Technology of flameless chemical-looping combustion

The chemical-looping combustion that doesn't involve flames operates differently from traditional flame combustion due to the absence of direct interaction between air and fuel, facilitated by two gas-solid interactions. Consequently, the resulting gas mixture contains elevated levels of CO_2 and H_2O, allowing for CO_2 to be captured without the need for a separation process. CO_2

extraction can be achieved without expending energy. Implementing flameless chemical-looping combustion has introduced an innovative approach to regulating GHG emissions. The special report from the IPCC regarding CO_2 capture and storage pointed out that chemical looping combustion offers a solution for complete CO_2 capture. This technique shows promise for diminishing GHG output. During the 1990s, researchers in China pioneered the discovery of how chemical-looping combustion leads to increased CO_2 concentration. The IEA and the US Department of Energy have identified the chemical chain as a crucial new strategy for achieving zero emissions from fossil energy sources in the future. Further advancements are necessary for oxygen carriers that exhibit high reactivity, mechanical properties and cycling efficiency. Additionally, more investigation is needed into new reactor designs suitable for chemical-looping combustion and the heat integration of the overall system (77).

The reliability and safety assessment of storage

At present, the main challenges facing the widespread implementation of CO_2 geological storage systems revolve around two key issues: the available storage capacity and the assurance of long-term safety. The intricate history of sedimentary formations, including tectonic structures and diagenetic processes over geological epochs, adds to the complexity of resource deposits. Technological constraints and limitations in interpretation lead to a lack of methods for accurately assessing geological data pertaining to the spatial distribution of aquifer layers and oil reserves suitable for CO_2 storage, complicating the task of calculating CO_2 storage capacities. Our existing knowledge and technologies present significant challenges regarding long-term safety and risk management (78).

Therefore, advancing technology is essential for the effective adoption of CO_2 geological storage solutions. Enhancements in crucial technologies and processes possess the potential to expedite progress towards carbon neutrality. This can be achieved by developing robust and secure theories, methods, technologies, software and equipment for CO_2 geological utilization and storage. Among the numerous essential technologies are systems for site characterization and evaluation, frameworks for collaborative optimization of carbon storage and underground resource extraction, safe transportation technologies for CO2 with multiple options and integrated monitoring, risk prediction and mitigation systems encompassing the "sky-surface-underground" model. Additionally, there is a need to scale up comprehensive carbon capture, utilization and storage (CCUS) projects (79, 80).

CO_2 utilization

Chemical utilization of CO_2 involves processes that transform carbon dioxide into higher-value chemicals under specific conditions of temperature, pressure and catalytic support. This approach not only helps in reusing CO_2 but also contributes to a tangible decrease in emissions. Furthermore, it presents an innovative chemical synthesis method that reduces reliance on fossil fuels or traditional raw materials (81).

The flow of carbon from the lithosphere to the atmosphere can be reframed into a new circulation model, yielding substantial indirect reductions in emissions and significant opportunities in future scenarios aimed at carbon neutrality. Various techniques have been devised for CO_2 conversion, including thermochemical, photochemical and electrochemical catalysis, among others like enzymatic and organometallic catalysis, with notable advancements achieved in recent years (Table 1) (82).

Electrochemical carbon dioxide reduction

The process of electrochemical CO_2 reduction (CO_2RR) stands out as a vital pathway for converting renewable energy from sources such as sunlight and wind into storable fuels and valuable chemicals, addressing the goal of carbon neutrality. Progress in understanding the mechanisms involved has been observed, alongside promising experimental results in this complex multi-electron and multi-proton transfer system. Utilizing theoretical simulations based on density functional theory (DFT) has proven to be an excellent approach for extracting mechanistic insights into the microscopic interactions at the electrode/electrolyte boundary as well as for obtaining essential thermodynamic and kinetic information. Electrocatalysis is distinct from

Table 1. The recent advances in CO_2 utilization technology

Emerging technologies	Reasons for probable adaptability	Reference
Metal-Organic Frameworks (MOFs)	New MOFs with large surface areas and adjustable pore structures have been developed to capture and convert CO_2 more effectively. These MOFs serve as efficient catalysts to turn CO_2 into useful chemicals.	89
Photocatalytic Conversion	New photocatalysts, such as titanium dioxide (TiO_2) mixed with metals or non-metals, have enhanced the ability to convert CO_2 into hydrocarbons and other organic compounds using sunlight.	90
Biocatalysis and Enzyme Engineering	Modified enzymes and microbial systems are now more efficient at turning CO_2 into biofuels and bioplastics. Progress in synthetic biology has led to microorganisms with better CO_2 fixation abilities.	91
Artificial Photosynthesis	Advances in mimicking natural photosynthesis have led to systems that convert CO_2 and water into glucose and oxygen using solar energy. These systems use advanced materials like nanostructured semiconductors to boost efficiency.	92
Carbon Nanotubes and Graphene Production	New methods have been developed to use CO_2 as a raw material to produce high-value materials like carbon nanotubes and graphene, which are used in electronics, energy storage and composites.	93
Thermocatalytic Conversion	Improvements in thermocatalytic processes, including new catalysts and reactor designs, have made converting CO_2 into chemicals like methane, methanol and synthetic fuels more efficient.	94
CO_2 Mineralization	New techniques for speeding up the natural reaction of CO_2 with minerals to form stable arbonates have been developed. These methods are being used to create construction materials and permanent carbon storage solutions.	95

traditional catalysis in that the voltage applied to the electrode can effectively alter both the thermodynamics of reactions (reaction-free energy) and their kinetics (activation energy barriers) (83).

Key technologies and future challenges of CO_2 catalysis

Despite substantial advancements in recent years, the conversion of CO_2 into fuels and chemicals continues to face significant challenges related to both thermodynamics and kinetics. In the realm of thermal catalysis, the variety of productive and spontaneous reactions involving CO_2 and other substances is quite limited. A deeper understanding of innovative reactions that allow CO_2 to engage with multiple chemicals simultaneously could enhance its conversion potential. Current applications for large-scale CO_2 transformation in photochemical and electrochemical catalysis have not yet come to fruition. A major obstacle in developing effective catalytic strategies is the intricate nature of catalysts, which complicates the activation of active sites. Consequently, there is a pressing need to enhance the efficiency of existing techniques and to explore viable catalysts and reaction environments. Additionally, the range of products derived from photocatalysis and electrocatalysis is constrained due to inadequate efficiency or unfavorable operating conditions. Exploring new processes that enable the combination of CO2 with other molecules may present opportunities to create long-chain carbon products within photochemical and electrochemical frameworks (84).

Neutralizing carbon based on observation of satellite and digital earth

The swift observation of worldwide GHG levels, alterations in terrestrial land use and the spatial assessment of natural carbon sinks globally play vital roles in carbon neutrality. They help identify the optimal timing for reaching the maximum carbon emissions and assessing the capacity of natural carbon sinks.

Observation of CO_2 emission through satellite

At present, the methods for observing GHGs encompass both ground-level monitoring and satellite-based remote sensing. In the initial stages, a worldwide system of observation stations for GHGs was set up to ensure precise data on gas concentrations. Nonetheless, the limited number of these locations often results in inadequate spatial resolution, falling short of the need for calculating global carbon fluxes (85).

Three satellites dedicated to monitoring carbon dioxide were launched in succession: Japan's GOSAT in 2009, the OCO-2 from the United States in 2014 and China's TANSAT in 2016. This series of launches greatly enhanced the ability to track carbon flow. Furthermore, Europe's Sentinel-5P satellite has excelled in monitoring other gases, including methane (CH_4), nitrogen dioxide (NO_2), carbon monoxide (CO) and ozone (O_3). Of particular interest is NO_2, a byproduct of fossil fuel combustion that has a brief photochemical lifespan. This gas can effectively identify emission sources. During the COVID-19 pandemic, it served as an important indicator of economic performance in multiple nations. The European Space Agency has plans to launch a new satellite in 2025, which will be capable of measuring both CO_2 and NO_2 simultaneously (86).

Neutralizing carbon using digital earth

Digital Earth intends to leverage vast amounts of data, primarily derived from satellite insights, to create models and simulate or predict the current and future state of global ecosystems across different geographic areas and timeframes. It will also facilitate the visualization of the outcomes. This suite of innovative technologies will play a crucial role in enhancing carbon neutrality and carbon trading for two main reasons: The carbon cycle is affected by a diverse range of environmental and human variables. Many earlier models struggle to accurately represent these components and predict the carbon sink. Estimating this is a complicated task and the outputs from various models often show significant discrepancies. By integrating multiple models with accurate data, Digital Earth can function as a robust platform for executing these models and validating their results, leading to a more precise assessment of the global carbon sink (87, 88).

Policy Issues

1. Establishing institutional mechanisms for collection and management of data for developing the GHGs inventory at the state and national levels.
2. Linking subsidy on fertilizer, water and other agri-inputs with GHGs mitigation and introducing the concept of 'green budgeting' at the state and national levels.
3. Inclusion of adaptation technologies with mitigation co-benefits in developmental schemes such as MGNREGA and national and state action plans on climate change.
4. Developing innovative payment mechanisms and support for mitigation for small holder farmers.

Conclusion

Ongoing studies lack a clear focus on how to incorporate renewable energy sources into industrial practices while decreasing reliance on fossil fuels. Key objectives involve expanding renewable energy usage, transitioning from fossil fuels and tackling challenges like storage solutions. Extensive research is necessary for developing sustainable food systems, enhancing waste recycling processes and making advances in carbon capture, utilization and storage technology. Additionally, satellite surveillance plays a vital role in monitoring greenhouse gas emissions and providing precise biomass tracking.

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Authors' contributions

SIP contributed to the writing of the original draft and conceptualization. LR helped in the revision of the draft, the inclusion of tables and figures and proofreading. SB contributed to revision, formatting and supervision. All the authors read and approved the final version of the manuscript.

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Declaration of generative AI and AI-assisted technologies in the writing process

For grammatical corrections, I have used Grammarly software.

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