The Innovation

Review

Technologies and perspectives for achieving carbon neutrality

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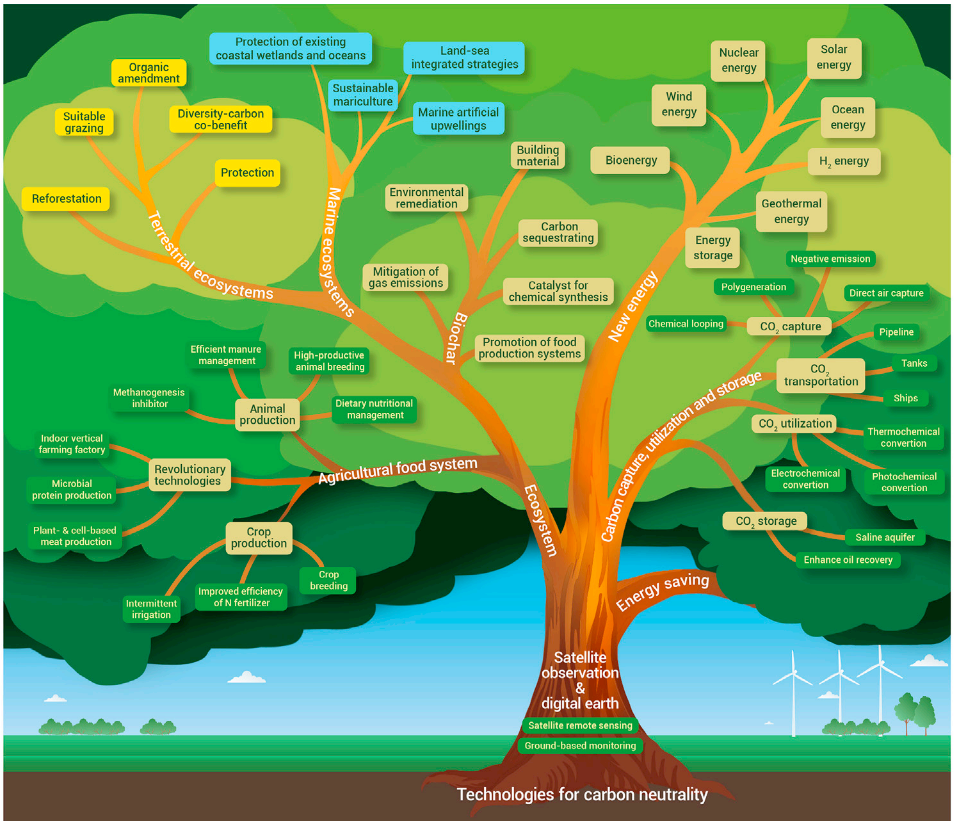
Graphical abstract



Public summary

- Carbon neutrality may be achieved by reforming current global development systems to minimize greenhouse gas emissions and increase CO_2 capture
- Harnessing the power of renewable and carbon-neutral resources to produce energy and other fossil-based alternatives may eliminate our dependence on fossil fuels
- Protecting natural carbon sinks and promoting CO_2 capture, utilization, and storage are conducive to mitigating climate change
- This review presents the current state, opportunities, challenges, and perspectives of technologies related to achieving carbon neutrality

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Global development has been heavily reliant on the overexploitation of natural resources since the Industrial Revolution. With the extensive use of fossil fuels, deforestation, and other forms of land-use change, anthropogenic activities have contributed to the ever-increasing concentrations of greenhouse gases (GHGs) in the atmosphere, causing global climate change. In response to the worsening global climate change, achieving carbon neutrality by 2050 is the most pressing task on the planet. To this end, it is of utmost importance and a significant challenge to reform the current production systems to reduce GHG emissions and promote the capture of CO_2 from the atmosphere. Herein, we review innovative technologies that offer solutions achieving carbon (C) neutrality and sustainable development, including those for renewable energy production, food system transformation, waste valorization, C sink conservation, and C-negative manufacturing. The wealth of knowledge disseminated in this review could inspire the global community and drive the further development of innovative technologies to mitigate climate change and sustainably support human activities.

Keywords: carbon neutrality; renewable energy; carbon sequestration; carbon capture and utilization; carbon footprint reduction; climate change mitigation

INTRODUCTION

Industrialization, the engine for economic expansion and urbanization, has accelerated the development of different sectors in association with the growth of the global population and affluence.[1,2] By 2050, the world's population is expected to grow from 7.8 billion in 2020 to 9.9 billion, requiring 80% more energy and 70% more food, when the accompanying increase in living standards is considered.[3,4] Over the past two centuries, the world economy has heavily depended on the overexploitation of natural resources and the alteration of the life-supporting biogeochemical cycles and processes in the biosphere.[5] The current boom in the use of petroleum resources and deforestation is a response to the pressure to meet the growing demand for energy, food, and other commodities.[4,6] These eco-unfriendly practices are the root causes of the increased emissions of anthropogenic sources

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of global greenhouse gases (GHGs), the primary drivers of climate change. In 2016, energy and food systems accounted for more than 90% of all global emissions of GHGs (mainly in the form of CO_2).[7] It is expected that GHG emissions will increase by 50% by 2050, mainly due to the expected 70% increase in energy-related CO_2 emissions.[4,8] If these emissions keep rising at their current rate, it will push the carbon (C) cycle out of its dynamic equilibrium, leading to irreversible changes in the climate system. Therefore, concerted efforts to reduce C emissions and increase C sequestration have to be initiated through a variety of socio-economic and technological interventions.[9,10]

In response to the ever-increasing global greenhouse effect, all countries signed a landmark United Nations climate agreement in Paris on December 12, 2015, to jointly tackle GHG emissions and combat climate change.[11] Under the 2015 Paris agreement, all countries agreed to keep warming below 2.0°C and make an effort to curb global warming to less than 1.5°C by achieving C neutrality by 2050.[12,13] The global average temperature in 2020 was 1.2°C warmer than the pre-industrial temperature, and the effects of this warming are felt globally.[14] Based on the current climate data, there is an urgent need to accelerate our efforts to reduce atmospheric GHG concentrations to reverse global climate change.

To achieve C neutrality and sustainably support human activities, it is of utmost importance to reduce fossil fuel and food C emissions while promoting C sequestration in terrestrial and marine ecosystems.[15] Different strategic paths to achieve C neutrality have been mapped out in different countries[16,17] but, due to the magnitude of the fluxes involved, reducing C emissions to net-zero is challenging. According to the International Energy Agency,[18] if the world is to become C neutral by 2050, the extraction and development of new crude oil, natural gas, and coal must stop in 2021. In this regard, investment in research and adoption of renewable energy from C-free sources (i.e., sunlight, tide, wind, water, wave, rain, and geothermal power) and biomass (i.e., organic materials from plants or animals) are the key to bridging the gap between the rhetoric and reality of net-zero CO_2 emissions.

Renewable resources can provide more than 3,000 times the current global energy demand.[19] The global demand for renewable energy (in the form of electricity, heat, and biofuels) has expanded considerably in the past decade, with the share of renewables in global electricity production growing from 27% in 2019 to 29% in 2020.[20] Despite this progress in renewable energy use, the pace of transition from conventional to renewable energy is not fast enough, and the world is not on track to achieve C neutrality and sustainable development by 2050. Therefore, more effort is needed to transform the energy sector into a climate-neutral hub. This can be accomplished through the collaborative work of various multidisciplinary research teams and the application of integrated approaches developed as a result of recent scientific and technological advances in civil and environmental engineering, biotechnology, nanotechnology, and other areas. In addition to the development of renewable energy, the management of food systems also needs to be optimized to increase production efficiency and reduce C emissions. This can be achieved through the development of new technologies for better fertilizer production and precision agriculture, integrating crop-livestock production systems, and developing C-neutral food production systems. Given that the world is unlikely to substantially reduce fossil fuel-based CO_2 emissions in the short term, harnessing the power of natural resources and processes to remove CO_2 from the atmosphere presents a feasible route toward C neutrality. To mitigate climate change, various potential strategies for enhancing C capture from the atmosphere through industrial means and C sequestration in terrestrial and marine ecosystems are being investigated. These include bioenergy with C capture and storage;[21] enhanced rock weathering by spreading crushed minerals, which are naturally capable of adsorbing CO_2 on land or in the ocean;[22] afforestation and reforestation;[23] soil C sequestration via biochar, compost, direct biowaste incorporation, and conservation tillage, among others;[24–26] ocean fertilization through the application of iron or/and other nutrients for promoting the growth of photosynthetic plankton;[27] coastal wetlands restoration; and direct air capture using chemicals to remove CO_2 directly from the atmosphere.[28] It is necessary to evaluate the practicality, cost, acceptability, and usefulness of each of those

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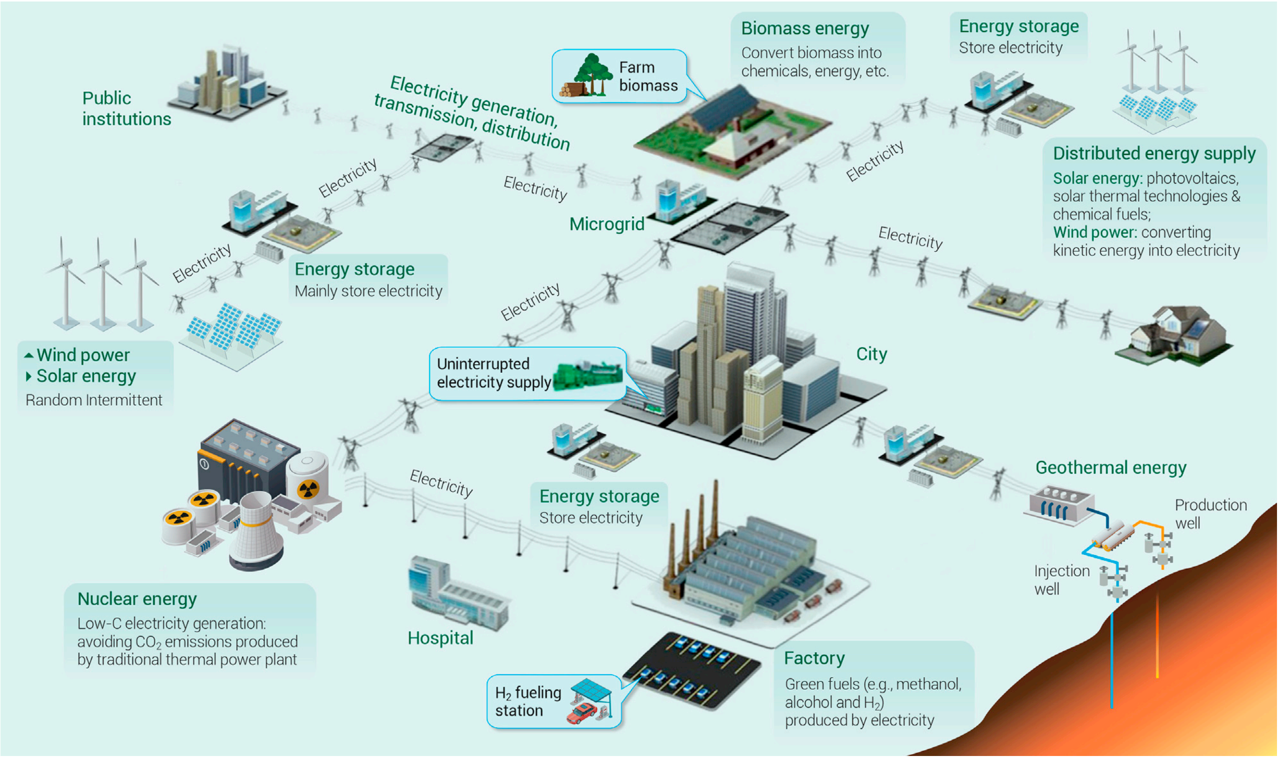


Figure 1. Core technologies for renewable energy production

so-called negative emission technologies (NETs) in mitigating climate change and its influence on global ecosystems and human activities.

There have been many reviews exploring pathways to C neutrality, with the focus on renewable energy sources,[19,29] C capture and storage in terrestrial and marine ecosystems,[22,30–35] and food system transformations.[36–41] However, to the best of our knowledge, no review has compared the strengths and challenges of all available new technologies toward C neutrality or highlighted uncertainties associated with those new technologies in climate change mitigation.

This review focuses on new technologies designed to accelerate our race to C neutrality in different areas, including those for renewable energy, sustainable food systems (increasing soil C sequestration and reducing C emissions), sustaining the health of Earth's largest C stores (restoration and protection of marine and forest ecosystems), and C-neutral chemical industrial production. The information disseminated in this review is expected to inspire the global scientific community and stimulate interest in further research on new pathways to achieve C neutrality and the United Nations Sustainable Development Goals.

TECHNOLOGIES FOR RENEWABLE ENERGY

The overconsumption of energy from non-renewable resources increases energy scarcity, greenhouse gas emissions, climate change, and environmental degradation, posing threats to mankind. As a result, the ecological awareness of humankind and the transition to low-C or C-free energy are more concerning now than at any time in the past. A series of policies have been developed on a global scale[42,43] to address those concerns.

Among clean energies, renewables, such as solar energy, wind power, and ocean energy, are regarded as some of the most important and efficient means to achieve C neutrality. In addition to nuclear and H_2 energy, which have the advantages of low resource consumption and low pollution risk, and are identified as the strategic approach to ensure national energy security and to achieve the goal of "C neutrality," bioenergy is also key to reorganizing the structure of energy supply and consumption. Core technologies for renewable energy (Figure 1), and the effects of these technologies on realizing C neutrality, are discussed below. In particular, the future development and feasible progress of these technologies are also presented.

Solar energy

Solar energy is an inexhaustible resource. Because of its clean, renewable, and ubiquitous nature, solar energy can play an important role in the global renewable energy supply.[44] Currently, fossil sources (e.g., oil, coal, and natural gas) still dominate the total energy consumption across the world. In contrast, solar energy, hydropower, wind power, and tidal energy, which do not produce C emissions, only constitute a small part of the energy consumption. To achieve C neutrality, it is essential to increase renewable energy use. Thus, replacing traditional fossil fuel with renewable energy from sunlight is highly desirable and crucial for reducing CO_2 emissions and decarbonizing energy systems toward C neutrality.

The rapidly developing photovoltaic technology has been recognized as a powerful method to harness solar energy.[45] Conventional thin-film solar cells using inorganic semiconductors, such as silicon, gallium arsenide (GaAs), copper indium gallium selenide, and cadmium telluride (CdTe) materials, have been industrialized on a large scale, as they have high power conversion efficiencies and salient operational stability. Some newly emerging solar cells, such as organic solar cells, perovskite solar cells, quantum dot solar cells, and other integrated devices, have been developed as promising photovoltaic technologies in recent years.[45–49] This new generation of solar cells can complement traditional solar cells and will act as alternative low-cost photovoltaic technologies in many specific areas to provide power generation and thus effectively reduce CO_2 emissions. Although their power conversion efficiencies have reached more than 18%, it is necessary to further improve the efficiency and stability of large-area solar cells and reduce the product manufacturing and decarbonization costs. In addition, solar cell panels and photovoltaic grid-connected systems are also essential to electricity generation and may accelerate our race to C neutrality. Recent research showed that installing solar panels on rooftops may decrease GHG emissions by 57% in the near term (approximately 10 years) and achieve C neutrality in the long term (about 30 years).[50]

Solar thermal technologies rely on photothermal conversion to achieve heat, steam, and electricity production for C-neutral operations, unlike photovoltaic techniques. When solar thermal technologies, such as concentrated solar power systems, are employed in commercial and residential sectors to replace natural gas as a source of energy, an obvious reduction in both energy consumption of fossil fuels and CO_2 emissions has been observed.[51,52] Besides photovoltaic and solar thermal technologies, some strategies to convert solar radiation into stable chemical fuels also provide feasible ways for large-scale utilization and storage of solar energy toward energy decarbonization. For instance, great efforts have been made on solar hydrogen production, demonstrating an extremely attractive route to produce hydrogen fuel by adopting renewable solar energy or solar-derived power to electrolyze water.[53,54] Note that hydrogen fuel is an ideal clean energy source to deliver C-free emissions, showing a great potential to reduce GHG emissions. Recently, a new concept of liquid sunshine has been proposed for combining solar energy with captured CO_2 and water to generate green liquid fuels, such as methanol and alcohol, which may deliver an ecologically balanced cycle between generation and utilization of CO_2 in global production systems.[55]

Solar energy represents an ideal solution to meet the energy demands in a low-C and C-free society. Owing to the low-operating costs, a series of useful measures based on solar energy techniques are good candidates to reduce C emissions and utilize CO_2 to form clean energy storage, thereby playing an irreplaceable role in the realization of C neutrality. The next decades will require accelerated development of advanced energy conversion/storage technologies and large-scale deployment of solar energy combined with clean resources to promote integrated pathways to C-neutral energy systems.

Wind energy

Wind results from the motion of air due to uneven heating of the Earth's surface by the Sun. This means that wind power could be regarded as indirect solar energy.[56] Like solar energy, wind energy will play a critical role in realizing "C peak and C neutrality."

The Earth has abundant wind resources, which are mainly distributed in grasslands, deserts, coastal areas, and islands.[57] The site location has a significant impact on the economy, technicality, and implementation of wind energy. The world attaches great importance to and vigorously supports the development of wind power. However, one of the issues that hinders wind energy utilization is the noise generated by wind turbines. Strategies to reduce or minimize the noise produced by wind turbines and further utilize wind sources sensibly are urgently needed. Another concern with wind energy production is that wind turbines may have an adverse effect on birds via collisions, disruptions, or habitat destruction if they are located inappropriately.

Although the wind resource on Earth is abundant, the uneven distribution of wind resources across the landscape poses a challenge to the transport of electrical energy produced by wind turbines. And the unpredictable nature of winds in terms of speed and direction will result in a variable and unstable phase, amplitude, and frequency for the generation of electricity, which may make it difficult to be integrated into the grid, resulting in a waste of wind energy. The cost of installing a wind turbine is currently quite high, which also hinders the widespread adoption of this technology. It is necessary to devote more efforts to exploring and developing wind energy technology to meet the needs of energy users.

Ocean energy

Ocean energy refers to the energy contained in the water body in the ocean and is both renewable and clean. The ocean energy reserve is enormous globally and is enough to power the entire world. There are typically five different energy forms: tidal energy, wave energy, ocean current energy, thermal energy, and osmotic energy. The tidal, wave, and current energies are mechanical energy. The research of exploiting ocean energy was started a few decades ago. The geographical distribution varies broadly for different energy forms, and the harnessing technologies are also quite different.

Tidal energy is the energy contained in the tide, including the potential energy related to the water level and the kinetic energy of the tidal current. The tide originates from the gravitational interaction of sea water with the Moon or the Sun. Tidal energy is estimated to be about 1,200 TWh per year, which is relatively low among all ocean energy forms[58] due to limited locations from where tidal energy can be harvested. The tidal barrage is adopted to harvest the potential energy of tides, which is relatively technologically mature. Early tidal barrages started to operate in the 1960s, and tidal energy now has the largest share of ocean energy being exploited (Khare et al., 2019). Harnessing tidal current power mainly relies on turbines, although other types of devices are also under development.

Wave energy is the kinetic and potential energy in water waves, which is widely distributed. It essentially comes from wind, which transmits part of its kinetic energy to the water at the ocean surface. The potential of wave energy globally is 29,500 TWh per year.[59] The technology for harvesting wave energy is less mature than that for tidal energy, and many different types of devices are being tested on a small scale toward commercialization. The major device forms include point absorber, attenuator, oscillating water column devices, and overtopping devices. Besides traditional large devices using electromagnetic generators, new technologies based on triboelectric nanogenerator networks are also being developed toward effective harvesting of wave energy economically.[60]

Ocean current energy is reserved in the large circulations of sea water globally. It is the kinetic energy in the water flow. The supply of this source of energy is stable with little fluctuation. It can be extracted using turbines. The device needs to be deployed in deep sea and far from the shore; thus, less effort has been devoted to harnessing this type of energy.

Thermal energy originates from the Sun's irradiation, which heats the upper layer of the sea water, making its temperature different from the water in the deep sea. Such temperature differences can be exploited for electricity generation mainly based on thermal cycles. Due to the high-temperature difference required for improved efficiency, this form of energy is mainly distributed in the tropical region. The potential for this energy is estimated to be 44,000 TWh per year.[61] The utilization of this form of energy is still at the research stage by universities and research institutes.

Osmotic energy, also called salinity gradient energy, is the energy that exists between water bodies with different salt concentrations. The salinity of sea water is not homogenous globally; for example, a salinity gradient is formed in estuaries where fresh water meets salt water. The harness of such energy relies on high-performance membranes that are robust in sea water. Two main technologies are being tested at present: pressure-retarded osmosis and reversed electrodialysis.[59] Osmotic energy is still a conceptual energy source and is not ready for commercialization.

The ocean energy reserve is enormous globally and is enough to power the entire world. Technologies to harvest tidal and wave energy are on the verge of commercialization. Technologies for harvesting ocean current energy, thermal energy, and osmotic energy are still in their early development stage. Major challenges of exploiting ocean energy lie in the economic cost-competitiveness and technological reliability in severe ocean environments. By overcoming these challenges, ocean energy will provide the world with abundant clean energy.

Bioenergy

Biomass is a renewable source of energy that originates from plants. The most important sources of biomass are agricultural and forestry residues, biogenic materials in municipal solid waste, animal waste, human sewage, and industrial wastes. Biomass provides 13%–14% of the annual global energy consumption.[62] Various processes are used to convert biomass into energy, including the following.

Thermochemical conversion of biomass includes gasification, pyrolysis, and combustion. Combustion produces approximately 90% of the total renewable energy obtained from biomass.[63] Pyrolysis can convert biomass into solid, liquid, or gaseous products by thermal decomposition at temperatures around 400°C–1,000°C in the absence of oxygen, producing components such as acids, esters, and alcohols.[64] Gasification converts carbonaceous materials into combustible or synthetic gas by reacting the air, oxygen, or vapor at a temperature of over 500°C, preferably over 700°C, yielding gases such as H_2, CO, and CH_4.[64,65]

Chemical conversion converts vegetable oils and animal fats into fatty acid esters through esterification or/and transesterification to produce biodiesel. The transesterification process is necessary since raw materials are composed of triglycerides, which are not a useable fuel. Triglycerides are converted into methyl or ethyl esters (biodiesel) using a mostly alkaline catalyst in the presence of methyl or ethyl alcohol, respectively. Rapeseed oil (accounting for 80%–85%) and sunflower oil (accounting for 10%–15%) are major vegetable oils used for biodiesel production.[63]

Biochemical conversion converts biomass into liquid fuels (e.g., alcohols and alkanes), natural gas (e.g., hydrogen and methane), different types of bio-products (e.g., carotenoids, omega-3 and omega-6 fatty acids), as well as other chemical building blocks (e.g., acetic acid and lactic acid) using microbes and enzymes as the catalyst.[66] The most popular biological conversions are fermentation and anaerobic digestion.

The most common biomass feedstock used for biological conversion is lignocellulosic biomass, such as agricultural and forestry residues. Lignocellulosic biomass is the most abundant and widely available renewable resource in the world, mainly composed of three heterogeneous biopolymers, namely cellulose, hemicellulose, and lignin. Three major steps are involved in cellulosic bioethanol production: (1) pre-treatment, (2) enzymatic hydrolysis, and (3) fermentation. Pre-treatment uses physical, chemical, or physicochemical methods to improve biomass accessibility by enzymes. Enzymatic hydrolysis splits cellulose and hemicellulose into monomer sugars, such as glucose, xylose, and mannose. The conversion of biomass-derived sugars into ethanol by *Saccharomyces cerevisiae* has received most research and development efforts. Another method for producing butanol is through fermentation, specifically through an acetone/butanol/ethanol process that is predominantly carried out by *Clostridia* strains.[67] Anaerobic digestion consists of hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These reactions break down the macromolecules in the biomass into simpler molecules with the generation of biogas in an anaerobic environment. One of the advantages of anaerobic digestion lies in the potential of the biogas to be used directly in ignition gas engines and gas turbines.

Despite the presence of abundant biomass resources, there is still a need for work on the use of biomass to produce energy, with main efforts needed to increase productivity and reduce costs to further expand the share of such renewable energy in the total energy consumption.[68] Some of the issues that need to be resolved are the high cost of transporting the biomass to the site for bioenergy production through various conversion processes and the sustainability of the production of bioenergy feedstocks.

H_2 energy

Hydrogen has been a necessity for industrial use over the past two hundred years. The demand for hydrogen (currently >80 Mt per annum) has grown more than three times since 1975 and continues to rise. Up to now, H_2 is almost entirely produced from fossil fuels, consuming around 6% of global natural gas and 2% of global coal, resulting in emissions of around 830 Mt of CO_2 per year.[69] Recently, hydrogen energy has drawn a great deal of interest because it can be used to establish a fully renewable energy system similar to an electricity grid, providing the sector integration needed for energy system transition and decarbonize energy end uses.[70]

Hydrogen production using renewable energy has a strong likelihood of both technological and economic viability in the near future. The decreasing costs of renewable energy and the increase in variable renewable power supplies' market share have put significant roadblocks in the way of cheap water electrolysis.[71] With the fast development of artificial intelligence, deployment and learning-by-doing are expected to reduce electrolyzer costs and supply chain logistics. After H_2 production via electrolysis, safe and low-cost hydrogen storage and transportation technology need to be developed. Hydrogen can be stored in gas, liquid, and solid states.[72,73] As of now, none of these technologies are mature for establishing a hydrogen economy. In addition, hydrogen offers the lowest cost option for long-term energy storage, such as inter-seasonal; however, the ability to store large quantities of hydrogen at low costs with a high safety is still a challenge. Underground H_2 storage in large salt caverns and hydrogen transport via existing and refurbished gas pipelines are available at low cost to support long-term energy storage and sector coupling. However, equipment standards need to be adjusted and are also limited by geographical conditions.[74,75]

Hydrogen fuel cell technologies have developed rapidly and are ready for commercialization, to the point that we now see commercial sales of hydrogen-powered passenger cars, such as Mirai, Clarity, and Nexo, and heavy-duty vehicles, trains, and ships. The main issue now is to reduce the cost while maintaining an acceptable level of durability and efficiency.[76] Other opportunities that pay more attention to the handling of energy-intensive commodities produced with hydrogen—synthetic organic materials/pharmaceuticals, iron and steel making, building/marine bunkers or feedstock to produce ammonia/methanol, and so on—seem to be prime markets. We now need to develop scale-up technologies, increase energy use/conversion efficiencies, optimize the upgrade of H_2 industrial structures, and lower costs to enable widespread use of H_2 energy. There needs a long-term devotion to fundamental understanding and development of new strategy/technology and infrastructure.

Nuclear energy

Nuclear energy is a major contributor to clean energy, accounting for 40% of low-C electricity generation worldwide, and avoids about 1.7 Gt CO_2 emissions a year globally. Therefore, nuclear energy is a strategic approach to ensure national energy security and achieve C neutrality. Nuclear energy is mainly generated through nuclear fission, while nuclear fusion technology is at the R&D stage. However, the future development of nuclear fission energy is highly uncertain for several reasons: rising costs, challenges with the disposal of radioactive spent fuel, plant safety, and risks for nuclear weapons proliferation. Therefore, Gen IV reactor nuclear fission systems have been proposed[77] based on the following considerations: safety, reliability, physical protection, cost-effectiveness, sustainability, and proliferation resistance. Furthermore, Gen IV reactor systems are key pillars of a sustainable and low-C energy mix, which can support environmental stewardship in both the electric and non-electric energy sectors.[78]

Molten salt reactors (MSRs) are in the framework of the Generation IV International Forum because of their nuclear safety and sustainability.[79] In 2011, the Chinese Academy of Sciences launched the "Thorium molten salt reactor nuclear energy system" project to realize effective thorium energy utilization and comprehensive utilization of nuclear energy for 20–30 years. The small modular design of MSRs can reduce the R&D challenge and difficulty of large commercial MSRs while increasing their economic return and safety. Near-term deployable MSRs will have safety performance comparable with or better than that of evolutionary reactor designs. In addition, the MSR uses high-temperature molten salt as the coolant, which can be combined with the molten salt energy storage system of concentrating solar power stations to realize various regions and large-capacity heat storage systems. In this case, MSR plays the role of baseload energy source and can provide regulation and supplement the unstable and intermittent renewable energy. A reliable energy supply can be ensured even under long-term severe weather conditions. An MSR with an outlet temperature above 700°C can also be applied to high-temperature electrolysis hydrogen production.[80] In short, advancing MSR research will play an important role in the transition to sustainable clean energy and in accelerating global efforts to achieve C neutrality. Nuclear fusion, the dominant reaction that powers the Sun, is another nuclear energy type besides atomic fission. Nuclear fusion produces no long-lived radioactive waste. There is no risk of a meltdown, such as that which might occur with a fission reactor, because a fusion reactor shuts down within a few seconds when interference occurs. Thus, fusion energy is regarded as the optimal energy source of the 21st century, which will benefit our effort to achieve C neutrality. A tokamak, a piece of equipment that confines plasma using magnetic fields, is the most widely researched configuration for fusion power generation worldwide, and it is regarded as the most suitable solution for future fusion power plants that can achieve steady-state operation. Based on the experience obtained from small- and mid-sized tokamaks, the International Thermonuclear Experimental Reactor (ITER) is being constructed as the world's largest tokamak through the cooperation of seven countries: China, EU, Japan, South Korea, Russia, US, and India. The goal of ITER is to demonstrate sustainable deuterium-tritium plasma formation to create a 500 MW fusion power (Q = 10) for a duration of 300–500 s.[81] According to the roadmap of fusion energy development, the construction of demonstration power plants (DEMO) will be the last step before building a fusion power plant. China,[82] the EU,[83] and Japan[84] have carried out their studies on DEMO, and the engineering design of the Chinese Fusion Engineering Testing Reactor was completed in 2021.

Geothermal energy

Geothermal energy is non-carbon-based heat energy contained in the interior of the Earth, with the advantages of stability, continuity, and high capacity.[85] It will play an important role in providing a stable and continuous basic load in the future energy structure.

As the primary form of utilization of geothermal energy, geothermal power generation utilizes natural geothermal steam (or low-boiling working fluid steam heated by geothermal fluid) to drive a turbine to generate electricity. At present, geothermal power generation technologies mainly include dry steam power, flash power, and binary power systems.[86]

Direct utilization of geothermal energy occurs in the form of thermal energy, which is usually applicable to medium- to low-temperature geothermal resources. At present, direct geothermal utilization technologies mainly include ground source heat pumps, geothermal heating, geothermal refrigeration, geothermal greenhouse, and geothermal drying.[87]

As a country with a high geothermal utilization rate, geothermal energy in Iceland provided 62% of the country's energy production in 2020, helping it achieve the goal of a zero-carbon country in the future.[88] In 2021, the US Department of Energy's (DOE) Frontier Observatory for Research in Geothermal Energy selected 17 projects for up to $46 million in funding for cutting-edge, domestic, and carbon-free enhanced geothermal projects.[89] Turkey is one of the fastest-growing countries in geothermal energy, with a geothermal power generation capacity of 1,549 MW as of 2020.[88]

In 2020, global geothermal utilization achieved an annual CO_2 emission reduction of about 300 million tons, and it has achieved an annual CO_2 emission reduction of about 100 million tons in China. The building area of shallow and deep geothermal heating is close to 1.4 billion m^2, which makes a great contribution to carbon reduction for buildings. Geothermal energy plays an important role in clean heating in northern China, and a number of major projects have emerged; for example, the "Xiongxian model" Beijing Sub-center, Beijing Daxing International Airport, among others.

Energy storage

The electricity produced from most renewables is random and intermittent, which hinders the widespread application of renewables.[90] Therefore, developing energy storage technology is pivotal to improving electricity output reliability and stability from renewables.[91]

Energy storage technologies can be divided into mechanical, electromagnetic, electrochemical, and phase change energy storage. Mechanical energy storage technologies, such as pumped hydro[92–94] and compressed air energy storage,[95–97] are currently the mainstream technologies for electric energy storage. Although pumped hydro is the most mature technology for large-scale energy storage, its use is restricted by site availability and the large initial investment. Compressed air energy storage is considered to be the least-cost storage technology but relies on the availability of naturally occurring caverns to reduce overall project costs.

Electrochemical energy storage technologies are one of the most promising electric energy storage applications because of their high efficiency and flexible design. Based on market prospects, battery technologies, one of the representative electrochemical energy storage technologies, can be divided into two types: (1) alkali (lithium, sodium, potassium)-based batteries, or advanced lead-C batteries for portable electronic devices and electric vehicles, and (2) flow batteries for renewable energy integration, microgrid, and power grid peaking. Lithium-ion batteries have already dominated our daily life because of their desirable electrochemical performance in both energy density and power density, as well as the advances in their system design and manufacturing.[98,99] Their upfront cost remains a big challenge for stationary applications because of the limited supply of lithium. As a result, sodium-ion batteries emerge as a promising alternative for their economic feasibility. Due to the higher redox potential of Na/Na^+ and larger ionic radius (as compared with Li/Li^+), sodium-ion batteries are currently suffering from low energy density and poor cycling stability. Compared with lithium- or sodium-ion batteries, solid-state lithium batteries have the advantages of high energy density and improved safety, making them very promising for next-generation energy storage applications. However, their application is confronted with many problems that need to be addressed, e.g., the large interfacial resistance between solid electrolyte and electrode and the limited power density. Moreover, the revolutionary technologies that dramatically increase safety and reliability remain urgently needed for the aforementioned battery types.[100,101] Hence, innovative materials design and development of control strategy that can endow alkali-based batteries with high safety, high energy density, and long life cycle can further accelerate the progress of these energy storage technologies.

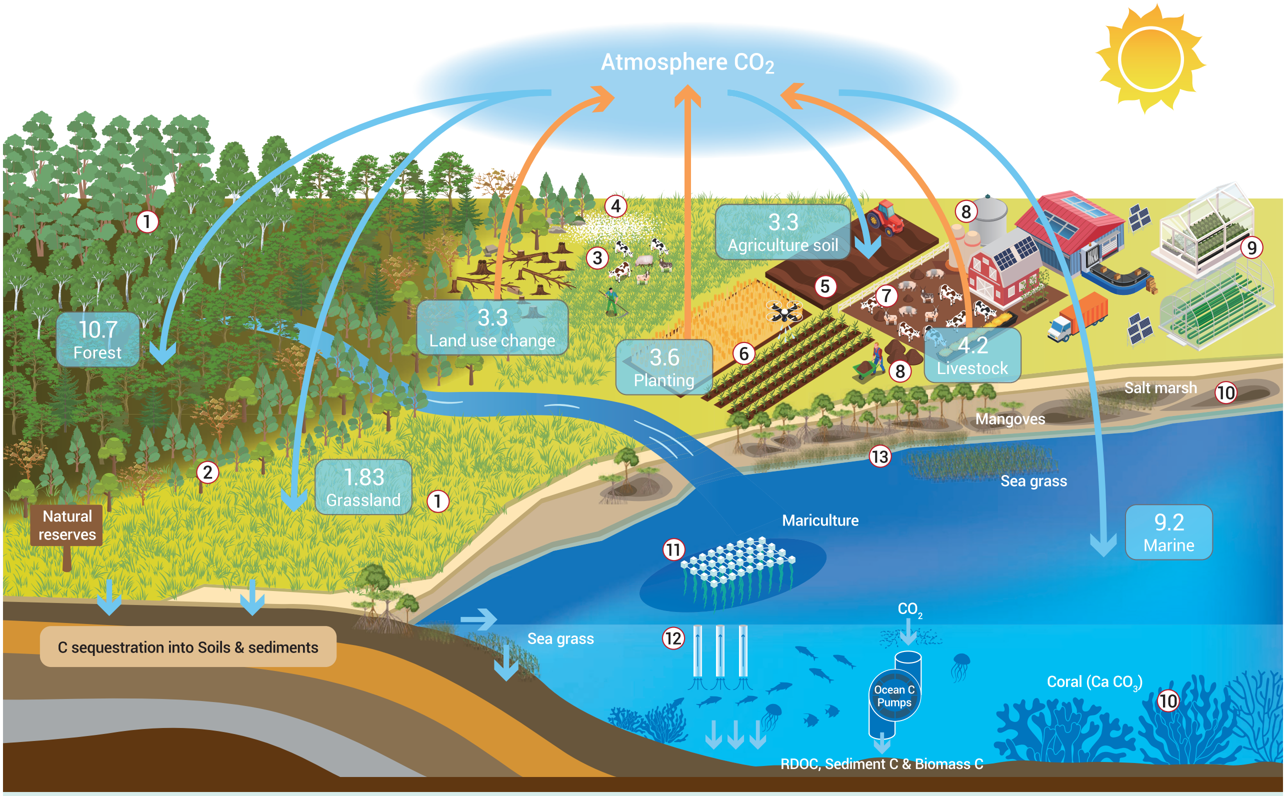
In contrast, flow batteries are well suited for large-scale energy storage applications because they have high safety, high efficiency, and flexibility.[102] The vanadium flow battery, led by the Dalian Institute of Chemical Physics, Chinese Academy of Sciences, has been developed as one of the most mature technologies and is currently at the commercial demonstration stage.[103] Currently, the world's largest vanadium flow battery project (200 MW/800 MWh) is being built in Dalian, Liaoning.[104,105] Different from vanadium flow batteries, zinc-based flow batteries have attracted great attention in distributed energy storage due to their advantages of low cost and high energy density. Some zinc-based flow batteries are currently at the demonstration stage. However, the issues of zinc dendrite/accumulation, limited areal capacity, and reliability need to be overcome to realize their commercialization and industrialization. In addition to vanadium flow batteries and zinc-based flow batteries, a growing interest in novel flow battery systems, especially investigations on novel organic or inorganic redox couples have emerged.[106–108] Although many research papers have been published and demonstrated the promise for energy storage applications, these flow batteries are currently in the early stages of their development.

Different energy storage technologies have different reliability, cost, efficiency, scale, and safety. These technologies complement each other, and their applications are dependent on many aspects, such as energy storage time, site requirements, and environmental concerns. Coupled with renewables, the development of energy storage technologies will contribute to reducing CO_2 emissions and achieving C neutrality.

TECHNOLOGIES FOR ENHANCED CARBON SINK IN GLOBAL ECOSYSTEMS

Global ecosystems contribute to the release and capture of CO_2, methane (CH_4), and nitrous oxide (N_2O) (Figure 2), and influence the atmospheric GHG composition and the climate. Over the last 50 years, the removal of about one-third of anthropogenic GHG emissions has been attributed to terrestrial ecosystems.[109] In the process of producing high quality and large quantity of food for a growing affluent population, global food systems are important GHG sources and account for more than one-third of the global anthropogenic GHG emissions, of which 71% came from agricultural crop-livestock production systems and land-use change activities.[110] Forest ecosystems are one of the most important global C sinks and absorb 45% of anthropogenic GHG emissions,[111] with 85%–90% of terrestrial biomass produced in forest ecosystems. The ocean covers more than 70% of the Earth's surface and plays an important role in capturing CO_2 from the atmosphere. Currently, 22.7% of the annual CO_2 emitted from human activities is sequestered into the ocean ecosystem.[112]

To prevent irreversible deterioration from global climate change, the biosphere must increase biomass production and food supply with lower GHG emissions, remove CO_2 from the atmosphere and store it as organic



Strategies to promote GHG reduction & absorption

Forest, grassland & soil

1 Protection of existing forest & grassland
Forest managements with biodiversity-carbon mutually benefit
2 Short-rotation young forest of fast-growing hardwood tree species
3 Sustainable grazing land management
4 Enhancement of rock weathering from basalt dust
5 Organic materials amendment

Crop production

6 Crop variety breeding
Precision irrigation
Improved efficiency of N fertilizers
Inhibitors for CH_4 & N_2O emissions

Animal production

7 High-productive animal breeding
Dietary nutritional management
Methanogenesis inhibitor
8 Efficient manure management

Revolutionary technologies

9 Indoor vertical farming factory
Microbial protein production
Plant- & cell-based meat production

Ocean

10 Protection of existing coastal wetlands & oceans
11 Sustainable mariculture
12 Marine artificial upwellings
13 Land-sea integrated strategies

Figure 2. Overview of global GHG influx (Gt CO_2-eq year^{-1}), and strategies to promote GHG reduction and absorption in global ecosystems

C in the biosphere, contributing to C neutrality. In this sense, we emphasize optimizing crop-livestock production systems, promoting forest ecosystem health with soil C sequestration, and utilizing soils and marine ecosystems as natural C sinks. These can provide breakthrough technologies for C reduction and immobilization in terrestrial and marine ecosystems (Figure 2) and are further discussed in the following subsections.

Carbon emission reduction in agricultural food production systems

The GHG emissions from agricultural food production systems have increased by around one-third during the past 20 years. Emissions are mainly due to the increase in crop and animal production,[113] with 4.2 Gt CO_2-eq year^{-1} from enteric fermentation, manure and pasture management, and fuel use in livestock production, 3.6 Gt CO_2-eq year^{-1} from synthetic N fertilizer application and crop production for human and animal food, and 3.3 Gt CO_2-eq year^{-1} from changes in land use for crop-livestock production systems.[114] Given the uncertainties surrounding the large-scale implementation of C capture and storage technologies in food production systems,[113] alternative technologies or approaches are needed to mitigate a substantial portion of GHG emissions from agricultural production systems. For example, we need to change our eating habits to diets with less animal-based but more plant-based foods. How to convince people to change their diet on a large scale is a sociological and behavioral question and will not be discussed in this article.

Crop production management. Optimization of fertilizer and water use in croplands can greatly reduce GHG emissions in crop production systems.[115] New synthetic N fertilizer types, such as slow- and control-release N fertilizers, and N fertilizers with urease and nitrification inhibitors, need to be developed to enhance N use efficiency.[116] Better cropping systems, fertilization, and irrigation practices, and the use of advanced digital agriculture technologies, such as multi-sensor drone technology to allow farmers to manage crops, soil, fertilization, and irrigation more effectively and precisely, can reduce N fertilizer input and N_2O emissions.[117,118] For example, intermittent irrigation can substantially reduce the production of CH_4 and increase CH_4 oxidation, and thus can be an important choice to mitigate CH_4 emissions from rice fields.[119,120]

Breeding crop varieties with a high N use efficiency (NUE) can reduce the N fertilizer application rate and reduce the emission of nitrogen oxides. Using transgenic and gene-editing technology, the introduction of proliferating cell factor domain proteins, such as OsTCP19-H, into modern rice varieties has been shown to enhance NUE.[66] Multi-sensor drone-based technology to conduct plant phenotyping can evaluate NUE under different N dosages, thereby allowing the selection of superior genotypes with high NUE.[100] In addition, the development of inhibitors for methanogenesis or the addition of biochar in rice paddies has a large technical potential to reduce CH_4 emissions.[121,122] Other options include using microbes to help crops fix N, thus saving N fertilizers and reducing the footprint of the N fertilizer industry.[111]

Animal production management. Manipulation of enteric fermentation is one of the key strategies to mitigate CH_4 emissions in ruminant livestock production systems. Methane is natural by-product disposal of hydrogen during enteric fermentation and released by methanogenic archaea. Methane inhibitors can be developed by inhibiting H_2 metabolism for methanogenesis.[123] Such inhibitors include alternative electron sinks, phytocompounds, ionophore antibiotics, and oil.[124–126] Among these, 3-nitrooxypropanol is the latest developed and promising inhibitor for methanogenesis,[127] which has been shown to reduce methane emissions in ruminant animals by up to 40%.[128,129] Vaccination, by inducing the host immune system to create antibodies capable of suppressing methanogens, has the potential to reduce CH_4 emissions and is particularly beneficial for pasture-based systems.[130] Given that ruminants fed with forage diets account for 70% of global ruminant methane emissions,[131] breeding new highly digestible forage species with increased non-fiber carbohydrates and less lignified fiber, as well as a high concentration of secondary plant metabolites, such as tannins, saponins, and essential oils, can be worthwhile.

Manure management practices could substantially mitigate indirect GHG emissions by optimizing grazing-land management, generating on-farm energy, and producing organic fertilizers that have a low emission factor.[132] The development of technologies spanning the entire manure management chain, such as advanced in-vessel composting to reduce C and N losses and reverse osmosis for concentrating and recovering N from liquid manure for long-distance transportation, may maximize the potential for recycling C and N from manure. Using manure to produce insect or fungal proteins is another value-added technology that may replace soy and fish proteins in animal feed and reduce GHG emissions associated with feed production.[133]

Animal breeding techniques are to genetically select highly productive animals with less GHG emission intensity,[134] thereby reducing the number of animals required to produce the same amount of food. Shotgun metagenomics provides a platform to identify rumen microbial communities and genetic markers associated with CH_4 emissions, allowing the selection of cattle with less CH_4 emissions.[135–137] Other high technologies include the use of cloned livestock animals and manipulation of traits by controlling target genes with improved productivity.

Revolutionary technologies for agricultural food production. The development of biotechnology, automatic control technology, and artificial intelligence has made it possible to produce vegetables, fruits, and meats in a factory setting. Plant-based meat and cell-based meat can be produced artificially from non-animal sources. Tempeh and tofu are traditional plant-based meats; new plant-based meats include proteins extracted from plants or fungi, then formulated and processed into meat substitutes.[39] Innovative technologies, such as shear cells and 3D printing, are utilized to improve the taste and texture of plant-based meat. Cell-based meat is produced through the development of stem cell and large-scale cell culture technologies and thus has a taste and texture similar to real meat.[138] However, obstacles to commercializing cell-based meat still exist, such as how to scale up, regulatory approval, and the high production cost. Significant progress has been made in recent years, and signals point to commercialization soon.[39]

Other novel biotechnology strategies include metabolic engineering to enable microbial utilization of using CO_2, CH_4, and other C1 feedstocks for the production of microbial proteins rich in essential amino acids.[139,140] These proteins can be used as substitutes for animal proteins. Current advances in biotechnology provide a powerful platform for the production of protein-rich feed or food additives in the form of fungal, algae, yeast, and bacterial cell biomass.[141] However, raising public awareness and obtaining regulatory approval of microbial proteins as feed or food additives still present major challenges requiring imminent actions to improve sustainable food supply with low C emissions.

A plant factory is an indoor vertical farming system that allows continuous food production throughout the year without being affected by seasonal changes and weather conditions. All environmental parameters, such as light level, temperature, moisture, and air composition, are intelligently controlled in a closed system. Several pilot plants demonstrate the feasibility of large-scale production requiring agricultural land.[142] Factories have been built for the commercial production of vegetables, fruits, and medicinal plants. Such systems can achieve extremely high productivity and low GHG emissions without altering land-use change compared with the traditional systems.[143,144] The high initial investment can be recovered quickly through the high rate of return from the operation, and the environmental impact from the operation can be minimized if renewable energy is used to run the plant factory.

Carbon sink in terrestrial ecosystems

Terrestrial ecosystems are vitally important C sinks on Earth. The global forest net C sink is estimated at 10.7 Gt CO_2-eq year^{-1},[112] which is mainly distributed in temperate regions.[145] Grasslands cover around 26% of the ice-free land on Earth and store around 34% of the global terrestrial C.[146] Soils of these grasslands store about 343 Gt C, which is about 50% more than the amount stored in forest soils and acts as a sink for about 1.83 Gt CO_2-eq year^{-1}. Despite the large C stock size, the annual C input rate and turnover times are subject to considerable uncertainty.[147] Agricultural soils can be an important C pool and contribute about 3.30 Gt CO_2-eq year^{-1} to C sequestration,[148] although agricultural food production is related to GHG emissions.[149] Terrestrial ecosystems could increase C sequestration readily by restoring vegetation and incorporating organic soil amendments.[150–152] In addition to these terrestrial ecosystems, inland waters also emit CO_2 to the atmosphere, known as CO_2 evasion. The global inland water CO_2 evasion rate was estimated to exceed 7.70 Gt CO_2-eq year^{-1}.[153] Furthermore, a substantial amount of terrestrial C sequestered through photosynthesis and from chemical weathering is transported laterally along the inland water continuum from terrestrial ecosystems to the ocean. Previous research indicates that anthropogenic perturbations have increased the flux of C[154] to inland waters by up to 3.67 Gt CO_2-eq year^{-1} since pre-industrial times, with over 40% of this additional C returning to the atmosphere via CO_2 evasion and 50% sequestered in sediments, leaving only 10% for the open ocean.

Factors driving the terrestrial carbon sink. Temperature, precipitation, and solar radiation are the three key climatic factors that influence plant photosynthesis and thus the C sink size of terrestrial ecosystems.[155] A great deal of soil C has been lost from natural ecosystems due to the influence of climate change and human disturbance.[156,157] A favorable climate (especially high precipitation) was directly associated with high biomass production and species diversity, which could promote soil organic carbon (SOC) stock, thus offsetting the negative impact of favorable climate on SOC.[158,159] However, the SOC storage and favorable climates (e.g., high temperature and precipitation) are consistently negatively related in shrub lands and forests, but not in grasslands.[160] Other factors, such as atmospheric CO_2 concentration, and growing season, also influence the absorption of CO_2 by terrestrial ecosystems.[161]

Anthropogenic disturbances (e.g., N deposition, P fertilization, pesticides,[162] road density, grazing, fire) have substantially altered ecosystem functions and services across different biomes, thus affecting C sink strength in terrestrial ecosystems.[163] The growth of terrestrial plants is widely limited by soil N and P availabilities. Therefore, adding these nutrients to the soil could enhance plant production and ecosystem C sequestration.[164,165] However, ecosystem C storage depends on the balance between production and decomposition.[166] If the stimulation of decomposition is more than production caused by fertilization, there would ultimately be a net C loss from the ecosystem.[167] The magnitude of nutrient limitation is determined by the environmental conditions, the variability of plant properties, and the potential physio-biochemical machinery of the autotrophs.[168]

Grasslands are one of the largest terrestrial ecosystems, and grazing is the primary land use of grasslands globally.[169] Through herbivory, trampling, and defecation of livestock, grazing induces changes in vegetation abundance and community composition and affects the ecosystem's capacity to fix C. Yet, grazing also regulates a series of C release processes: plant respiration related to biomass loss and microbial C mineralization associated with changes in the soil environment. Ultimately, these jointly affect the C sink function.[170] In recent years, overgrazing has become one of the dominant causes of grassland degradation. A high percentage of rangelands worldwide suffers from overuse of the land, such grasslands support a declining livestock number and, consequently, economic and social problems are created in the communities supported by those grasslands.[171] All of these would have a profound impact on the ecosystem C cycle and deserve more attention.

Technologies for enhancing carbon sinks. Nature-based NETs on land rely on biomass C sequestration through interventions, such as reforestation and afforestation, sustainable forest management, soil C sequestration from increased inputs to soils, and biochar additions.[22,172,173] A recent study suggests that there is a significant reduction of global CO_2 emission from an increase in forest coverage, from a mean of 4.3 (between 1991 and 2000) to 2.9 (between 2016 and 2020) Gt CO_2-eq year^{-1}. During this period, forest land was a C sink globally, but its strength was decreasing, which could be attributed to the removed forest land counterbalancing the C emission from net forest conversion (i.e., deforestation).[174] Therefore, maintaining forest area is the basis of enhancing the C sink of terrestrial ecosystems. Since the late 1970s, China has implemented six major ecological restoration projects, covering 44.8% of China's forests and 23.2% of its grasslands.[175,176] The total annual C sink of the project area was 132 Tg C year^{-1} in 2001–2010, over half of which was attributed to the implementation of these projects.[176] Furthermore, for C sequestration in forest ecosystems, optimizing forest management strategies such as selection of suitable tree species, rotation length, and fertilization regimes are effective ways to increase the amount of forest C sequestration.[177–179] Regulating stands into a more complex vertical structure will lead to faster growth and greater C sequestration in forests because multilayered canopies will occupy a range of light environments, resulting in high light acquisition and light-use efficiency.[180,181] Since the SOC storage of broad-leaved forests is significantly higher than that of coniferous forests, afforestation should use mixed species planting and trees should be arranged according to the tree species' shade tolerance and successional characteristics.[182] Fertilization, usually with N or P, could relieve plants from nutrient limitation and allow them to sequester more C in stems and soils. For example, excess N deposition can significantly increase soil C in N-rich tropical forests.[183]

Promoting sustainable grazing management practices, including appropriate stocking rates, introducing beneficial forage species, and allowing sufficient rest time for plant recovery between grazing, livestock rotation, and adopting silvopasture in livestock production systems, can help reduce GHG emissions and increase C sinks in grazing lands/pastures.[147] For example, when agroforestry systems, such as silvopasture, are applied in suitable locations, C is sequestered in soil as well as in tree biomass, which could promote C uptake by expanding the niches from which water and soil nutrients are drawn, lengthening the growing season, and enhancing soil fertility when N-fixing species are included as part of the system.[184]

The use of organic fertilizers and crop residues in agricultural soils enhances C sequestration, and new technologies need to be developed to improve the C sequestration efficiency, e.g., by repeated changes of redox conditions similar to rice paddies[185] and by promoting microbial diversity[152] and abundance in SOC with powering the "microbial C pump" and improved storage of microbial necromass in soils.[185,186] This may need additional fertilizing measures when leaving crop residues in (poor) agricultural soils. Biochar amendments can also be an effective approach to increase SOC stocks due to the stable (on a millennium timescale) nature of the C contained in the biochar.[187,188] Soil acidification due to atmospheric nitrogen deposition in forest and grassland and excessive nitrogen fertilizer application in croplands should also be avoided to reduce the loss of soil inorganic C.[189,190] Application of crushed calcium- and magnesium-rich silicate rocks to soils is proposed for large-scale CO_2 removal.[191] This technology was called enhanced rock weathering, which increases soil alkalinity, and thus atmospheric CO_2 can be converted into dissolved inorganic C to be finally transported to the ocean, where the stored C has a long lifespan via land surface runoff. Peatlands make up 60% of the wetlands in the world and play a crucial role in the C cycle. Raising water tables and avoiding draining peatlands should be executed to conserve the vital C stored in peatlands.[192]

Carbon sink in marine ecosystems

The total amount of C stored in the ocean is about 44 times greater than that in the atmosphere, and the stored C has a mean residence time of several hundred years.[112,193,194] Atmospheric C fixed and stored in these marine ecosystems is referred to as blue C.[195,196]

Ocean carbon sinks and coastal blue carbon. Several physical and biological processes determine the ocean C sink size. The "solubility C pump" removes atmospheric CO_2 as air mixes with and dissolves into the upper ocean. The "biological C pump" is the photosynthetic absorption of atmospheric CO_2 by ocean microorganisms,[193] and transported to the deep ocean as sinking biogenic particles or as dissolved organic matter, resulting in long-term sequestration of C in the deep ocean.[197] However, the fate of most of this exported material is remineralization to CO_2.[197] During this process, a portion of the fixed C is not mineralized but is stored for millennia as recalcitrant dissolved organic C. Jiao et al.[197] proposed that microorganisms play a vital role in this process and described it as a microbial C pump. The microbial C pump sequesters C by producing recalcitrant dissolved organic C with a lifespan of >100 years[198] and was regarded as the invisible hand behind a vast C reservoir.[199] The estimated magnitude of the microbial C pump in the world ocean is 0.2 Tg C year^{-1}, and some models suggest that climate change would enhance C sequestration by the microbial C pump.[198] The scientific understanding of ocean solubility C pump, biological C pump, and microbial C pump provides a practical and consistent foundation for the research and potential sustainable management of C cycling between land and ocean.

Although the original concept of blue C proposed in 2009 refers to the C that is captured by marine ecosystems covering both coastal and open ecosystems,[200] practical research and development of blue C have predominantly involved coastal wetlands, such as mangrove, seagrass, and salt marsh.[201,202] These coastal ecosystems are highly productive in photosynthetically sequestering atmospheric CO_2,[203] and a varying fraction of C is buried in tidally inundated suboxic and anoxic sediments and thereby largely prevented from returning to the atmosphere.[204] Globally, tidal marshes and mangroves capture 196.72 Tg CO_2 per year, which is 30% of the organic C deposited on the ocean floor.[205] It was estimated that seagrass ecosystems accumulate 176–411 Tg CO_2-eq year^{-1}.[203] The C stored in these coastal ecosystems as blue C can be preserved over millennia, together with the continuous accretion of soil and sediment organic C driven by sea-level rise, the C sequestration efficiency in marine ecosystems is much higher than that of terrestrial ecosystems.[205,206]

Practice for blue carbon management. The sustainable management, conservation, and restoration of these marine ecosystems are vital to support the provision of C sequestration and other ecosystem services that humans depend on.[207] One possible way to increase blue C is to promote microbial C sequestration in marine ecosystems by reducing the application of chemical fertilizers on land (Figure 2), as initially proposed by Jiao et al.[208] This suggests the need to adopt land-sea integrated strategies to achieve C storage and sustainable development. In addition to halting untreated sewage flow into rivers, the reduction of chemical fertilization in agriculture may minimize anthropogenic nutrient flux to marine ecosystems, thereby reducing the mobilization of dissolved organic C for degradation and respiration.[209] This process may reduce the eutrophication and red tides in rivers and oceans and increase the deep ocean C sequestration through the microbial C pump.

Due to the importance of coastal ecosystems in storing large amounts of C and providing other ecological functions, policies to protect and restore coastal and open water ecosystems need to be strengthened.[201,205,210] Preventing the conversion of these ecosystems to other land uses and restoring degraded coastal wetlands can increase C sequestration.[211,212] Recent simulations suggested that the protection and restoration of global coastal wetlands can provide half of forest soil C migration potential by 2030.[211]

Although coral calcification is accompanied by the release of CO_2 into the atmosphere, the importance of coral reefs as a C sink in the ocean cannot be ignored[213] because they rapidly convert inorganic C into carbonate minerals, principally as calcium carbonate ($CaCO_3$) accretion. Coral reefs need to be protected and restored to improve their ability to adapt to climate change.

The implementation of sustainable practices in all industries that impact the ocean and coastal ecosystems, including mariculture and tourism, is also needed. For example, mariculture has a huge potential for the development of negative C emissions in the ocean. However, the C sequestration process of bivalves and seaweed farming is complicated, and the scientific principles and processes are gradually being recognized and are yet to be resolved.[214] Technological approaches and policies are needed in mariculture to implement the C sequestration, such as expanding mariculture space and increasing unit yield, sustainable development of mariculture, integrated multi-trophic aquaculture, blue C engineering through ocean ranching, and artificial marine upwelling.[214]

In short, marine ecosystems, including coastal wetlands and open waters, are considered the largest C sink on Earth. Coastal ecosystems producing blue C are also some of the most efficient natural ecosystems to bury C into sediments. Improving these marine ecosystems' C sequestration or negative C emission capacity is a fundamental opportunity for achieving C neutrality. Protection and restoration of marine ecosystems is the first step and the quickest way to enhance C sequestration. Eco-engineering practices and approaches, such as land-sea integrated strategies for C sequestration, sustainable mariculture, and marine artificial upwellings, are also needed to increase C sequestration in marine ecosystems. Theoretical underpinnings, experimental scenarios, and ultimate technological viability plans for negative C emissions in the ocean require further in-depth investigations to increase ocean C storage. Public and government support for further blue C research could lead to eco-solutions for sustainable marine ecosystem management and innovative climate change mitigation technologies.

Tackling the carbon footprint of global waste

Zero waste biochar as a carbon-neutral tool. Driven by the extensive expansion of food, urban, and industrial systems, billions of tons of solid waste are generated globally every year. It is estimated that, by 2050, the amount of waste generated annually in the world will jump from 2.01 billion tons in 2016 to 3.4 billion tons.[215] Despite having only 16% of the world's population, high-income countries produce 34% of the world's waste. According to the US Environmental Protection Agency, solid waste landfills are the third-largest source of CH_4 emissions in the United States, emitting the same amount of CH_4 as almost 21.6 million passenger vehicles driven for an entire year or annual CO_2 emissions from energy use of nearly 12 million households in 2019.[216] The most common way to treat the waste is open waste burning, which promotes the emission of GHGs, carcinogenic compounds, and other toxic substances, thereby posing long-term threats to the environment and human health.[217] Addressing these problems associated with waste landfills and open waste burning is far more expensive than creating and running safe waste management systems. Therefore, it is essential to find and develop alternative methods to deal with the ever-increasing volume of solid waste. Ideally, such alternatives should be cost-effective, based on eco-friendly processes, contribute to climate change mitigation, promote sustainable development, and lead to economic and ecological benefits. In this way, the thermochemical conversion of solid waste into biochar can bring multifunctional benefits to the circular economy in addition to climate change mitigation and C sequestration.

Biochar, a fairly new term but an ancient tool, is a porous solid material that is produced from the treatment of feedstocks at high temperatures (300°C–900°C) under limited oxygen or oxygen-free conditions.[218,219] The thermochemical decomposition of feedstocks into biochar can be carried out by various methods, including pyrolysis, hydrothermal carbonization, torrefaction, gasification, and traditional carbonization.[220] Among these methods, pyrolysis is widely employed to produce biochar since it preserves one-third of the feedstocks as persistent biochar products while also generating bio-oils and non-condensable gases.[221] A plethora of organic resources, such as crop residues,[222] forest residues, livestock manure, food wastes, industrial biowastes, municipal biowastes, and animal carcasses, are feedstocks that can be used to produce biochar for different purposes.[223,224] Some researchers have made great progress by investigating the pyrolysis of plastic waste for char production,[225,226] while others have studied the co-pyrolysis of organic materials and plastics.[227] Char production from fossil-fuel-derived materials neither constitutes a way to withdraw carbon dioxide from the atmosphere nor qualifies as a soil amendment (and is therefore not called biochar) but has application as construction material. Interestingly, biochar can be produced on many different scales, from large industrial to small household scale, and can also be produced on farmland.[228] Therefore, bio(char) production from widely distributed waste has socio-economic and environmental significance in the race to achieve C neutrality. The possibility of producing biochar with multiple functions in a sustainable way positions the biochar industry as a viable hub to create a more sustainable and prosperous future for all people and the environment.[218]

Biochar for sustainable development. In addition to cleaning up wastes, biochar also plays a key role in a variety of human activities in the realization of a circular economy and sustainable development (Figure 3). Driven by the possibility to create either a highly charged surface and multiple functional groups or hydrophobic surfaces, biochar is emerging as an effective and safe natural adsorbent that can capture CO_2[229] and remove diverse organic contaminants[152] (e.g., antibiotics, aromatic dyes, agrochemicals, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons) and inorganic contaminants (e.g., phosphate, ammonia, sulfide, and heavy metals) from solid, aqueous, and/or gaseous media.[137,230–232] As a soil amendment, it can improve plant productivity and photosynthesis rate by enhancing the physical, chemical, and biological properties of the soil,[233] thereby contributing to C sequestration in terrestrial ecosystems and mitigating climate change.[234] Biochar addition to agricultural soils has improved soil water availability, water holding capacity, and nutrient availability,[235–237] increased soil microbial biomass and activity,[238] reduced risk of crust formation and soil erosion,[239] enhanced antibacterial activity,[240] and reduced mobility and toxicity of environmental pollutants in the soil.[241,242] By supplementing it with nutrients and microorganisms, biochar may be used as a carrier material for agricultural inputs, thus increasing the nutrient use efficiency, viability, and activity of the inoculated microorganisms in the soil.[243] Biochar can also serve as a source of nutrients for plant growth and suppress soil-borne, pathogen-based diseases to alter the agricultural environment.[242,244] In addition, biochar can also reduce the emission of CH_4, N_2O, and other air pollutants during the degradation of biomass in the soil, mainly by adsorbing free C and N compounds to its surface, changing the properties of the systems.[245] For example, biochar used as a soil amendment can reduce soil CH_4 emissions by 39.5%,[246] and soil N_2O emissions by 30.92%.[247] Furthermore, biochar has been shown to mitigate the emission of GHGs (CH_4, N_2O, and CO_2) during composting, and its application is highly recommended for optimizing the composting process and conservation of C, N, and other compost minerals.[187,248] Therefore, the conversion of agricultural waste into biochar to improve soil health is regarded as a promising strategy for storing soil nutrients and reducing GHG emissions.[249]

Owing to its controllable and tailorable electrical conductivity and inherent functional groups, biochar could be easily designed to have photonic, electronic, acoustic, and bio/redox interactions with other reactive substances, making it a viable alternative to replace unsustainable solid C-based catalysts.[250–254] In addition, the possible use of biochar in the manufacturing of value-added construction materials has been explored.[255,256] For instance, in a study, Das et al.[257] obtained wood polypropylene composites with enhanced physical and mechanical properties after mixing wood and malleated anhydride polypropylene with biochar, suggesting that biochar with a high surface area may act as a reinforcing filler in the production of biocomposite materials.

Research on waste valorization using biochar as a low-cost C-based additive in the manufacturing of construction and building materials has produced promising results.[258,259] Biochar can replace cement in ultra-high-performance concrete[260] and strengthen the interface bond between cement matrix and polypropylene fiber.[261] Other benefits include improving cement composite flexural strength by 66%, toughness by 103%, and compressive strength by 40%–50%,[262] reducing the water permeability and adsorption of the mortar, thereby enhancing the impermeability of the biochar-enriched mortar.[263] With the help of the C-negative manufacturing

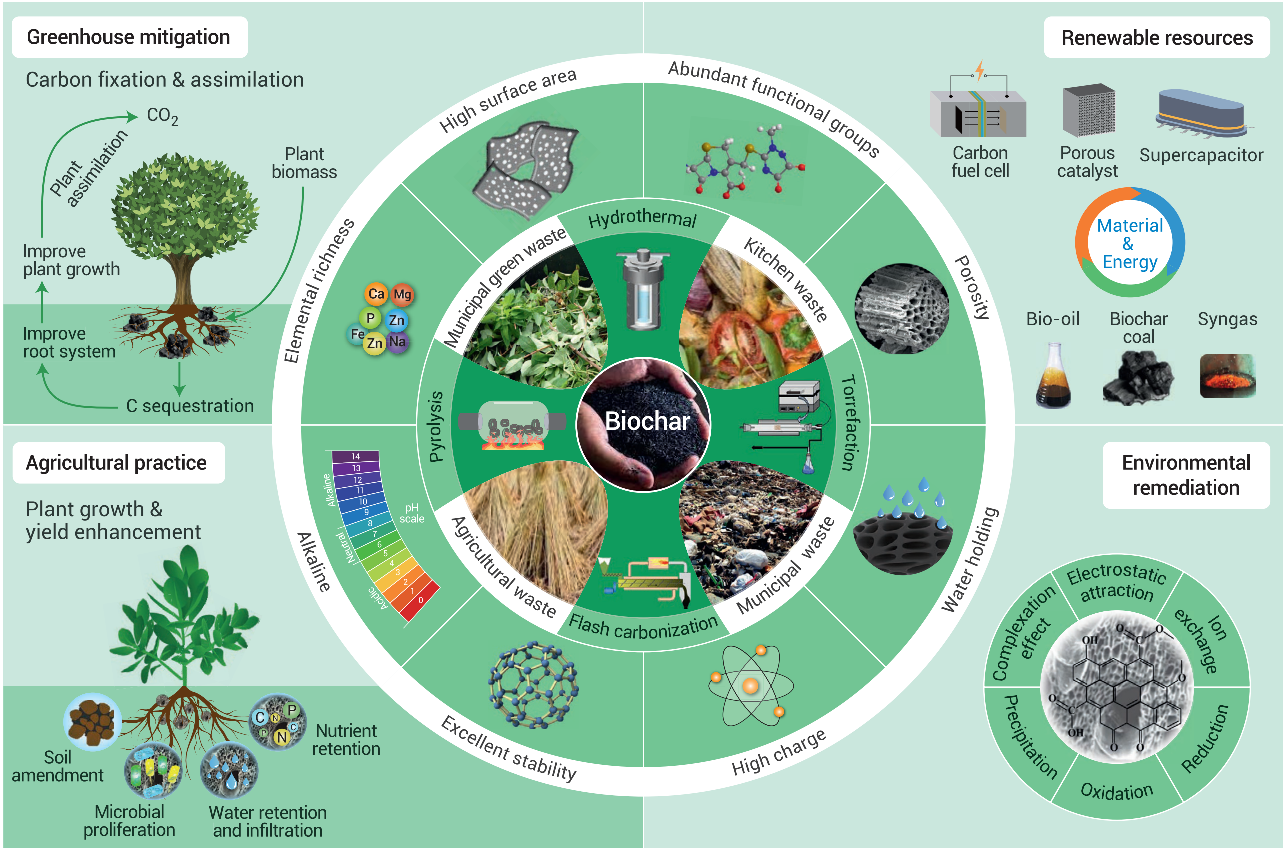


Figure 3. Zero waste biochar as a carbon-neutral tool for sustainable development

process, biochar occupies a special position in the production of green cement and concrete. It may become a key tool for building a better world for the progress of human civilization.

Besides its usage in environmental protection and sustainable development activities, biochar application as a feed additive in animal production systems is also gaining more attention. More recently, it has been shown that adding biochar to animal feed reduces ruminant methane generation, improves animal growth and health, egg production, and suppresses disease occurrence, thus boosting animal productivity.[264] In addition, there is a possibility that biochar may find its application in the human healthcare industry, but it has yet to be explored.

Although biochar may contribute to a sustainable platform to realize the goal of C neutrality and zero waste, not all forms of biochar are environmentally friendly or beneficial.[249] This is because the effectiveness of biochar depends on its physical and chemical properties, which are affected by various production factors and operating settings, such as the type of raw material and the thermochemical conversion process used to produce the biochar, temperature, time, and heating rate, etc., in addition to the post-production processes.[265,266] For example, when used as a soil amendment, biochar with an excessively high pH, too much ash, or high concentrations of residual organic and inorganic toxicants may negatively impact plants and beneficial microorganisms in the soil.[267] Therefore, it is necessary to develop an in-depth understanding of suitable raw materials and production conditions to obtain biochar with the characteristics required for a specific application.

Many recent studies have shed light on biochar's constructive features and potential applications in promoting a circular economy and mitigation of climate change toward sustainable development. For instance, Ghodake et al.[228] investigated the connection between feedstock source, production conditions, and physicochemical properties of biochar, bringing together aspects required for establishing viable systems for the production of biochar with desired attributes. Bolan et al.[223] discussed the trends in biochar applications in different areas, including crop-livestock production, environmental remediation, direct climate change, air pollution mitigation, chemical and materials industry, and construction industry. Beyond elucidating multi-purpose benefits of biochar, Bolan et al.[223] also summarized the negative side of biochar applications, stressing the need for biochar life-cycle analysis from an environmental, energy, economic perspective before its intended use. Although the above reviews offered a wealth of information on waste valorization, they focused only on biochar generated from biomass wastes, leaving out char made from plastic wastes, which can be effective in environmental remediation.[225]

To achieve sustainable development in a C-neutral world, in addition to the need to decentralize biochar production units and increase public awareness of its multifunctional values, there is a need to determine the critical factors for the biochar system to advance its potential in GHG reduction, carbon dioxide removal, and environmental protection. Because the properties and applicability of biochar are significantly different due to different pyrolysis conditions and types of raw materials, future development in biochar optimization should focus on feedstock pre-treatment, pyrolysis process, operating factors, and product yield. Finally, integrating ecological strategies to optimize the process of biochar production, characterization, and life-cycle analysis, and formulating standards based on models and experimental routes will enable policymakers, biochar producers, users, and other relevant stakeholders to work together toward C neutrality.

Carbon sequestration in bio-based products. Using biomass to transform, reuse, and recycle CO_2 is a sustainable way to mitigate climate change and promote a circular bioeconomy. Potentially, all fossil fuel products can be produced from biomass. In addition to providing bioenergy, inedible biomass can replace non-renewable fossil fuel resources in the industrial production of plastics, lubricants, medical devices, paint, and other valuable commodities.[268] This is not a myth because recent scientific and technological advances in various fields, including biotechnology, nanotechnology, and nanobiotechnology, have paved the way for the utilization of biomass for the truly sustainable development of global production systems. For instance, microorganisms, especially bacteria, can use most biological resources, such as starch, fatty acids, cellulose, sugars, proteins, and other organic materials, as sources of nutrients and convert them into various monomers appropriate for the production of biopolymers.[269]

Unlike traditional polymers derived from fossil fuels, biopolymers are in line with our principles of C neutrality and sustainable development, as they are directly or indirectly derived from photosynthetic plants that capture CO_2 from the atmosphere. Starch-based polymers are the most widely used and cost-effective biomaterials due to their biodegradability, biocompatibility, tensile strength, and thermal efficiency, and account for 50%–80% of the global bioplastics and biopolymers market.[270] Plastics from different biomass feedstocks, their uses, and their environmental impacts compared with petrochemical plastics have been thoroughly documented.[271–275] Undoubtedly, harnessing the power of biomaterials can reduce the C footprint and environmental impact of petroleum-based polymers, offering a wider range of applications than conventional polymers. Different bio-based materials are now extensively tailored using cutting-edge technologies to offer sustainable innovative materials with the properties required for specific applications.[276,277] For instance, fibrillated cellulose obtained from renewable sources, due to its mechanical, thermal, optical, and fluid properties, is a multifunctional nanomaterial that may be utilized to produce materials spanning from composites, nanofillers, and macrofibers to thin films, gels, and porous membranes.[277] In addition, modification and functionalization of wood materials using nanotechnology processes can provide large-scale bio-templates with improved properties. These wood-based materials can be used to implement the concept of hierarchically structured nanomaterials for large-scale applications in various advanced technologies, including energy storage, solar-steam-assisted desalination, water treatment, and production of lightweight structural materials, plastic, electronics, glass, and ionic devices.[276]

The application of wood nanotechnology for producing bioinspired functional materials, with a particular emphasis on novel nanotechnological approaches for developing new wood-based materials, has been developed for sustainable use in various production systems.[276,278,279] These advances in the development of a circular bioeconomy are a promising path toward C neutrality as C will be stored in these bio-based products.

TECHNOLOGIES FOR CO_2 CAPTURE, UTILIZATION, AND STORAGE

The CO_2 capture, utilization, and storage (CCUS) technology comprises three different processes: separating CO_2 from emission sources, CO_2 conversion and utilization, transportation, and storage underground with long-term isolation from the atmosphere.

The CCUS is a necessary technology to realize the CO_2 emission reduction target.[280] The International Energy Agency (IEA) forecasts that the task of reducing emissions cannot be accomplished only by improving energy use efficiency and adjusting the energy structure, but also 19% of CO_2 emissions must be captured and stored to keep global temperature rise below 2°C by 2050.[281] Without CCUS, the total cost of CO_2 reduction will rise by 70% by 2050.[281] The technology in C capture and utilization is summarized in Figure 4.

CO_2 capture and storage

The concept of CO_2 capture and storage (CCS) was first developed in 1977,[282] and it has gone through three stages of development so far. The first stage, from 1977 to 1996, was the technology development phase. In 1989, the Massachusetts Institute of Technology launched the first CCS technology project. While financially supporting CCS projects, the Norwegian government imposed a C dioxide tax in 1991 to ensure that the country can meet its climate goals. As a result, the C tax promoted the operation of the world's first platform-based C dioxide capture facility at the Sleipner gas field.[283] The second stage from 1997 to 2018 was the large-scale demonstration phase of the technology. In 2005, the IPCC released a special report on CCS, which identified CCS as one of the important emission reduction technologies. Subsequently, Australia, the United States, Canada, the United Kingdom, and other countries developed corresponding regulations or modified existing regulations for CCS to solve the regulatory problems of large-scale CCS demonstration projects. At the same time, international organizations, such as the IEA and CSLF, have developed CCS technology roadmaps to advance CCS demonstrations and applications. Those technology roadmaps are updated as the technology develops. By the end of 2018, there were 23 commercial CCS facilities in operation or under construction, including four operational and two projects under construction. The third phase began in 2018, and CCS technology entered the early stages of commercialization. It was marked by the US amendment of tax 45Q, which provides a tax credit of up to \$50/t CO_2 for CCS projects. Since then, the number of large-scale commercial CCS projects has gradually increased.

Current status of carbon capture technology. At present, the technical routes of CO_2 capture mainly include post-combustion capture, pre-combustion capture, and oxygen-fuel combustion. Post-combustion separates CO_2 from the exhaust gas and is one of the simplest ways of CO_2 recovery in energy systems. The gas separation technologies used in post-combustion capture technology include physical absorption, chemical absorption, membrane separation, etc. Due to a large amount of post-combustion flue gas treatment and low CO_2 concentration, the chemical absorption method is the most suitable separation technology for post-combustion CO_2 capture. The advantage of post-combustion capture is that it can be operated easily, and there is no need to modify the power generation system too much. Due to N_2 dilution, the concentration of CO_2 in the tail gas of an energy system is usually very low (generally, the concentration of CO_2 in the tail gas of coal-fired power plants is 10%–15%, and that of natural gas power plants is even lower, about 3%–5%), and the amount of tail gas treatment is large. When using the chemical absorption method to separate CO_2 from the exhaust gas of coal-fired power plants, the energy consumption is about 0.37–0.51 MWh/t CO_2, which means that 90% CO_2 separation will reduce the efficiency of the energy system by 11.0–15.0 percentage points, and the unit investment of a power plant increases by 50%–80%. The current research focus of post-combustion separation is to find efficient absorbers and optimize the separation process to reduce the energy consumption of CO_2 separation. However, the fundamental reason for the high energy consumption of post-combustion separation is the low CO_2 concentration in the tail gas. It is difficult to significantly reduce the energy consumption of separation only by improving the absorbers and optimizing the process.

The way to separate CO_2 before combustion is called pre-combustion. Fuel is gasified into syngas (mainly composed of CO and H_2), then CO in the syngas is converted into CO_2 and hydrogen and, afterward, CO_2 is separated from H_2. Since the CO_2 separation takes place before the fuel combustion process and the fuel gas has not been diluted by nitrogen, the CO_2 concentration in the syngas is over 30%. The results show that 90% CO_2 capture before IGCC combustion can reduce the net power efficiency by 8.0–10.0 percentage points,[284] which is smaller than that of post-combustion capture. However, for IGCC pre-combustion, advanced coal gasification technologies and gas turbines fueled by hydrogen-rich gas need to be further developed.

Oxygen combustion is proposed because of the defect that conventional air combustion can dilute CO_2. The fuel is burned in an environment of oxygen and CO_2, and a part of the flue gas is returned to the system for circulation. The concentration of CO_2 in the flue gas can be more than 95%. The oxygen required is produced mainly by air separation, including the use of polymeric films, pressure-swing adsorption, and cryogenic technologies. The advantage of oxygen combustion is that the flue gas mainly consists of CO_2 and vapor, and thus the energy consumption of CO_2 separation is close to zero. However, due to the need for oxygen production, the power consumption of the air separation unit is large, and the power output of the system is still reduced greatly (around 10%–25%). Meanwhile, the air separation will increase the additional investment of the system. If 90% CO_2 is captured, the net power efficiency will decrease by 10.0–12.0 percentage points for

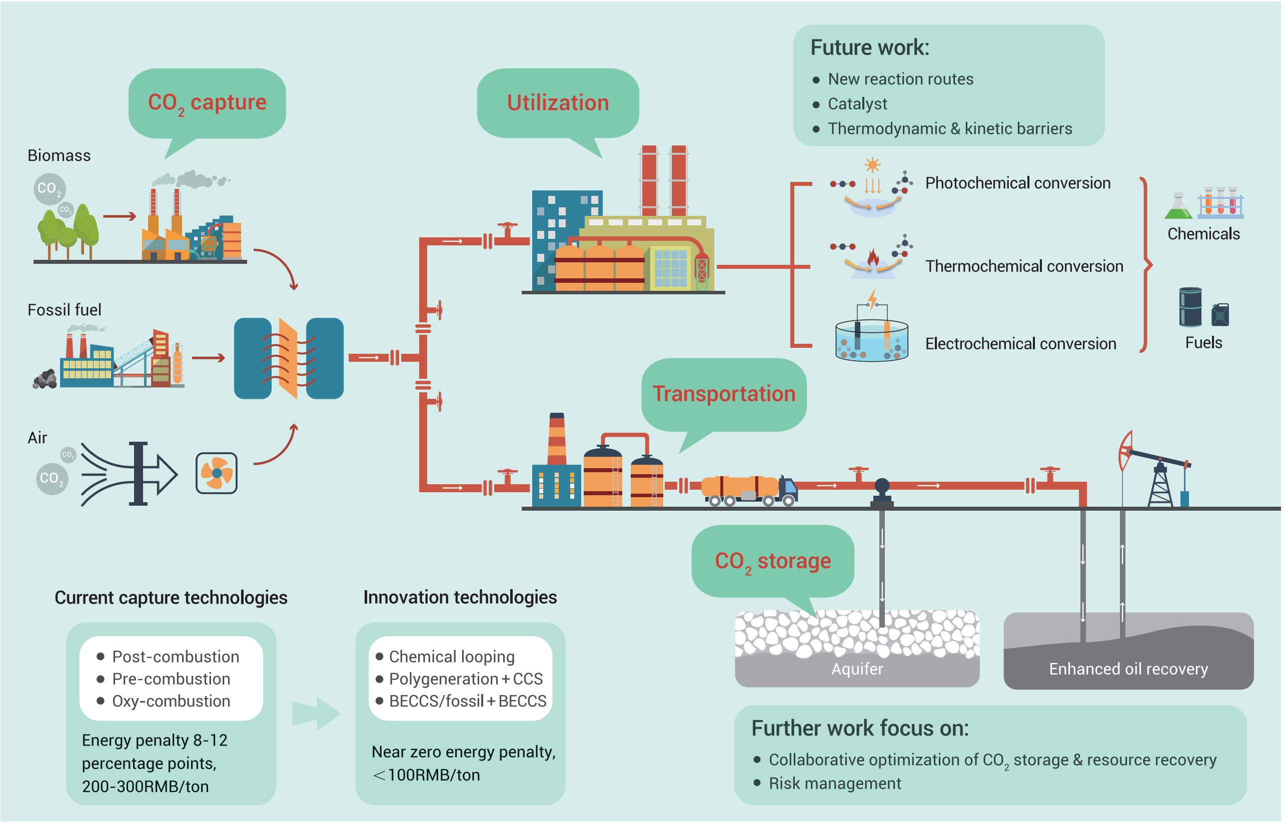


Figure 4. The roadmap for CO_2 capture technology development in the industry

oxygen combustion.[284] The bottleneck of improving the efficiency of the oxygen combustion system is the development of efficient air separation technology.

Current status of CO_2 transportation. CO_2 transportation means the process of transporting the captured CO_2 to use or the storage area. In some aspects, CO_2 transportation is similar to the transportation of oil or gas, which includes pipelines, ships, railways, roads, and so on, among which pipeline transportation technology has the most potential for application. In recent years, there have been many practices for CO_2 pipeline transportation around the world. For example, the United States has built a trunk pipeline network of more than 5,000 km. At present, CO_2 transportation in China is mainly based on low-temperature storage tanks by road transportation. In the area of low-pressure CO_2 transportation, we can learn from the experience of mature oil and gas pipeline transportation; meanwhile, the research on high-pressure, low-temperature, and supercritical CO_2 transportation has just started.

Current status of CO_2 storage. CO_2 storage refers to storing the captured CO_2 in geological structures through engineering and technical means. It could achieve long-term isolation of CO_2 from the atmosphere. Different storage geological bodies mainly include the storage of onshore saline aquifers, the storage of saline aquifers on the seabed, and the exhausted oil and gas field storage and other technologies. At present, long-term safety and reliability are the main obstacles to CO_2 geological storage technology development.

Challenges and future technology development directions. The CO_2 capture technologies currently being demonstrated and commercialized around the world are mainly post-combustion separation technologies. However, such technologies have high energy consumption and cost and have limited potential for reduction. In the early stage of CCS technology promotion, post-combustion technology is relatively simplistic and has low technical difficulty. This type of technology is often used in CCS demonstration projects. It could achieve CO_2 emission reduction effects in the short term. However, in the long run, since the nature of this type of technology is to use more energy in exchange for CO_2 emission reduction, using it as the main technology for long-term CO_2 emission reduction will cause countries to pay unbearable energy and economic costs. For this reason, if the application of CCS technology needs to be promoted on a large scale, countries must develop low-energy, low-cost CCS technologies suitable for developing countries for the clean utilization of coal, such as new poly-generation technology, chemical chain technology, NET with multi-energy complementary technology CO_2 capture, etc.

Chemical-power poly-generation technology with low energy consumption CO_2 capture. Chemical-power poly-generation refers to the technology of producing both synthetic fuels/chemical products (such as methanol, dimethyl ether, and other alternative fuels) and electricity. Chemical-power poly-generation technology can achieve not only substantial energy savings in the chemical and power industries but also produce coal-based alternative fuels to reduce our dependence on fossil fuels and reduce CO_2 emissions on a large scale at the cost of low energy consumption.[285–287] Efficient gasification and gas turbines fueled by hydrogen are future breakthroughs of poly-generation technologies.

Flameless chemical-looping combustion technology. The "flameless" chemical-looping combustion is essentially different from the traditional "flame" combustion: through two gas-solid reactions, no contact between fuel and air is realized. Thus, the gas product is high concentration of CO_2 and H_2O, and the CO_2 can be recovered without the separation process. CO_2 can be separated with zero energy consumption. The use of a "flameless chemical-looping combustion" has opened a new way to control GHGs. The special report on the capture and storage of CO_2 by IPCC emphatically pointed out: "Chemical looping combustion is a way to achieve 100% capture of CO_2. It is a promising way to control greenhouse gases."[284] In the 1990s, Chinese scholars took the lead in discovering the new phenomenon of high-concentration CO_2 enrichment in chemical-looping combustion.[288] The IEA and the US DOE have identified the chemical chain as the primary new direction for zero emissions of fossil energy in the future. Oxygen carriers with high reactivity, mechanical properties, and cycle index still need to be further developed. New reactors suitable for chemical-looping combustion and heat integration of the whole system also need further investigations.

Negative emission technology: Fossil energy combined with biomass and solar energy. With the gradual decrease in the proportion of fossil energy and the increase in the proportion of renewable energy consumption, the CCS technology coupled with fossil energy and biomass/solar energy could achieve negative emissions. It could be used for the areas that have to be emitted to achieve C neutrality. The development of this kind of multi-energy complementary technology still needs to develop system integration theory and solve the problems of space-time complementation between fossil energy and renewable energy.

The safety and reliability assessment of CO_2 storage. At present, the storage potential and long-term safety are the main obstacles to the large-scale deployment of CO_2 geological storage technology. Due to the complex sedimentary history, tectonic structures, and diagenesis processes of sedimentary systems and resource deposits in a history of a geological era. The spatial distributions of aquifer layers and oil fields suitable for CO_2 storage lack sufficient technologies to obtain detailed geological data because of the limitations of technologies and interpretations; and then, the assessments of the CO_2 storage capacities face extreme difficulties. Long-term risk and safety issues also face the challenges of current understandings and technology levels.

Therefore, technical innovations are keys to the large-scale deployment of CO_2 geological storage. The breakthrough of these key technologies and methods can provoke the process of realizing C neutrality targets in the future to develop efficient and safe CO_2 geological utilization and storage theory, methods, technology, software, and related equipment. Among various vital technologies, establish the site characterization and site evaluation technical system; construct the specialized system for collaborative optimization of C storage and underground resource recovery; form a safe CO_2 transportation technology system of various options; the development of "sky-surface-underground" integrated monitoring, risk prediction, and risk mitigation technology system; and finally integrate the full-chain CCUS project at scale to systematically and creatively solve the key scientific, technical, software and equipment problems facing CCUS scale and commercialization.

CO_2 utilization

The CO_2 chemical utilization refers to processes of converting CO_2 into other high-value chemicals under certain conditions of temperature, pressure, and the presence of a catalyst. The CO_2 chemical utilization can directly realize the conversion and utilization of CO_2 and has a certain direct emission reduction effect.[289] Meanwhile, this type of technology can also form a new chemical synthesis route to replace the utilization of fossil fuels or raw materials. The C flow from the lithosphere to the atmosphere will be transformed into a new model that circulates in the atmosphere, which has a huge indirect emission mitigation effect and has important application prospects in future C-neutral scenarios. To facilitate CO_2 conversion, diverse routes, such as thermochemical catalysis, photochemical catalysis, electrochemical catalysis, and others (enzymatic catalysis and organometallic catalysis) have been developed, and substantial advances have been made in recent years.

Thermochemical catalysis. Among various approaches for CO_2 conversion, the thermochemical processes have been intensively investigated, and some have been commercialized. In thermochemical catalysis, the integration of CO_2 into certain organic substrates to form new C–X bonds in catalytic sequences would broaden the reaction pathway to produce valuable chemicals. Generally, new covalent bonds between CO_2 and substrate molecules can be formed by constructing C–X bonds, including C–H, C–O, C–N, and C–C bonds.[290] (1) The generation of C–H bonds originates from the hydrogenation of CO_2 to produce syngas, CH_4, HCOOH, and alcohols.[291–293] (2) The construction of C–O bonds is established via the cycloaddition of epoxides with CO_2, the condensation of 1,2-based polyols with CO_2, oxidative cyclization of olefins with CO_2, and carboxylative cyclization of propargyl alcohols with CO_2 to afford organic carbonates.[294–296] (3) Catalytic formation of C–N bonds resulting from the reactions of CO_2 with various amines to the synthesis of N-containing compounds. Various N-containing compounds, including oxazolidinones, quinazolines, ureas, imidazolinones, and benzimidazoles, can be produced via these routes.[297–300] (4) The formation of C–C bonds is through a direct carboxylation reaction (i.e., carboxylation of CO_2 with alkenes, alkynes, or aromatic heterocycles), affording carboxylic acid derivatives as the target products.[301,302] However, from a thermodynamic point of view, many catalytic reactions are thermodynamically unfavorable and/or need harsh reaction conditions (i.e., high pressure and high temperature) because CO_2 is thermodynamically stable and kinetically inert. Therefore, photochemical and electrochemical catalysis have been prompted as attractive alternative techniques for a sustainable and environment-friendly pathway.

Photochemical catalysis. Photoelectrochemical reduction of CO_2 has gained increasing interest as it can enhance CO_2 efficiency under mild conditions. In a typical photochemical reaction, the inexhaustible solar light is used as an energy source, and CO_2 photoreduction can be carried out using various semiconductors photocatalysts under light irradiation. An efficient photocatalyst should possess the following properties: (1) fast migration of multiple electrons from photocatalytic centers to CO_2; (2) easy adsorption of reactants onto the catalyst and desorption of products into the system; (2) more negative potential of the photocatalyst's conduction band bottom level than the redox potential of CO_2 is required; and (4) the photogenerated holes on the valence band of the photocatalyst should be consumed by oxide species. Therefore, an efficient photocatalytic CO_2 conversion can be promoted via optimization of the light harvesting, fast charge transfer, together with abundant active centers that can adsorb and/or activate CO_2.[303] Recently, several semiconductors, including metal oxide/sulfide (e.g., TiO_2, ZnO, ZnS, $SrTiO_3$, and CdS) and their modified materials, are most widely investigated for the photocatalytic reduction of CO_2 to fuels.[304,305] Many valuable fuels, such as CO, CH_4, CH_3OH, HCOOH, and C_{2+} products have been generated through proton-assisted multiple electron-transfer processes.[306–310] To improve the catalytic efficiency, many efforts have been made via morphological control, structure architecture, heterojunction construction, surface defect engineering, and doping with heteroatoms.

Electrochemical CO_2 reduction. The electrochemical CO_2 reduction reaction (CO_2RR), enabling the conversion of intermittent renewable electricity from sunlight and wind into storable fuels and useful chemical products, is an important approach for CO_2 conversion and utilization to meet the requirement of C neutrality.[13,311,312] Since the pioneering works by Hori et al.,[313,314] massive efforts have been devoted to boost the catalytic performance of electrochemical CO_2RR, especially within the past decade.[315–321] There has been increasing mechanistic understanding as well as many encouraging signs of experimental progress on this complicated multi-electron and multi-proton transfer reaction system.[192,315,322–326]

Theoretical simulations using density functional theory (DFT) have become a powerful tool for providing mechanistic insights into microscopic processes at electrode/electrolyte interface and obtaining critical thermodynamic and kinetic data. A significant difference between electrocatalysis and classical catalysis is that both the reaction thermodynamics (reaction free energy) and kinetics (activation barrier) can be effectively modulated by the applied electrode potential. A simple way to treat the electrode potential effect was developed by Nørskov et al.[327] The combination of the proton-coupled electron-transfer model with the computational hydrogen electrode model was applied to explain the unique ability of copper to convert CO_2 into hydrocarbons. The onset potential and potential-determining steps ascertained from thermodynamic computations are useful in determining the catalytic activity toward a certain reduction product based on linear scaling relations and the volcano model (Sabatier's principle).[328,329]

Other catalysis. Enzymatic and organometallic conversions of CO_2 have also emerged as attractive alternatives in certain applications. Various useful reduction products such as CO, HCOOH, carboxylic acids, and cyclic carbonates have been successfully obtained.[330–333] However, development in these fields is still in its infancy; considerable effort needs to be dedicated to understanding structural features controlling the catalytic activity and achieving practical catalysts suitable for the conversion of CO_2 to useful chemicals.[334]

Future challenges and key technologies of CO_2 catalysis. Although significant efforts have been made over the past several years, the conversion of CO_2 into fuels and chemicals is still challenging in overcoming both thermodynamic and kinetic barriers. For thermal catalysis, the number of valuable and spontaneous reactions of CO_2 with other chemicals is very limited. Deep insights in seeking new reactions in which CO_2 reacts with multi-compounds simultaneously will provide more opportunities for CO_2 conversion. For photochemical and electrochemical catalysis, large-scale application of CO_2 transformation has not been realized. One of the main obstacles in developing rational strategies for catalysis is that the complexity of catalysts hinders the efforts of the active sites. Therefore, much more work needs to be carried out to enhance the existing routes' efficiency and explore efficient catalysts and reaction mediums. In addition, the products for photocatalysis and electrocatalysis are still limited due to the relatively poor efficiency or unfavorable operating conditions. Seeking more reactions in which CO_2 reacts with other compounds may open ways to produce long-chain C products in photochemical and electrochemical systems. To approach the neutral cycle in the future, we must continue developing more efficient catalytic systems to accelerate industrialization. For electrocatalytic CO_2 reduction, this field still faces challenges of (1) slow electron-transfer kinetics, (2) large overpotential, and (3) unsatisfactory selectivity, restricting its practical application and technological commercialization.[335,336] All of the above three important performance indexes are intrinsically related to the kinetic properties of catalytic processes. The current density and overpotential reflect the polarization relation of electrochemical rate, while the faradic efficiency stands for the distribution relation of parallel reaction rate. Thus, intensively kinetic studies based on first-principles calculations and simulations are crucial whether interpreting the electrocatalytic performance of reported catalysts or promoting catalytic properties by designing new catalysts. Microkinetic models are needed to use the DFT-calculated activation energy barriers to determine the reaction rates, the catalytic activity, the product distribution, and the current density under real experimental conditions.[312]

In addition to improving energy efficiency and adjusting the energy structure through renewable energies, CCUS is a necessary solution for achieving C neutrality. The role of CCUS in carbon emission reduction depends on its competition with renewable energy with energy storage. When the target of C neutrality is proposed, it is hoped that renewable energy may replace almost all fossil fuels. However, this hope seems to be impracticable as renewable power is not stable and cannot meet the requirement of energy safety. Although large-scale energy storage can enforce the stability of renewable powers, its total cost and environmental impacts need to be reconsidered. In addition, the transition to renewable energies may mean that there needs to be a complete reconstruction or retrofit of current fossil fuel-based energy production, transmission, and supply systems, and this cost is huge. Also, innovative CCUS technologies can be cost-competitive to renewable powers. Thus, in consideration of the stability and safety of energy supply, environmental impacts, and total cost, CCUS may play a big role in realizing C neutrality in the future. High cost and high energy consumption are still the main challenges for CCUS in the power, steel, and cement industries. Opportunities with low-cost CO_2 capture exist in the chemical industry and may contribute to around 0.4–1.0 billion tons of CO_2 emission yearly in China. CCUS can be combined with clean fuel productions, such as hydrogen production from fossil fuels, and will a play role in the future. There are only two examples of large-scale CCUS technology in power sector currently, and they both adopt post-combustion technologies. The high investment and energy consumption of the two demonstrations indicate that CCS needs technological innovations to reduce its cost further. Low-cost chemical-looping combustion, renewable energy poly-generation, and hybrid renewable fossil fuel energy systems are promising technologies that can help build a C-neutral world. However, the above innovative technologies are at the early stage of R&D and may play an important role after ten years (more than one billion tons of CO_2 emission reduction per year in China). Furthermore, the conversion of CO_2 into valuable chemicals and fuels can also reduce several million tons of CO_2 emissions per year in China.

CARBON NEUTRALITY BASED ON SATELLITE OBSERVATION AND DIGITAL EARTH

In the area of satellite observation and Digital Earth technology, the support for C neutralization includes the rapid monitoring of global GHG concentration, ground land cover change, and the spatial analysis of global natural C sink, which plays an important supporting role in the assessment of when to achieve the peak of C emissions and the potential of a natural C sink.

Satellite observations of CO_2 emissions

At present, greenhouse gas observation methods include ground-based monitoring and satellite remote sensing. A global network of greenhouse gas observation stations was established in the early stage to provide accurate greenhouse gas concentration data.[337] However, due to the limitation of the number of sites, the spatial resolution is often not sufficient to meet global C flux calculation needs. Three CO_2 satellites were launched successively, including GOSAT launched by Japan in 2009,[338] OCO-2 launched by the United States in 2014,[339] and TANSAT launched by China in 2016,[340] which significantly improved the ability of C flux observation. In addition to CO_2 observation, the Sentinel-5P satellite launched by Europe has achieved good results in CH_4, NO_2, CO, O_3, and other gas inversions. Among them, NO_2, as the gas produced by fossil energy combustion, the photochemical lifetime of which is only a few hours, can effectively track the emission source.[341,342] It is often used as a barometer of economic stagnation or recovery in various countries during the COVID-19 pandemic.[343] It is expected that, in 2025, the European Space Agency will launch a new satellite by combining CO_2 and NO_2 observations together.[344]

Digital Earth for carbon neutrality

Digital Earth will integrate a massive amount of data mainly from satellite observation, and develop models, simulate or predict current or future global ecosystems at multiple resolutions in space and time, and then visualize the results. These new technologies and features will provide very powerful benefits for C neutrality and C trading for the following two reasons: (1) the C cycle is influenced by many natural and human factors.[345] Many current models cannot effectively simulate these factors and estimate the C sink. Its estimation is complex, and results from many models differ considerably.[346] However, Digital Earth, which combines these models and comprehensive data, can provide a platform to run these models and compare or validate their results to get a more realistic global C sink. (2) The Principle of Common and Separate Responsibilities was clearly stated in United Nations Framework Convention on Climate Change in 1992. It was adopted in the Kyoto Protocol in 1997, which was widely accepted because countries at different stages of development have different capacities to deal with international environmental issues. Different countries or regions differ in C emissions and sequestration and, consequently, different levels of responsibilities for C neutrality.[347] Global C estimation or prediction and even their driving mechanisms are conducted and shown on Digital Earth at the pixel level. It is apparent that to find the spatial distribution and differences among countries or regions which will bring great convenience to quantify the responsibility for C neutrality taken by governments and the C trading among countries or regions. Moreover, these digital replicas of the global C estimation and their driving mechanisms are helpful to provide essential information for climate and C neutrality policymaking.

CONCLUSIONS AND FUTURE PERSPECTIVES

Carbon is one of the most important elements that contribute to the existence of life on Earth. Since the Industrial Revolution, C-based resources have been exploited to produce energy, food, and other commodities, affecting the global ecosystems in countless ways. The extensive use of fossil fuels and deforestation to promote anthropogenic activities and urbanization are entwined with global climate change, which stems from the greenhouse effect associated with increased atmospheric CO_2 and other GHGs. Currently, the international community is confronted with developing cost-effective and sustainable methods for minimizing C emissions and promoting C sequestration. As the global community is moving towards C neutrality, there is a need to revise our understanding of the current state of C flows in the total environment. Therefore, it has become imperative to switch from non-renewables to renewables that sustain current production systems and address climate change issues to protect human health and the environment. As presented in this review, harnessing the power of renewable resources in energy, food, and industrial production systems and promoting C sequestration in terrestrial and marine ecosystems are seen as possible routes towards C neutrality and achieving sustainable development goals. However, the current level of research has not overcome the major challenges to efficiently use renewable resources in production systems and prevent us from depending on fossil fuels. Many problems still require scientific, socioeconopolitical, and technological solutions to adopt practices that reduce GHG emissions in current global production systems. These include:

1. Given that the potential of global renewable energy resources surpasses global energy demand, the most pressing research needs in sustainable development are enhancing the current renewable energy production trend to phase out the use of fossil fuels. Increasing the amount of power and heat generated from C-free sources (i.e., sun, wind, and ocean) is one aspect of this, but so is the production of biofuels and hydrogen from biomass. The intermittency of wind, solar and other renewable energy sources is one of the major challenges limiting the replacement of fossil fuels with renewable energy. Energy storage is the apparent answer to the intermittency of some of the renewable energy sources. However, the scalability and cost-effectiveness of energy storage are subject to many constraints and limitations. Energy storage development and promotion entail scientific and technological challenges, as well as economic and regulatory concerns that must be addressed in order to drive investment and competition in the energy storage industry. Improving energy efficiency (including residential heating/cooling) has a major impact on reducing GHG emissions in our daily lives. Therefore, more research is needed to fully understand how to maximize energy efficiency and support C-neutral economic growth. As there is a clear link between energy conservation and climate change mitigation, efforts to minimize energy consumption in end-use sectors will contribute to sustainable development as well as carbon neutrality targets.
2. Considering that unsustainable management practices in food systems, spanning from the production and application of chemical fertilizers to waste landfilling and burning, continue to account for a significant portion of GHG emissions, more research is needed to reduce emissions from food systems and enhance sinks of C and other important nutrients (i.e., nitrogen, potassium, phosphorus, and sulfur). To achieve this, developing new methods for further optimization of waste recycling and nature-based processes in agroecosystems, along with the technological development of food factories, has the potential to reduce the need for chemical fertilizers and sustainably support human activities. Given that biochar has multifunctional values in addition to carbon sequestration, as discussed in this review, there is a need to integrate ecological strategies to optimize biochar production, characterization and life cycle analysis, and to formulate model-based standards and experimental evidence to spur biochar-assisted sustainable development. Since terrestrial and marine ecosystems are the largest C reservoirs on Earth, strengthening policies that promote afforestation and reforestation and use of C-negative materials to conserve terrestrial ecosystems and sustainable management of aquatic ecosystems could contribute to increasing C sequestration, thereby mitigating climate change.
3. Even though the CCUS approach has a pivotal role to play in our pursuit of carbon neutrality, the adoption of current CCUS technologies is hampered by their high energy consumption and costs. Carbon capture and storage in the power industry require scientific and technological innovations to achieve low or even net-zero energy use. Polygeneration, chemical looping combustion, and technologies that combine fossil fuels and renewable energy sources for capturing CO_2 could open a new era for CCUS. At the same time, the conversion of CO_2 to fuels and chemicals is also a promising possibility, but the obstacles of thermodynamics and kinetics need to be overcome.
4. Given the utmost relevance of monitoring GHG emissions from space to ensure the world is on track to meet its climate change mitigation goals, the accuracy and spatiotemporal resolution of monitoring GHG emissions from satellites need to be further strengthened so as to monitor greenhouse gas emission sources and rates more comprehensively and timely. The capacity and accuracy of satellites in monitoring terrestrial ecosystem biomass also need to be improved. Remote sensing monitoring of marine carbon sink potential needs new theoretical breakthroughs. Carrying out accurate carbon budget calculation based on land-sea-air joint observation is an important basis for carbon peak and carbon neutralization decision-making.

In summary, this review sheds light on the current status, challenges, and prospects of technologies for building a carbon-neutral future. However, to bridge the gap between the C-neutral world rhetoric and reality, the urgent need to restructure global development systems and protect natural resources requires swift and collaborative actions by researchers, policymakers, investors, and consumers around the world, aiming at reducing GHG emissions and promoting carbon sequestration in technical and natural systems. Furthermore, the global scientific and technological innovations that foster the green economy must be financially and strategically rewarded to accelerate the trend towards carbon neutrality.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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