Journal of Soil Science and Plant Nutrition (2023) 23:1421–1437
https://doi.org/10.1007/s42729-023-01215-5

REVIEW

# Soil and Ocean Carbon Sequestration, Carbon Capture, Utilization, and Storage as Negative Emission Strategies for Global Climate Change

Divya Pant[1] · Kabita Kumari Shah[2] · Sadikshya Sharma[3] · Maya Bhatta[4] · Subina Tripathi[5] · Hari Prasad Pandey[6,7] · Himanshu Tiwari[8] · Jiban Shrestha[9] · Ashbin Kumar Bhat[10]

Received: 4 July 2022 / Accepted: 15 March 2023 / Published online: 30 March 2023

## Abstract

Carbon is stored in vegetation, soils, woody products, and aquatic habitats through biological carbon sequestration. Biological carbon sequestration requires the implementation of advanced management strategies that enhance the quantity of carbon stored by vegetation (cropland, grassland, forest), soil, ocean, and microorganisms. However, biological carbon sequestration alone cannot achieve net zero emissions by 2050. Carbon capture and storage (CCS), bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), and carbon capture and utilization (CCU) hold the potential for decreasing emissions of greenhouse gasses by lowering the use of fossil fuels and advancing the adoption of clean and sustainable energy sources. CCS, CCU, and DAC approaches can deliver the steep $CO_2$ emissions reductions necessary with the promise of large-scale deployment given strong structural and policy support, research and development, and reduction in cost. Along with human intervention, the definite variation in carbon sequestration capacity of each technology, our best estimations for global negative emission technologies (NETs) potentials based on extensive literature study in 2050 for BECCS, ocean carbon sequestration, biochar, DAC, and soil carbon sequestration is 0.5–5 gigaton of carbon dioxide ($GtCO_2\,yr^{-1}$), $2.2 \pm 0.4$ $GtCO_2\,yr^{-1}$, 1–1.8 $GtCO_2\,yr^{-1}$, 0.5–5 $GtCO_2\,yr^{-1}$, 5.5–6.0 $GtCO_2\,yr^{-1}$, respectively. However, to solve climate change, no one single technology can acquire it and the review concluded that a collective deployment of feasible and scalable NETs could help to reduce $CO_2$ emissions and combat climate change.

**Keywords** Negative emission technologies · Carbon capture and storage · Direct air capture · Soil carbon sequestration · Carbon capture storage · Utilization

### Abbreviations

| | |
|---|---|
| BECCS | Bioenergy with carbon capture and storage |
| CCS | Carbon capture and storage |
| CCU | Carbon capture and utilization |
| DAC | Direct air capture |
| NETs | Negative emission technologies |
| SOC | Soil organic carbon |

✉ Divya Pant
divyapant027@gmail.com

Extended author information available on the last page of the article

## 1 Introduction

Over the past 50 years, carbon dioxide emissions have experienced an augmentation of greater than 90%, with fossil fuel combustion and industrial processes being responsible for approximately 78% of this increase from 1970 to 2011. These emissions reached a record high in 2020 (US EPA 2020). Climate change and global warming pose a hazard to practically all ecosystems on the planet. As a result, in a world facing a climate crisis, all areas of human activity, from industry to agriculture, energy generation to mobility, forestry, and conventional land use to the built environment, will need to decarbonize. In 2015, the Paris Agreement established a goal of maintaining the rise in global temperature below 1.5 to 2 °C above pre-industrial levels (Intergovernmental Panel on Climate Change 2014). According to the IPCC projections, $CO_2$ emissions must reach zero between 2040 and 2060 (IPCC 2014). The time to reduce global emissions by half has also narrowed drastically. It was 30 years in 2010, and it is now 10 years for 1.5 °C and it is about 25 years for 2 °C which is a very limited time. However, the Paris targets are in peril based on current trends in emissions, planned infrastructure, and national policy pledges, particularly without strict climate policies (Höhne et al. 2020). Negative emission technologies are mechanisms for the absorption and storage of $CO_2$ and other atmospheric greenhouse gasses. They are also called greenhouse gas removal technologies as it allows for the removal of greenhouse gasses from the atmosphere. NETs capture $CO_2$ from a variety of sources, such as industrial point sources or the air, and deliver it for use in value-added goods, with the goal of increasing access to new carbon sources while lowering emissions (Hauck et al. 2020; Nicolle 2020; Olfe-Kräutlein et al. 2022; Paustian et al. 2019; Sick et al. 2022; Smith 2016). Several negative emission strategies can be used to reduce $CO_2$ levels in the atmosphere such as minimizing $CO_2$ generation, converting and utilizing $CO_2$, sequestering $CO_2$, and extracting and storing $CO_2$ from climatic equilibrium (Jeffry et al. 2021; Kell 2012; Smith 2016; Smith et al. 2007).

The primary working mechanism for most NETs is preventing the release of carbon emissions into the environment and avoiding the environmental consequences caused by the conventional manner of producing products (Sick et al. 2022; Hauck et al. 2020; Lal 2004; Paustian et al. 2019; Smith 2016; Smith et al. 2007; Costandi 2015). NETs are key to attaining net zero carbon emissions and preventing the worst effects of climate change. The predicted environmental and societal benefits of such technologies, on the other hand, are dependent on a variety of factors and vary significantly across the wide spectrum of potential applications (Olfe-Kräutlein et al. 2022; Ravikumar et al. 2021). The main drawback of negative emission technologies (NETs) is that the majority of their practical uses are still in the developmental phase, which can be linked to regulatory hurdles, greater economic costs than conventional products, and most applications' high renewable energy requirements (Olfe-Kräutlein et al. 2022; IEA 2020). Furthermore, there is no reliable method for comparing the relative climate benefits of producing CCU chemicals, concrete, and minerals. To achieve a net-zero scenarios, $CO_2$ emissions must be reduced to the absolute minimum practicable, and the residual emissions must be offset by capture and storage, as well as the targeted use of $CO_2$ in the manufacturing of materials (Sick et al. 2022).

Principal carbon removal approaches include biological NETs; ocean and soil carbon sequestration; geological NETs; CCS, BECCS, and technological NETs; DAC, and CCU (Schumer and Lebling 2022) as shown in Fig. 1. The carbon sequestration capacity of different NETs, on the other hand, varies depending on the specific technologies used, the economic costs of deploying and managing NETs based on scale, and the number of co-products being produced

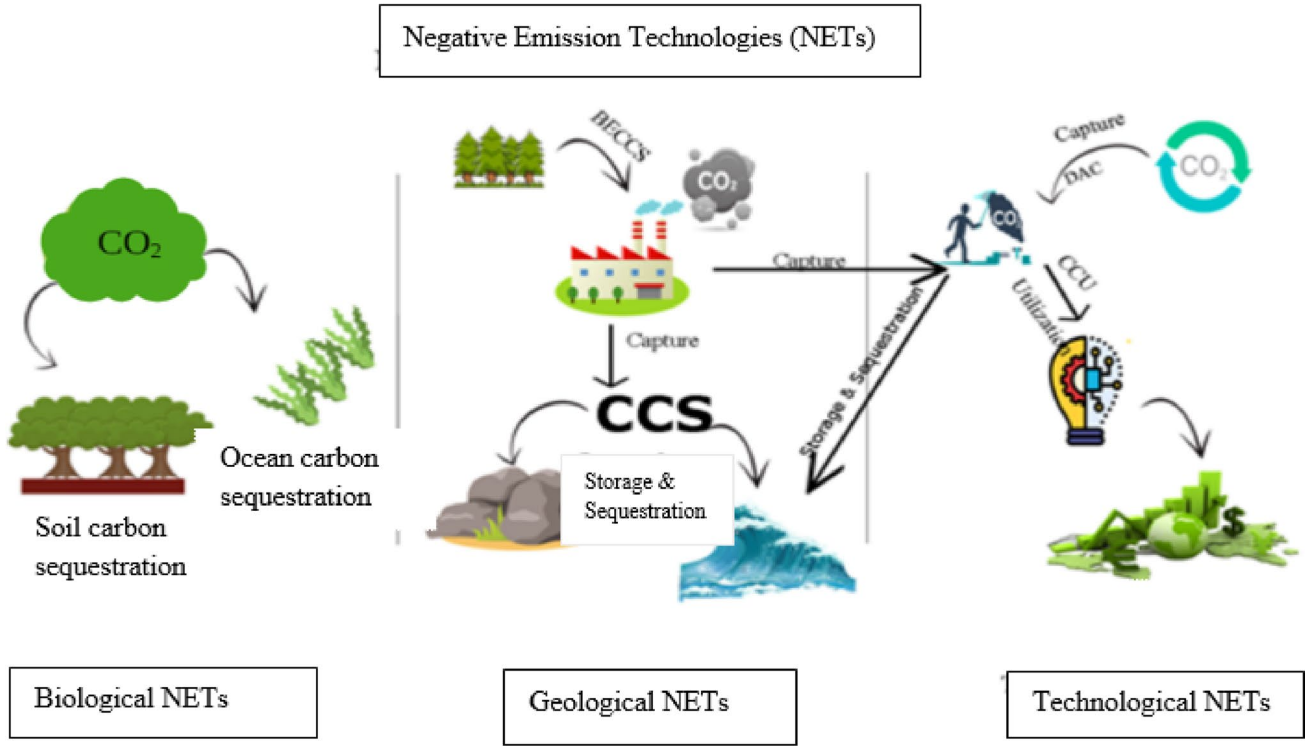

**Fig. 1** An overview of carbon storage and sequestration by biological, geological, and technological negative emission technologies

consideration as well as specific to the site. NETs that extract and absorb carbon dioxide from the air must be deployed at a huge scale to achieve this significant reduction in greenhouse gas emissions. This review intends to provide (i) a brief overview of different approaches to negative emission technologies and (ii) to summarize and assess biological, geological, and technological NETs in relation to their potential to mitigate greenhouse gas emissions.

## 2 Geological Carbon Sequestration

Geologic carbon sequestration is a technique for storing $CO_2$ in deep geologic formations to prevent its release into the atmosphere and contribution to global warming as a greenhouse gas. The act of storing carbon dioxide in natural pore spaces in geologic formations, which serve as long-term carbon dioxide storage reservoirs, is known as geological carbon sequestration (e.g., depleted oil and gas reservoirs, non-mineable coal bed, deep ocean or seabed, and deep saline formations). In industrial production, geological carbon sequestration is currently being used. Industries such as steel, energy, and natural gas production inject carbon dioxide into sedimentary basins in a supercritical state for long-term storage and trapping, preventing it from leaking into the atmosphere. Global storage capacity in depleted oil and gas reservoirs or saline aquifers is projected to be several thousand Gt of $CO_2$. This is more than enough to accommodate the equivalent of 50 to 100 years of emissions (Bickle2009). Carbon capture and storage can allow the use of fossil fuels until a new energy source is widely introduced and adopted (Damideh et al. 2015). Currently, alternative energy sources cannot satisfy the emission reduction targets, and the climate change framework requires emission reductions, where CCS technology can be employed as a mitigation technique.

### 2.1 Carbon Capture and Storage (CCS)

Carbon capture is predicted to play a major role in the world economy's power, industry, and economic structure. CCS is a method of capturing carbon dioxide from big sources such as fossil fuels, power plants, and heavy industry in order to prevent $CO_2$ from entering the atmosphere. The captured $CO_2$ from industrial processes is transported to a storage site and injected into deep underground geological formations for long-term storage where it is effectively sequestered and prevented from entering the atmosphere (Bickle 2009; Raza et al. 2019). In simple terms, it works by storing $CO_2$ in deep geological formations to stabilize the earth's temperature. $CO_2$ capture and separation from other gasses, $CO_2$ purification, compression, and transportation to the chosen sequestration site, and finally $CO_2$ injection and storage into the geological surface of the reservoir or in the ocean make up the integrated CCS system. It can capture up to 90% of $CO_2$ emitted and is one of the most promising strategies for reducing $CO_2$ released into the atmosphere (Beck 2020; Raza et al. 2019; Smith et al. 2016). By removing $CO_2$ emitted from huge industrial processes, CCS can significantly reduce greenhouse gasses that contribute to climate change. Additionally, CCS can also be used in conjunction with other technologies, such as enhanced oil recovery, where $CO_2$ is injected into oil reservoirs to increase the amount of oil that can be extracted (Kashkooli et al. 2022), thus providing an additional economic benefit (Al-Shargabi et al. 2022; Kashkooli et al. 2022; Núñez-López and Moskal 2019). CCS is the only available option to tackle carbon dioxide emissions from natural gas processing, and this is particularly crucial as natural gas is expected to remain a significant energy source in the coming decades (IEA 2020).

However, this technology necessitates a significant financial commitment and is limited by the availability of suitable geological sites for $CO_2$ storage. Costs are expected to be spread out across three stages in the case of CCS: (1) capture, (2) transport, and (3) storage (including monitoring and verification). Due to a long history of government backing for CCS technologies, the USA hosts more than half of the world's large-scale CCS facilities as of November 2022. According to a 2012 report by the National Energy Technology Laboratory, the lower-bound estimate for $CO_2$ storage capacity in the USA and Canada is 2102 $GtCO_2$ in saline formations, 226 $GtCO_2$ in oil and gas reservoirs, and 56 $GtCO_2$ in non-mineable coal seams (NETL 2012). Furthermore, the USA is in a strong position to commercialize CCS technology owing to its political and economic qualities, which include supportive policies and a framework for an innovative manufacturing sector across the country. To decarbonize the global economy, similar characteristics must be broadly understood over the world (Beck 2020). And particular, there has been a growing interest in CCS in recent years, and several countries have announced plans to increase their use of the technology. The European Union has set a target of deploying at least 30 large-scale CCS facilities by 2030, and the USA has announced plans to deploy up to 30 commercial-scale CCS facilities by 2025 (IEA 2020). The use of carbon capture and storage (CCS) technology has been increasing in recent years, but it still represents a small fraction of total global greenhouse gas emissions reductions and has not lived up to its promise. CCS technology needs to be scaled up at a much faster rate to play a significant role in the decarbonization of power and industry sectors. According to the International Energy Agency, the global installed capacity for CCS was around 40 million metric tons of $CO_2$ per year in 2020, which represents only about 1% of global $CO_2$ emissions (IEA 2020).

## 2.2 Bioenergy with Carbon Capture and Storage (BECCS)

BECCS, like CCS, has been capturing $CO_2$ from a wide range of businesses and sectors safely and effectively since 1972. BECCS deployment has been slow in the past, but the potential of BECCS is significant, and wide-scale CCS technologies deployment is required to see an impact on carbon sequestration (Azar et al. 2013; Baik et al. 2018; Fuss et al. 2018). BECCS has a biomass component to it, and carbon removal techniques are used to convert organic material into heat, electricity, or liquid or gas fuels. The bioenergy conversion's captured released carbon is buried in geological formations or imbedded in long-lasting products (Azar et al. 2013). Because biomass absorbs carbon from the atmosphere as it grows, BECCS has the potential to be a negative emissions technology that contributes to the reduction of global mean surface temperature (Azar et al. 2013). BECCS has a positive net energy balance, with energy production ranging from 3 to 40 gigajoule (GJ $t^{-1}$Ceq) for energy crops and carbon sequestration capability ranging from 0.5 to 5 $GtCO_2\ yr^{-1}$ (Fuss et al. 2018; Smith et al. 2016). By 2100, BECCS has the potential to remove around 15 $GtCO_2\ yr^{-1}$ (median, 3–31 full range) of $CO_2$ from the atmosphere, according to the most recent and comprehensive set of 1.5 °C scenarios given by Rogelj et al. (2018). BECCS-combustion/co-firing has potential to sequestrate 2–10 Gt $CO_2\ yr^{-1}$ with sustainable supply of biomass as limiting factor (McLaren 2012). However, BECCS has substantial deployment obstacles, which include the availability of land, water, and fertilizer to feed biomass, the suitability of existing storage sites, and the availability of transportation of biomass and/or $CO_2$ to be used in the system (Abt et al. 2012; Baik et al. 2018). Also, BECCS ignores emissions from changes in land use as well as life cycle emissions, such as the $CO_2$ released during planting, harvesting, and transportation which is crucial to be accounted. To address this, a collaborative effort between research and development, government policies, international initiatives, and the integration of various NETs methods would be required. As an example, to a certain extent, the BECC technique could be used in conjunction with soil carbon sequestration and biochar by employing technologies that produce biochar as a co-product of biomass energy generation (Woolf et al. 2010). Furthermore, the system can be changed to prefer carbon allocation to $CO_2$ for CCS or to biochar for use as a soil supplement (Woolf et al. 2010) consequently and their potential for carbon sequestration is increased. A lower negative emission potential (0.7 $GtCO_2eqyr^{-1}$) is achieved by soil carbon sequestration and biochar compared to BECCS and DAC (Woolf et al. 2010).

CCS is an energy intensive and expensive technology, particularly in the initial stages of development where the cost of capturing, transporting, and storing $CO_2$ tend to be prohibitive (Schmelz et al. 2020) specially for smaller or less industrialized countries. The technical, financial challenges hinder the large-scale implementation of the system as a whole. While the potential for CCS and BECCS to mitigate climate change is promising, there are important questions that remain about the environmental hazards and safety risks associated with the geological storage of CO2. These concerns need to be thoroughly evaluated and addressed in order to ensure the safe and effective deployment of CCS and BECCS technology (Benson and Hepple 2005; Bielicki et al. 2015; van der Zwaan and Smekens 2009; Vinca et al. 2018). When talking about risk with CCS, the primary concern is the potential for leakage at the subsurface storage site. A sudden leak at an injection site could potentially harm the health of local residents and wildlife. The possibility of carbon escape from CCS systems could lead to an additional release of up to 25 $GtCO_2$ during the twenty-first century, if there is a yearly leakage rate of 0.1%. The regions with the highest expected leakage include China, Latin America, the USA, and Canada (Vinca et al. 2018). Studies have demonstrated that, at leakage rates of 1% per year, the use of carbon capture and storage (CCS) to reduce $CO_2$ emissions would be ineffective, with a total leakage of approximately 45,000 $MtCO_2$. These results indicate that in order to effectively utilize CCS as a mitigation strategy, measures must be implemented to ensure low leakage rates (Benson and Hepple 2005; van der Zwaan and Smekens 2009). CCS can change the pH of the soil and can change the chemistry of groundwater and surface water, which can have a range of impacts on aquatic biodiversity and terrestrial biodiversity. According to studies, sequestering a range of 0.5 to 5 Gtonne of $CO_2$ per year through lignocellulosic crop-based bioenergy with carbon capture and storage (BECCS) would necessitate the use of hundreds of millions of hectares of land. This would also lead to the extinction of tens of terrestrial vertebrate species (Hanssen et al. 2022). Leakage reduces the effectiveness of CCS deployment by up to 30% for fossil-based and 10% for BECCS, as per recent research studies (Vinca et al. 2018; van der Zwaan and Smekens 2009). Further leakage, if not considered or priced, can lead to an additional increase in temperature of 0.01–0.02° (Vinca et al. 2018; van der Zwaan and Smekens 2009). Injecting $CO_2$ into the ground can potentially contaminate nearby water sources by acidifying groundwater and releasing harmful substances like brine, minerals, and metals. It can also disrupt natural reservoir fluids and gasses, and change the properties of surrounding geologic layers, potentially impacting the ability to extract water. CCS is a promising technology, but it is not without its challenges where it becomes crucial to address the downside of the technology to bring a significant dent on the reduction greenhouse gas emissions.

## 3 Biological Carbon Sequestration

### 3.1 Ocean Carbon Sequestration

Carbon dioxide is stored in plants such as grasslands and forests, as well as soils and oceans, as part of the biological NET. The oceans contain an estimated 38,000 gigatons of carbon, making them the largest C pool (Mcleod et al. 2011). Ocean carbon sequestration is a technique where throughout the ocean depth, there is an even distribution of $CO_2$ while minimizing surface ocean impacts. There are two primary methods of ocean carbon sequestration which are direct injection and ocean fertilization where the process promotes photosynthetic fixation of $CO_2$ by ocean organisms (Chow 2014). Ocean carbon sequestration include the vast amount of ocean available for storage, the ability to sequester large amounts of $CO_2$, and the potential to enhance marine biodiversity and fisheries. Ocean carbon sequestration as NET provides nearly endless potential for negative emissions, even though the costs and implications of these technologies are only beginning to be described (Canadell et al. 2007; Hauck et al. 2020; Mcleod et al. 2011). According to the global carbon project's 2019 assessment, the ocean absorbed 2.5 0.6 $GtCO_2\ yr^{-1}$ on average, or 23.5% of global anthropogenic $CO_2$ emissions from 2009 to 2018 (Canadell et al. 2007; Hauck et al. 2020), roughly accounting to one-quarter of carbon sequestration. The ocean, on the other hand, just serves as a stopgap. The ocean will absorb carbon from the atmosphere (negative flux) and release it back to the atmosphere (positive flux) in a process known as atmospheric flux. In colder climates, the ocean can absorb more carbon, making the rise in polar temperatures even more concerning. However, a variety of techniques are being researched, with promising results focusing on encouraging coastal ecosystems to sequester carbon in soils and sediments. Moreover, blue carbon, carbon sequestered by vegetative coastal ecosystems such as seagrass, tidal marshes, and mangroves, plays a great role in providing carbon sequestration. However, the loss of a third of the worldwide cover of these ecosystems, on the other hand, results in the loss of $CO_2$ sinks and the annual emission of 1 $GtCO_2$ (Duarte et al. 2013). As a result, immediate action is essential to prevent further deterioration and loss of blue carbon from marine sediment. Warming, $CO_2$ levels, water depth, nutrients, runoff, bioturbation, physical disturbances, and tidal exchange are all factors that influence ocean carbon sequestration (Mcleod et al. 2011). There are concerns about the potential unintended consequences of ocean fertilization, such as changes in ocean chemistry and the potential for harmful algal blooms (Powell, 2008). Additionally, there is a lack of long-term monitoring and research on ocean carbon sequestration, and the cost of large-scale implementation is still uncertain. The use of ocean carbon sequestration is still in the early stages of development and there are many unknowns and uncertainties about its potential impacts and effectiveness. The carbon cycle dynamics in the ocean are far more complex and volatile, and additional studies and spatially detailed datasets are needed to fully comprehend the carbon sequestration process in these complex ecosystems (Macreadie et al. 2017).

#### 3.1.1 Bio-Geoengineering Possibilities for Ocean Carbon Sequestration

The process of ocean alkalinization is a technique to eliminate carbon by incorporating alkaline elements into the ocean to enhance its inherent capability to absorb carbon. These materials can either be natural minerals such as olivine, or synthetic substances such as lime or industrial waste products. Raising the pH level of the ocean through alkalization leads to the removal of carbon dioxide from the atmosphere. This is achieved through a series of chemical reactions that transform the dissolved $CO_2$ into stable bicarbonate and carbonate compounds. As a result, the ocean is capable of absorbing additional $CO_2$ from the air to achieve balance (Macreadie et al. 2017). There are several methods for increasing ocean alkalinity. These methods encompass the dissemination of alkaline materials in a finely divided form across the ocean, placement of alkaline sand or gravel on beaches or ocean floor, as well as inducing chemical reactions between seawater and alkaline minerals within specialized fuel cells before reinjection into the ocean. Ocean afforestation, specifically ocean macroalgal afforestation, entails offshore transport and concurrent growth of nearshore macroalgae (seaweed), followed by export into the deep ocean. It has the potential to reduce atmospheric $CO_2$ levels by increasing natural populations of macroalgae, which absorb $CO_2$ and are harvested to produce biomethane and biocarbon dioxide via anaerobic digestion (Mcleod et al. 2011).

### 3.2 Soil Carbon Sequestration

The amount of carbon in soil accounts for a considerable proportion of the carbon found in terrestrial ecosystems throughout the world. The total amount of carbon in terrestrial ecosystems is roughly 3170 Gt, nearly 80% (2500 Gt) of this total is discovered in the soil (Lal 2004, 2010). Over the last 150 years, human activities have caused modifications in these processes, resulting in the depletion of soil organic carbon

(SOC) and a worsening of global climate change (Paustian et al. 2019; Smith 2016; Lal 2004). However, the same human activities now offer the possibility of carbon sequestration in soil. Soil carbon sequestration begins with plant photosynthesis to "remove" carbon from the atmosphere, and then results from interactions between the dynamic ecological processes of decomposition, soil respiration, and soil organic matter creation, predominantly in cropland and grazing lands (Lal 2004). This process of taking $CO_2$ from the atmosphere (Fig. 2) and storing it in the soil's carbon pool is known as soil carbon sequestration. SOC lies in the form of a labile and stable carbon pool which can increase by adding carbon-rich agricultural waste like animal manure, crop residues, and compost as well as by reducing the pace at which this organic matter decomposes in the soil (Paustian et al. 2019; Smith 2016). Because soils have such a vast storage capacity, even a small increase in soil storage makes a significant difference in terms of carbon sequestration. Increasing soil health can be correlated to increasing soil carbon sequestration capacity where soil health is defined as the ability of soil to support ecosystem services, crops, humans, and soil's flora and fauna while maintaining optimum soil chemical, physical, and biological function (Beddington et al. 2012; Meybeck and Gitz 2010; Paustian et al. 2019; Smith 2016; Lal 2004). Soil carbon sequestration relies upon the adoption of improved management practices that increase the amount of carbon stored as soil organic matter, primarily in cropland and grazing lands (Paustian et al. 2019). Despite this enormous potential for soil to function as a carbon sink, soil carbon sequestration rates vary significantly by soil type and climate region. It is projected that by 2030, the global technological mitigation potential from agriculture, excluding the offset of fossil fuel emissions through biomass, will approximate 5.5–6 gigagrams of $CO_2$eq $yr^{-1}$. In comparison to the ability to counteract emissions from fossil fuels, soil carbon sequestration contributes 0.4 to 1.2 gigatons Cy-1, or 5 to 15% of worldwide fossil-fuel emissions (Lal 2007). At carbon prices of up to 20, up to 50, and up to 100 US$ $tCO_2$ $eq^{-1}$, the economic potentials are roughly 1.5–1.6, 2.5–2.7, and 4–4.3 gigagram $CO_2$eq $yr^{-1}$, respectively (Smith et al. 2007). Increases in soil organic matter/soil C content are particularly favorable from the aspect of soil health and fertility, in addition to carbon dioxide removal capability (Paustian et al. 2019; Smith 2016). As of right now, SOC is considered a long-term sustainable practice, since agriculture must confront three linked concerns at the same time: ensuring food safety through improved income and productivity, adjusting to climate change, and making a contribution to climate change mitigation (Beddington et al. 2012; Meybeck and Gitz 2010).

### 3.2.1 Recommended and Promising Management Practices for Soil Carbon Sequestration

Farmers may adopt a number of best management practices (Table 1) that increase inputs of C into soils: organic matter additions, planting of high-residue crops, seasonal cover crops, intercropping (reduced fallow frequency), and planting of permanent or rotated perennial grasses, perennial vegetation (grasses, trees), conservation or no till, improved irrigation, integrate biochar application, holistic/improved

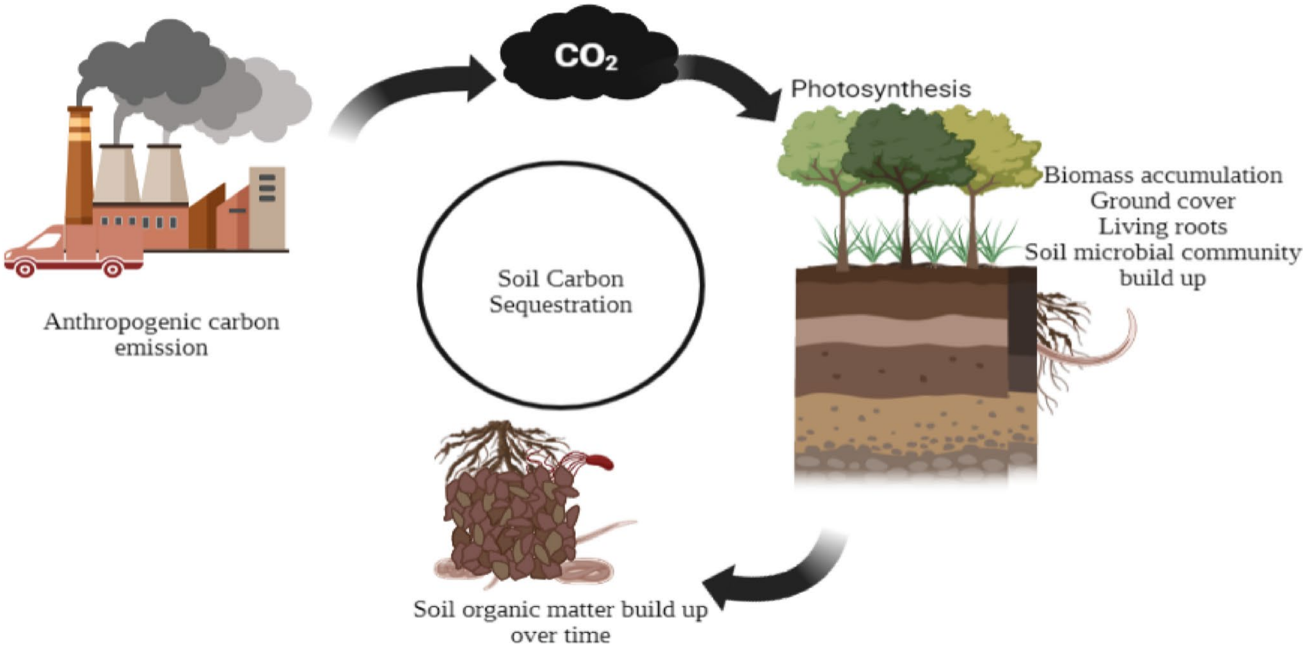

**Fig. 2** An overview of the mechanism of soil carbon sequestration

**Table 1** List of practice that builds and depletes soil organic matter content, crucial for soil carbon sequestration

| S.N | Practices that deplete soil organic carbon content | Practices that contribute to soil organic carbon buildup |
|---|---|---|
| 1 | Conventional till | No till/ strip till/conservation till |
| 2 | Poor irrigation, water infiltration, and nutrient flow | Improved irrigation with better water and nutrient cycling |
| 3 | Barren fields or minimum soil cover | Cover cropping and residue mulch |
| 4 | Excessive use of chemical fertilizers | Organic manuring/composting |
| 5 | Removal of harvest residue, litter, biomass | Biomass and biochar application and incorporation |
| 6 | Intensive monocropping | Crop diversification, intercropping, and perennial crops |
| 7 | Continuous/over-grazing | Prescribed animal grazing |

grazing land management (Conant et al. 2017; Paustian et al. 2019; Poeplau and Don 2015; Ryals et al. 2015; Six et al. 1999; Al-Kaisi and Yin 2005; Curtin et al. 2000; Gross and Glaser 2021; Jensen et al. 2020; Lal 2008; Wagg et al. 2021; Zhu et al. 2020). Best management approaches that are highly recommended increase soil C contents, both by virtue of the added C through reduced soil disturbance and by virtue of increased plant biomass (roots, leaves, stem) addition, the buildup of soil organic matter, microbial community, and thereby improved soil physical, biological, and chemical properties increase soil C contents (Paustian et al. 2019; Poeplau and Don 2015; Ryals et al. 2015; Smith 2016). Research has shown that the return of crop residues or the use of residue mulch can improve soil quality and enhance SOC storage and sequestration capacity. This has been linked to an increase in crop yields, the promotion of ecologically sustainable agriculture and mitigation of climate change (Lal 2008; Wang et al. 2001; Yao et al. 2015). Cover crops are incorporated in cropping systems as a management strategy for increasing SOC stores. The reason for this is that adding carbon back to the soil through crop residues, aboveground cover crop biomass, and weeds has been found to be positively correlated with increased soil health and SOC over time (Blanco-Canqui 2022; Mazzoncini et al. 2011). Cover crops have a mean annual sequestration rate of 0.32 tons of carbon dioxide ($tCO_2ha^{-1}y^{-1}$), according to a recent global study on the subject, with numerous research showing rates greater than $1tCO_2ha^{-1}y^{-1}$ (Poeplau and Don 2015).

The application of organic manure as a management practice is a well-established method for improving soil organic matter content. Studies have shown that on average, the use of organic manure leads to an increase in SOC stocks by 35.4%, which corresponds to a 10.7 Mg $ha^{-1}$ (Gross and Glaser 2021) on agricultural soils. Studies have found that manure application strengthened macroaggregate-stabilized carbon, improved soil structure, and increased SOC (Gross and Glaser 2021; Huang et al. 2022; Roß et al. 2022). Research has found that stable macroaggregates in soil, as found in manure-amended soil, are associated with greater stocks of SOC and increased acquisition of organic nitrogen by microorganisms (Huang et al. 2022). Soils under non-tropical climates exhibit higher increases in soil organic matter content, an average of + 2.7 Mg $ha^{-1}$, as compared to soils under sub-tropical climates. Furthermore, studies have found that the application of farmyard, cattle, and pig manure have demonstrated the highest increases in SOC among all types of organic matter (Gross and Glaser 2021). A study was carried out to investigate the use of compost as an amendment to grassland. With compost application, growth in soil microorganisms, increase in soil structural stability water, and nutrient holding capacity are seen which in turn increase soil carbon pool. Three years after compost addition, they calculated an increase in carbon storage of 0.5 tons of carbon per hectare, which is equivalent to 1.8 tons of $CO_2$ per hectare, and 3.3 tons of carbon per hectare which is equivalent to 12.1 tons of $CO_2$ per hectare at two contrasted rangeland sites, respectively (Ryals et al. 2015) from the addition of compost. In a global analysis of no till practice (Six et al. 1999), a carbon increase of 0.1 t $CO_2ha^{-1}y^{-1}$ has been documented under no till in dry climates, and 0.22 $tCO_2ha^{-1}y^{-1}$ has been reported in humid climates. A recent study shows that no till systems have a 66% lower global warming potential ana 71% lower greenhouse gas emissions per unit of yield than conventionally tilled systems, which is a significant reduction in both (Sainju 2016). Increased plant production has the potential to raise the net removal of $CO_2$ from the atmosphere even more.

Conservation tillage, specifically no till with residue and strip till, is considered one of the most effective agricultural practices for reducing $CO_2$ emissions and sequestering atmospheric carbon in the soil. Studies have shown that conservation tillage practices result in greater SOC and mineral fraction C in the top 0–10 cm depth, and lower $CO_2$ fluxes compared to conventional tillage practices. This is attributed to the reduced decomposition of crop residues, aggregate degradation, improved soil structural stability, and increased microbial activity over time (Al-Kaisi and Yin 2005; Curtin et al. 2000). Reducing tillage intensity can lead to reduced soil disturbance and a decrease in microbial activity (González-Rosado et al. 2022) which in turn, lowers $CO_2$ emission (Curtin et al. 2000). When 1 ton of soil carbon is restored to degraded farmland soils, it has been shown that crop yields can rise by 20 to 40 kg per hectare (kg $ha^{-1}$) for wheat, 10 to 20 kg $ha^{-1}$ for maize, and cowpea it was 0.5 to 1 kg $ha^{-1}$ (Lal 2004). According to a study, annual agricultural conversion to permanent vegetation results in a 39% increase in carbon stock, with an average rate of almost 0.9 $tCha^{-1}y^{-1}$ (Conant et al. 2017). A number of practices have been adopted to improve animal grazing efficiency while reducing impact on soil health and they are often referred as prescribed grazing, management intensive grazing, and rotational grazing but the key of the concept is to reduce exposure of the soil to animal impact followed by a rest period leading to uniform distribution of animal traffic and manure deposits. There is evidence that limited animal hoof impact and uniform urine and manure distribution help in the recovery of soil from the action of grazing, even possibly improving soil health (Martínez-Mena et al. 2020; Pant and Duiker 2021; Xu et al. 2018). A study found that the management of grazing land with best management practices (fencing, regular animal movement, right animal stocking density, grazing intensity, managing plant species) resulted in SOC stock increases of 0.07–0.3 t $Cha^{-1}y^{-1}$ when studied on rangelands and 0.3–1.4 $tCha^{-1}y^{-1}$ on managed pastures (Morgan et al. 2010; Pant and Duiker 2021).

The cropping system can have an impact on $CO_2$ emissions through its influence on above- and belowground biomass production, which in turn affects the quality and quantity of residues returned to the soil, leading to changes in $CO_2$ flux (Al-Kaisi and Yin 2005; Curtin et al. 2000). Improvement in irrigation practices, through better water and nutrient cycling, leads to an increase in crop productivity and carbon storage in the watershed. The addition of water to arid and semiarid soils promotes plant growth and increases productivity and input of carbon to the soil. Irrigation also intensifies the rate of denitrification and mineralization during the growing season, which strengthens the interactions between soil mineral nitrogen, the atmosphere, and freshwater systems, leading to increased productivity (Zhu et al. 2020). Further deployment of perennial grain crops with deep and wide root systems, as well as a higher proportion of dry matter allocation belowground than standard annual crops, has been the focus of further breeding efforts for the past three decades. The soil's structure and the steady pool of carbon content could both be improved by breeding crop plants with deeper and bushier root systems. Researchers have found a strong positive correlation between deeper and bushier crop roots system to ecosystem services, crop yield, and biomass growth as they catch nutrient, and water by exploring extensively in the soil horizon (Pierret et al. 2016). Carbon inputs from perennial crops to soil are significantly greater than those from annual crops; hence, perennial crops support significantly greater SOC reserves. On land converted from continuous annual crop production in the central US grain belt, perennial grains might sequester around 1 $tCha^{-1}y^{-1}$ (about 3.6 $tCO_2ha^{-1}y^{-1}$) or several of years. More progress is being made in breeding annuals with longer, more widespread roots that can penetrate deeper into the soil profile and store soil carbon (Kell 2012).

An increase in belowground biomass production leads to an increase in root and rhizosphere respiration, which in turn causes an increase in $CO_2$ flux (Amos et al. 2005). Crop diversification has been shown to lead to increased carbon inputs, improvements in soil biological health, increased soil stability, and greater SOC sequestration in both annual and perennial cropping systems (Martínez-Mena et al. 2021; Sprunger et al. 2020). In addition, several studies have demonstrated that intercropping significantly promotes agroecosystem services and enhances soil productivity, nutrient, and water use, promoting bacterial community structure changes which in turn has been found to increase total nitrogen content, or soil aggregate stability, soil quality, and SOC (Jensen et al. 2020; Martínez-Mena et al. 2020; Morugán-Coronado et al. 2020; Tamburini et al. 2020; Wagg et al. 2021).

Biochar is a promising soil-based carbon sequestration approach. Biochar is a pyrogenic carbon-rich solid formed from the thermochemical, oxygen-limited combustion of lignocellulosic crop residues, wood, and other solid biomass (Lehmann 2007). One kilogram of biochar has the potential to counteract the same amount of carbon, which is equivalent to 3.6 kg of $CO_2$eq (Zhang et al. 2010). Due to its resistant character, high carbon content, and availability as a readily accessible fuel, biochar can be applied to soil at large rates without disrupting land-use patterns. Biochar presents a very sustainable and rapid option for carbon sequestration into the soil (e.g., 30–60 t $ha^{-1}$: Genesio et al. 2012; Zhang et al. 2010) as it requires less land, i.e., 1hat $CO_2^{-1}$ and has a high negative emissions potential per hectare (Smith 2016). Biochar's potential for the net removal of greenhouse gasses from the atmosphere, according to recent estimations, is around 1–1.8 Gt $CO_2$ $eqtyr^{-1}$ (Paustian et al. 2019; Smith 2016; Woolf et al. 2010). Biochar has been proven to have a major impact on soil fertility by increasing the levels of soil organic carbon, essential nutrients, water retention, plant growth, and crop production (Baiamonte et al. 2015; Coomes and Miltner 2017; Ding et al. 2017; Haider et al. 2022; Lone et al. 2015; Major et al. 2010; Rawat et al. 2019; Zhang et al. 2010). In contrast to biochar, which contributes mostly to the stable SOC pool, fresh crop residues contribute to the more bio-accessible component of the soil C reserve, allowing for more appropriate long-term C sequestration in the soil. This is because biochar decomposition progresses at a rate that is typically 10–100 times slower than that of uncharred biomass, owing to the increased half-life of biochar (Paustian et al. 2019). It has been estimated that biochar production has a worldwide carbon sequestration potential of C 0.16 Gt $yr^{-1}$ when residues from mills, field crop, and forest wastes from urban are used in its creation (Lehmann et al. 2006). It is possible to deploy soil carbon sequestration and distribute biochar without competing for additional land. Because of this, soil carbon sequestration and biochar provide negative emissions with fewer potential drawbacks than geological and technical sequestration (Smith et al. 2010). The improved soil health led carbon sequestration, crop productivity, and environmental benefits via best management practices studied through the years and proven to be effective (Conant et al. 2017; Paustian et al. 2019; Poeplau and Don 2015; Ryals et al. 2015; Six et al. 1999). Therefore, if their hasty and wider adoption could be fostered, then, agricultural soils have the potential to act as a sink for carbon sequestration. As a result, it plays a role in attaining the goal of keeping the average global temperature rise below 2 °C in a sustainable manner, while also addressing issues related to food security and environmental preservation. But with its large-scale implementation comes the concern for the availability of residue for its production, and the risk of biomass depletion and contamination, and these concerns demand more attention and weightage from a research point of view.

## 4 Technological Carbon Sequestration

Technological carbon sequestration pulls carbon dioxide out of the air by employing carbon dioxide removal technologies that enhance natural removals and manually sequester and store carbon. It aims to turn excess carbon dioxide into a valuable by product. DAC and CCU are classified under technological carbon sequestration, but one thing needs to be noted down. If the carbon captured from both DAC and CCU is stored under geological structures than both of them could further be classified under geological carbon sequestration. However, for this study, we are looking more at the byproduct generation from DAC and CCU, hence, considered under technological carbon sequestration.

### 4.1 Direct Air Capture

DAC extracts $CO_2$ from the atmosphere through a chemical reaction (Beuttler et al. 2019; Lebling et al. 2022; Smith et al. 2016). Chemicals can be in the form of liquid solvents or solid sorbents, allowing for carbon removal through geological or technological methods. While some data on the amount of CO2 produced during the production of chemicals from carbon capture exists, it is presented vaguely and requires further research to determine more precise numbers. The $CO_2$ captured can be permanently stored by injecting it into deep geological formations, resulting in negative emissions via geological carbon sequestration (Lebling et al. 2022). There are advantages to using direct air capture technology for the on-site generation of $CO_2$ for a variety of purposes around the world (Peters et al. 2011). Under technological carbon sequestration, extracted $CO_2$ can be used as a chemical feedstock for the synthesis of value-added products, like the production of plastic, synthetic intermediates for pharmaceuticals (Takeda et al. 2012) construction material, food industry (Lebling et al. 2022), or can combined with hydrogen to produce synthetic fuel (Nikulshina et al. 2006; Rau et al. 2013), which, however, will have minimal impact from carbon sequestration perceptive. Furthermore, there is no influence on soil nutrients with direct air capture because it requires very less land or water use in the immediate vicinity of its plant (much lower than BECCS). DAC can be set up on underutilized land like arable land that provides little ecosystem services. While the land footprint may be significant if solar photovoltaic panels or wind turbines are employed to provide the required energy (McQueen et al. 2021; Smith et al. 2016). Also, the energy inputs for direct air capture along the process of mining, processing, transport, and injection are much greater, perhaps as much as 45 GJ $t^{-1}$Ceq and 46 GJ $t^{-1}$Ceq, respectively (Renforth 2012) with a carbon sequestration capacity of 0.5–5 $GtCO_2\,yr^{-1}$. Supported amines from DAC have capacity to sequestrate 10 (plus) Gt $CO_2$ pa but the energy supply and storage capacity are the limiting factors (McLaren 2012; Fuss et al. 2018; Smith 2016; Smith et al. 2007). DAC using sorbents is still in its early stages, with substantially higher energy inputs limiting its use. According to recent estimates, the overall costs of DAC technologies which are comprised of phases capture, transport, and storage range from \$1600 to \$2080 $t^{-1}$Ceq, with capital expenses accounting for around two-thirds and operating costs accounting for the remaining one-third (Smith et al. 2016). Carbon Engineering company (Canada), Climeworks (Switzerland), and Carbon Clean Solutions and Global Thermostat (USA) have been working direct air capture technology and trying to improve the impact of the technology over time (IEA 2020). Institute of Coal Chemistry, Chinese Academy of Science is also dedicated to research on DAC in China. However, direct air capture technology is still in the initial stages of development, and it remains to be seen how it will be adopted on a larger scale in different countries which will be highly dependent on the government policies, regulations, and the cost of the technology as it matures (Fuhrman et al. 2019).

Despite ongoing research efforts worldwide, it has been observed that a mere 10.8% of the CO2-equivalent emissions produced by carbon capture and utilization plants, and 10.5% of the CO2 removed from the air by synthetic direct capture and use facilities, are captured over a period of 20 years. Furthermore, only 20 to 31% are captured over a 100-year span due to uncaptured emissions from sources such as natural gas combustion, coal burning, and upstream emissions

(Jacobson 2019). The case is sensitive for DAC as these massive deployed technologies might not work and leaving future generations vulnerable to substantial climate change effects, huge mitigation costs, and unacceptable trade-offs (Field and Mach 2017).

Based upon the nature of treatment to the direct air captured carbon dioxide, it further leads to following two technologies:

a. Carbon capture and utilization (CCU)
b. Carbon capture and storage (CCS)

### 4.2 Carbon Capture and Utilization

$CO_2$ from emissions or the atmosphere is captured and repurposed under CCU. CCU gains attention compared to CCS in the perspective that leakage is a risk with CCS technology during transit and storage, and CCS requirement for additional electricity increases the cost for its implementation significantly (Vinca et al. 2018). A study evaluated various institutional and economic mechanisms for accounting for carbon leakage and found that leakage from CCS can result in up to 25 $GtCO_2$ of additional emissions throughout the twenty-first century for a leakage rate of 0.1% per year. The study also found that the effectiveness of CCS deployment is reduced by as much as 30% for fossil-based systems and 10% for BECCS when leakage is considered (Vinca et al. 2018). CCU, on the other hand, adds value to waste by producing $CO_2$-based goods while avoiding the expense and risks of geological storage of captured $CO_2$ (Alqarni et al. 2021; Biset-Peiró et al. 2019; Hussin and Aroua 2020). CCU is usually accomplished by capturing $CO_2$ emissions from power plants or industries. The captured $CO_2$ is then converted using electricity, heat, or catalysts in biological conversion, food, and drink industry, plastics, extractants, refrigerants, enhanced fuel recovery, chemicals production, mineralization, and many more (Lebling et al. 2022; Nikulshina et al. 2006; Rau et al. 2013; Takeda et al. 2012). However, rather than permanent geological storage, captured $CO_2$ is used in the process. $CO_2$ and $CH_4$ are used in CCU technology to create valuable products through four distinct processes: (i) electrochemical reduction, (ii) advanced catalyst methanation, (iii) photocatalytic reduction, and (iv) plasma technology. Being a catalyst-dependent process, a functional catalyst with good selectivity and stability for catalysis is extremely necessary for success (Kumaravel et al. 2020). When it comes to carbon dioxide capture and utilization, electrochemical reduction technology is considered to be the most promising approach. It has managed to attract the attention of researchers due to its high reaction rate, high $CO_2$ conversion efficiency, and shows greater potential in terms of performance and cost when compared to the other $CO_2$ utilization approaches (Isaacs et al. 2018; Khoe Dinh et al. 2018; Merino-Garcia et al. 2019; Panzone et al. 2020). It also has a very minimal environmental impact, as evidenced by the low amount of waste produced. CCU does not emit any toxic emissions, and electrochemical reduction is a scalable process (Jeffry et al. 2021) but needs more research and development to cut the heavy cost and support at the policy level to be deployed on a large scale. However, if the product generated from CCU releases $CO_2$ back into the environment upon its immediate use, CCU will have minimal impact on the carbon sequestration perceptive. Therefore, designing products with long-term sustainability is a must with CCU.

DAC is a less preferable alternative for reducing $CO_2$ because of restrictions like high prices and energy needs as well as the possibility of contamination (Isaacs et al. 2018; Khoe Dinh et al. 2018; Merino-Garcia et al. 2019; Panzone et al. 2020; Smith 2016; Smith et al. 2007). Another downside is that it has a bigger environmental impact from its large land footprint than other mitigation techniques like carbon capture CCS. CCU and DAC, being a costly and energy intensive process, make it difficult to compete with traditional fossil fuel-based industries (Khoe Dinh et al. 2018; Merino-Garcia et al. 2019; Panzone et al. 2020). Further, the lack of infrastructure to transport and store captured $CO_2$ makes it difficult to implement on a large scale. Furthermore, the implementation of DAC technology could have a significant impact on land, water, and energy resources, and it is important to ensure that these resources are managed responsibly to minimize negative environmental impacts (Smith 2016; Smith et al. 2007). The technologies' uncertainties in terms of long-term stability of the storage reservoirs and the potential for leakage present risk and hurdle associated with the system as whole and its development. In addition, carbon capture poses uncertainties ranging from possible environmental hazards, biodiversity degradation both aquatic and terrestrial, human safety risks, degradation of water quality, and habitat destruction (Isaacs et al. 2018; Khoe Dinh et al. 2018; Benson and Hepple 2005; Bielicki et al. 2015; van der Zwaan and Smekens 2009; Vinca et al. 2018). Sensitivity analysis, government laws and policy, research and development, and proper monitoring and assessment could address the above challenges to some extent. DAC and CCU are not a substitute for reducing emissions at source; it is an additional measure that needs to be combined with reduction of emissions in order to mitigate the effects of climate change.

### 4.3 Comparative Evaluation of Different NETs

This study so far presented details and descriptions to each type of NETs comprising biological, geological, and technological carbon sequestration. Now, we are presenting supporting data behind each NETs in the table provided below. Tables 2 and 3 provide data to current status, pros and cons

**Table 2** Comparison of pros and cons alongside the status of different negative emission technologies

| | Soil carbon sequestration | Bioenergy with carbon capture and storage | Direct air capture | Ocean carbon sequestration | Carbon capture and storage | Carbon capture and utilization |
|---|---|---|---|---|---|---|
| Technical status | Existing | Demonstration | Demonstration/commercial | Research | Commercial and demonstration | Research |
| Potential in literature (Gt C/year with human intervention) | 5.5–6 | 0.5–5 | 0.5–5 | 2.2 ± 0.4 | 4+ | 3.3 |
| Consistency in $CO_2$ removal | Case specific | Case specific | Yes | Uncertain | Yes | Yes |
| Long-term usability | Vulnerable | Vulnerable | Yes | Uncertain | Yes | Yes |
| Climate mitigation effects | Yes | Yes | No | Yes | No | No |
| Effect on ecosystem and biodiversity | Yes | Yes | No | Yes | No | No |
| Limiting factors | Sustainable biomass supply; suitable soils for storage | Storage; sustainable supply of biomass, suitable facilities | Energy supply: storage capacity | Supply of crop residues. Impacts on ocean biology | Energy supply: storage capacity | Product diversification, R&D budget |

*Adapted from* European Academies' Science Advisory Council (2018), Haszeldine et al. (2018), and McLaren (2012)

**Table 3** Broad guide to the annual potential of different types of negative emission technologies forecasted for the period of 2030–2050

| Technique | Potential capacity | Limiting factors |
|---|---|---|
| Soil mineralization with olivine (Köhler et al. 2010) | 1 Gt-$CO_2$ pa | Finite solubility of silicic acid; availability of suitable land |
| Biochar — pyrolysis or gasification (Shackley and Sohi 2010) | 0.9–3.0 Gt-$CO_2$ pa | Sustainable biomass supply; suitable soils for storage |
| Supported amines for direct air capture (Eisenberger et al. 2009) | 10 Gt-$CO_2$ pa (plus) | Energy supply: storage capacity |
| Sodium or calcium scrubbers via wet calcination DAC (Socolow et al. 2011) | 10 Gt-$CO_2$ pa (plus) | Energy for calcination, storage capacity |
| BECCS — combustion/co-firing (Karlsson et al. 2010) | 2.4–10 Gt-$CO_2$ pa | Storage capacity; sustainable supply of biomass |
| BECCS — ethanol fermentation (Karlsson et al. 2010) | Currently no more than 48 Mt-$CO_2$ pa | Storage; sustainable biomass supply, suitable facilities |
| BECCS — black liquor/pulp (Karlsson et al. 2010) | 250–375 Mt-$CO_2$ pa | Storage; sustainable supply of biomass, suitable facilities |
| Ocean calcination (Rau 2011) | Multiple Gt-$CO_2$ pa | Energy for calcination. Vessels and port facilities |
| Ocean liming (electrochemical splitting: Renforth et al., 2013) | 1 Gt-$CO_2$ pa | Supply of CaCO3, application rates of bicarbonate |
| Ocean fertilization with iron es (Shepherd 2009) | 0–1 Gt-$CO_2$ pa | Impacts on ocean biology. Suitable locations |
| Ocean fertilization (macro-nutrients — e.g., phosphate: Shepherd 2009) | 0.2–0.5Gt-$CO_2$ pa N; 0.5 Gt-$CO_2$ pa for P | Sustainable supply of nutrients |
| Ocean "burial" of biomass (Shepherd 2009) | 2.2 Gt-$CO_2$ pa | Supply of crop residues. Impacts on ocean biology |
| Forest restoration/creation and enhanced management (Shepherd 2009) | 1.5–3 Gt-$CO_2$ pa | Land availability; climate |
| Habitat restoration: peatlands and other wetlands (Parish et al. 2008) | "Several hundred" Mt pa | Land availability; climate |
| No-till or organic agriculture practices (Lal 2004) | 2.3 Gt-$CO_2$ pa max | Land availability |

*The information above has been adapted from* McLaren (2012) of NETs, and give a broad guide to the annual potential of different types of NETs for period of 2030 to 2050 such that it could be adjusted for technological and other socioeconomic advances expected with time.

## 5 Policy Level Change for Negative Emission Technologies

In the past, climate actions and strategies were treated independently. But now, given the scale of climate adversity happening around the globe and the narrow time frame at hand for humans' adoption and mitigation, strategies should go hand in hand in order to make drastic reductions in carbon emission. To bring this into action, the role of policymakers becomes inevitable. Policymakers need to make national and global interconnected policies based on in depth studied carried on technological, economic, environmental, and social aspects of each negative emission strategy (Chen et al. 2022). A study in several provinces of China has found a reduction in carbon emissions with continuous implementation of carbon trading policy and carbon tax (Wang et al. 2001). Another study from Victoria University, Australia highlighted urgency of policy level reform in terms of awareness, knowledge dissemination, and learning of NETs among the general public, private, and government entities. Furthermore, it highlighted the need to ramp up more research, incentives, policies' reforms, and investment in NETs (Sen et al. 2022). This type of policy reform is being seen around the globe where now, 58 counties have included carbon neutrality targets aligned with sustainability goals in their policy record. But aggressive action, stringent carbon curb rules, and more incentives for research and development have to be given in order to comply with the Paris Agreement.

## 6 Challenges

In most cases, the NETs have just become a political panacea over action plan for global politics. Many a times, things are interrelated with each other; development of CCS is a precondition for BECCS but failures to deploy the technology of CCS have increased uncertainties to meet goals set by Paris Agreement (European Academies' Science Advisory Council 2018). Despite advances in negative emission technologies (NETs), there are challenges to their long-term viability when it comes to large-scale implementation, including competition with other land and biomass demands for food security and biodiversity preservation, protection of habitats, avoiding leakage and maintaining water quality, as well as ensuring secure and lasting storage for captured carbon (Fuss et al. 2014 Benson and Hepple 2005; Bielicki et al. 2015; van der Zwaan and Smekens 2009; Vinca et al. 2018). The utilization of negative emissions in present-day scenarios, in spite of the paucity of knowledge, necessitates the initiation of a substantial, interdisciplinary research program. Another challenge is successful operation of these technologies at people's level; since two decades of research and pilot plants have failed to prepare technically and economically viable model of power generation with CCS, even when combusting relatively homogeneous fossil fuels (Anderson and Peters 2016). Furthermore, researches have concluded that the term "Negative Emission Technologies" has created barriers to ground level implementation which can be better connected with peoples when replaced by "Negative Emission Practices" (Buck 2016).

## 7 Conclusion

Global warming is hastening and the Paris Agreement with its target is in peril given the insufficiency in cutting down the emissions with inadequate infrastructure, and national and global policy pledges. To steeply battle climate change and achieve net zero by 2050 negative emission technologies like soil and ocean carbon sequestration, carbon capture storage and utilization seem very promising. These approaches work by capturing the $CO_2$, sequestrating it in biological ecosystem or storing it in a permanent geological structure, or by replacing fossil feedstock, avoiding upstream emission by developing products from captured carbon. Soil and ocean carbon sequestration has been in practice for decades with improvement going around best management practices. The greenhouse as removal process could be accelerated by extensive implementation of direct air capture, carbon capture storage, and utilization as their technological and carbon sequestration component is generally well understood and researched across globe. Despite the pressing need to commercialize the direct air capture, carbon capture storage, and utilization, their large-scale deployment has been slow. Negative emission technologies, both technological and geological, have mostly been limited to demonstration projects due to their high cost and energy requirements. Research, development, and demonstration of robust $CO_2$ pricing mechanisms, adoption strategies, and accounting frameworks are inevitable to reduce the cost and energy dynamics of negative emission technologies. Further large-scale demonstrations of direct air capture, carbon capture, storage, and utilization technologies in the near term will necessitate specific government support, such as grants, tax credits, and public procurement of $CO_2$ removal. Large-scale adoption of negative emission technologies has a variety of biophysical, biogeochemical, energy, and economic resource implications. Therefore, the major carbon emitting countries can accelerate the deployment of carbon capture technologies by targeting these factors and accelerating the cost-reduction process. This would not only reduce the collective-action problem that climate change represents but also bring the world closer to tackling its global emissions problem. Integrated approach to large scale demonstration of zero carbon strategies where technological, biological, and geological carbon sequestration aid each other in carbon removal and sequestration process is indispensable to reach the Intergovernmental Panel on Climate Change goal by 2050.

**Acknowledgements** The authors gratefully acknowledged Penn State library for providing information for preparing this article. The numerous contributors to carbon sequestration datasets are gratefully acknowledged for providing access to their data for public use through open access research and review articles.

**Author Contribution** DP: data collection, paper preparation, methodology, and interpretation. KKS: conceptualization, incorporation of recent research data, editing, and reviewing. SS, MB, ST, and HPP: conceptualization, data modification, and reviewing. HT, JS, and AKB: resources, editing, reviewing, paper correction, and formatting. All authors agreed with the final draft.

## Declarations

**Conflict of Interest** The authors declare no competing interests.

**Disclaimer** The views expressed in this work belong to the authors, and they do not necessarily reflect or represent those of their universities.

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## Authors and Affiliations

**Divya Pant[1] · Kabita Kumari Shah[2] · Sadikshya Sharma[3] · Maya Bhatta[4] · Subina Tripathi[5] · Hari Prasad Pandey[6,7] · Himanshu Tiwari[8] · Jiban Shrestha[9] · Ashbin Kumar Bhat[10]**

Kabita Kumari Shah
agri.kabita35@gmail.com

Sadikshya Sharma
saduparajuli@gmail.com

Maya Bhatta
bhattamaya5@gmail.com

Subina Tripathi
subina.tri@gmail.com

Hari Prasad Pandey
pandeyhp123@gmail.com

Himanshu Tiwari
himanshu1996nduat@gmail.com

Jiban Shrestha
jibshrestha@gmail.com

Ashbin Kumar Bhat
ashbinbhat@gmail.com

[1] Department of Agricultural and Biological Engineering, College of Agricultural Sciences, Pennsylvania State University, University Park, PA 16802, USA

[2] Institute of Agriculture and Animal Science, Gokuleshwor College, Tribhuvan University, Baitadi, Nepal

[3] Department of Ecosystem Science and Management, College of Agricultural Sciences, Pennsylvania State University, University Park, PA 16802, USA

[4] Prithu Technical College, Institute of Agriculture and Animal Science, Tribhuvan University, Dang, Nepal

[5] Department of Biochemistry, Molecular Biology, Entomology and Plant Pathology, Mississippi State University, Mississippi State, MS 39762, USA

[6] Ministry of Forest and Environment, Singha Durbar, Kathmandu, Nepal

[7] Terai Arc Landscape (TAL) Program, Chitwan, Nepal

[8] Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, UP, India

[9] Nepal Agricultural Research Council, National Plant Breeding and Genetics Research Centre, Khumaltar, Lalitpur, Nepal

[10] Institute of Agriculture and Animal Science, Lamjung Campus, Tribhuvan University, Lamjung, Nepal