Singh *et al.*
Biotechnology for Biofuels and Bioproducts (2026) 19:12
https://doi.org/10.1186/s13068-025-02724-4

Biotechnology for Biofuels
and Bioproducts

REVIEW **Open Access**

Bioenergy carbon capture storage and utilization: a critical review of market dynamics and policy implications

Dig Vijay Singh[1†], Senthil Nagappan[1†], Chyi-how Lay[2], Bartłomiej Igliński[3], Grzegorz Piechota[4], Gopalakrishnan Kumar[5*], Roberto Parra Saldivar[6] and Vinod Kumar[6,7*]

Abstract

Bioenergy with carbon capture, utilization, and storage (BECCUS) is a competent technology with the potential to address global climate change challenges. However, its deployment faces significant hurdles across technological, economic, and policy domains. The production of biofuels including ethanol, methane, butanol, and biogas is accompanied by the release of carbon dioxide (CO_2). This CO_2 can be incorporated into organic molecules through various biochemical routes as part of the metabolic mechanisms of carbon absorption. The efficiency of these carbon assimilation pathways can be improved through ongoing developments in metabolic engineering, which can increase the production of valuable bioproducts, improve carbon sequestration, and support efforts to mitigate climate change. The present review recognizes critical avenues for advancing BECCUS, emphasizing market mechanisms, technological innovations, and cross-sector integration in both developed and developing countries such as India. The review recommends policy modifications aimed at establishing a transparent framework related to carbon pricing, emission trading systems, and proper certification mechanisms for biogenic carbon utilization. These modifications, coupled with the integration of renewable energy systems, would not only stimulate BECCUS adoption, but also foster its economic feasibility and sustainability. Additionally, promising technologies such as chemical looping and microalgae-based carbon capture should be technologically scaled up to ensure industrial-level applications. The integration of BECCUS with other sectors is also critical to optimize the impact of this technology on climate change mitigation. Therefore, the present review highlights the need for a robust policy framework, technology-driven innovation, and cross-sector research collaboration to resolve the challenges associated with BECCUS, boost its adoption, and ensure its economic feasibility and environmental sustainability. Moreover, providing regulatory support, augmenting market competitiveness, and aligning research on BECCUS play a transformative role in attaining the goals of the Paris Agreement and promoting environmental sustainability.

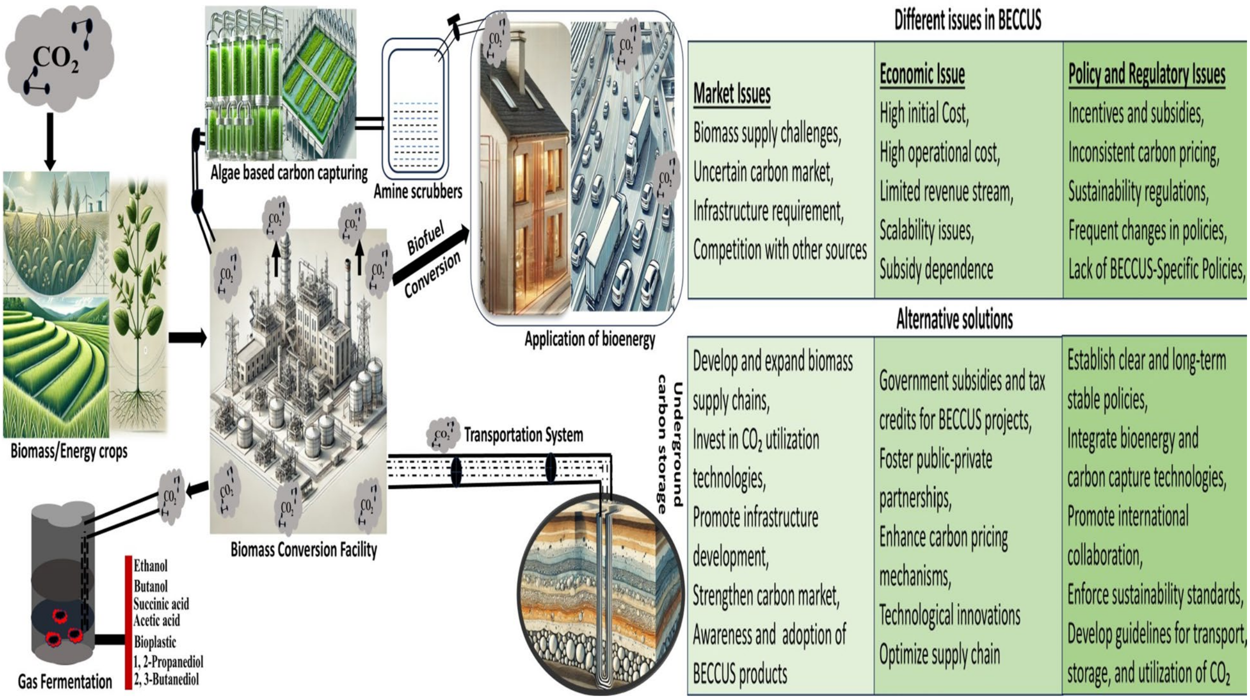
Keywords Biomass, Bioenergy, CO_2, Carbon capture and storage, BECCUS, Market, Policy framework

---

[†] Dig Vijay Singh and Senthil Nagappan contributedequally to this manuscript.

*Correspondence:
Gopalakrishnan Kumar
gopalakrishnanchml@gmail.com
Vinod Kumar
Vinod.Kumar@cranfield.ac.uk
Full list of author information is available at the end of the article

Graphical Abstract



Different issues in BECCUS

Market Issues	Economic Issue	Policy and Regulatory Issues
Biomass supply challenges, Uncertain carbon market, Infrastructure requirement, Competition with other sources	High initial Cost, High operational cost, Limited revenue stream, Scalability issues, Subsidy dependence	Incentives and subsidies, Inconsistent carbon pricing, Sustainability regulations, Frequent changes in policies, Lack of BECCUS-Specific Policies,

Alternative solutions

Develop and expand biomass supply chains, Invest in CO_2 utilization technologies, Promote infrastructure development, Strengthen carbon market, Awareness and adoption of BECCUS products	Government subsidies and tax credits for BECCUS projects, Foster public-private partnerships, Enhance carbon pricing mechanisms, Technological innovations Optimize supply chain	Establish clear and long-term stable policies, Integrate bioenergy and carbon capture technologies, Promote international collaboration, Enforce sustainability standards, Develop guidelines for transport, storage, and utilization of CO_2

Introduction

Bioenergy with carbon capture, utilization, and storage (BECCUS) is a transformative technology with the competence to mitigate climate change through carbon capture and bioenergy production [210]. BECCUS, a variant of BECCS (bioenergy with carbon capture and storage), is considered a potential technique for carbon removal [149]. This technique is based on the use of biogenic carbon dioxide (CO_2), which will eventually reduce carbon emissions and generate additional revenue streams compared to BECCS through utilization of CO_2 as feedstock for the production of valuable products [57]. In the BECCUS system, the primary step is photosynthesis that involves fixation of atmospheric carbon to sustain plant metabolic processes and ultimately promote growth. The biomass generated serves as a substrate in bioenergy plants, and the carbon capture technology installed prevents the emission of CO_2 into the environment. The CO_2 captured can be exploited for product biomanufacturing or can also be injected into geological formations for permanent storage. BECCUS goes beyond bioenergy and ensures capturing of carbon, its utilization, and eventually storage.

Carbon capture and storage (CCS) and bioenergy together have the potential to remove a substantial quantum of CO_2 to produce negative emissions, which is urgently required to reduce the intensity of global warming [94]. BECCS can aid in negative emissions by capturing CO_2 and ultimately injecting it into geological formations [190]. The captured carbon can also be exploited to improve oil recovery (EOR) by introducing CO_2 into oil fields [105]. Both technologies, BECCS and BECCUS, have multilevel applications in processes responsible for CO_2 generation such as bioenergy production, gasification, power, and heat-generating systems [144]. BECCS is intended as an important component of the energy sector and has appeared in several climate stabilization scenarios [38] of China, Japan, the European Union, and Australia.

The decarbonization of the transportation and electricity sectors where these technologies could be highly influential is emphasized in the fifth assessment report [34]. In three out of four illustrated paths, BECCS is presented in the IPCC special report as a crucial technique in meeting mitigation targets [87]. Numerous research centers globally dealing with energy modeling have recognized the importance of BECCS [84]. This technology appears promising given the ambitious global goals for cutting down the CO_2 level in the atmosphere. Additionally, sectors like industry and agriculture are unable to reach carbon neutrality; however, employing the BECCUS system may be the primary means of enabling negative CO_2 emissions after afforestation and direct capture of carbon.

Currently, the total carbon capture and utilization-based facilities are 63 around the globe, and only 40% of them are in operational conditions, while others are in the early and advanced development stages (Fig. 1). BECCUS not only generates renewable energy, but also reduces atmospheric levels of CO_2, thus placing it as an important component of carbon reduction strategies. BECCUS works as a chain of processes. Biomass, such as the residues of agriculture, forestry, and energy crops, can be converted to energy through combustion, gasification, or anaerobic digestion [26]. However, the uniqueness about BECCUS is that instead of CO_2 emissions into the pristine environment, it is captured by site-specific technologies [163]. The captured carbon can then be used for synthetic fuels and chemicals production, injected into the earth for storage, or exploited for micro-/macroalgae cultivation, which makes it different from BECCS [182]. It can be used to make compounds such as ethanol, polymers, and methanol that can be sold to industrial markets to generate extra income [64, 136]. The synthetic fuels can also be used in the current energy market to possibly reduce the reliance on traditional fossil fuels [196].

The conversion of captured CO_2 into several products enables a circular economy that further facilitates the achievement of climatic goals. This sort of capability has positioned BECCUS not only as a method for energy production, but also as a technology that actively contributes to carbon sequestration. Besides carbon capture, BECCUS is at the center of net-zero emission targets and supports global objectives on net-zero emissions [82]. This carbon capture technique has promising potential to create a negative carbon footprint by eliminating more CO_2 from the air than it emits [13]. It also aligns with agreements related to climate change mitigation like the Paris Agreement, where massive greenhouse gas emissions are necessary to be made to keep warming within a manageable threshold. BECCUS is a futuristic technology for the mitigation of climate change and ensures energy security, which marks a transition into a future that is more sustainable [106]. Although the overall implications of BECCUS might be positive, its deployment is still challenging and can be made feasible by adopting suitable modifications and advancements in the social, policy, and technology sectors [210] (Fig. 2).

The economic viability is a major concern in the implementation and adoption of BECCUS-based systems for carbon mitigation. The upfront capital investment for the deployment of BECCUS technologies is significantly high enough to hamper its large-scale adoption [146]. The high cost involved in the CO_2 capture, transportation, and storage may be significant enough to discourage investments, which can also result in elevated technical barriers for the implementation of BECCUS projects, especially in regions with limited access to resources [182]. Finally, efficiency and scalability improvements

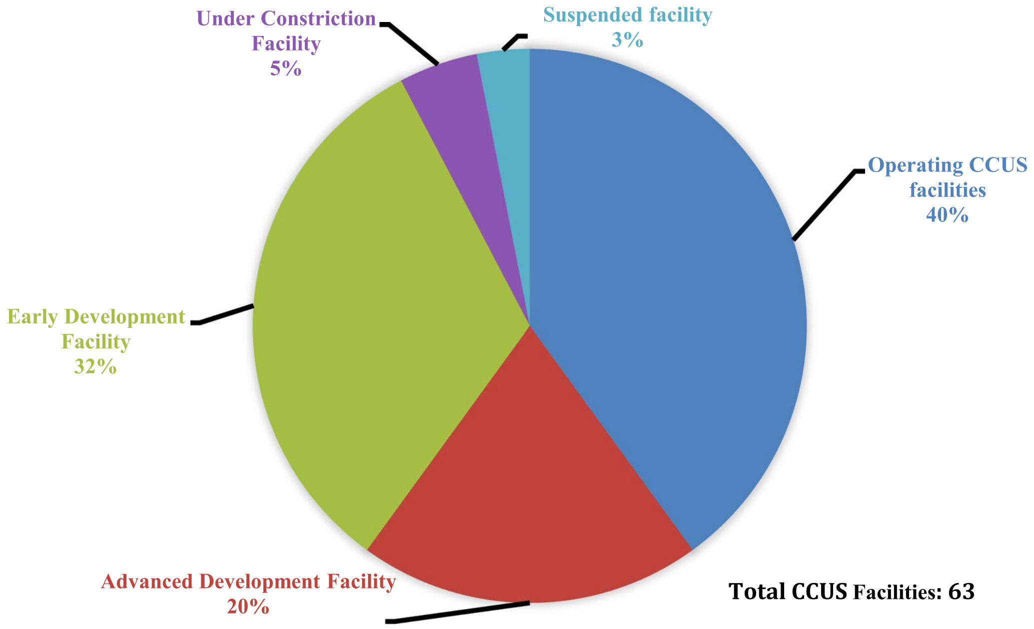


Fig. 1 Global status of carbon capture and utilization facilities

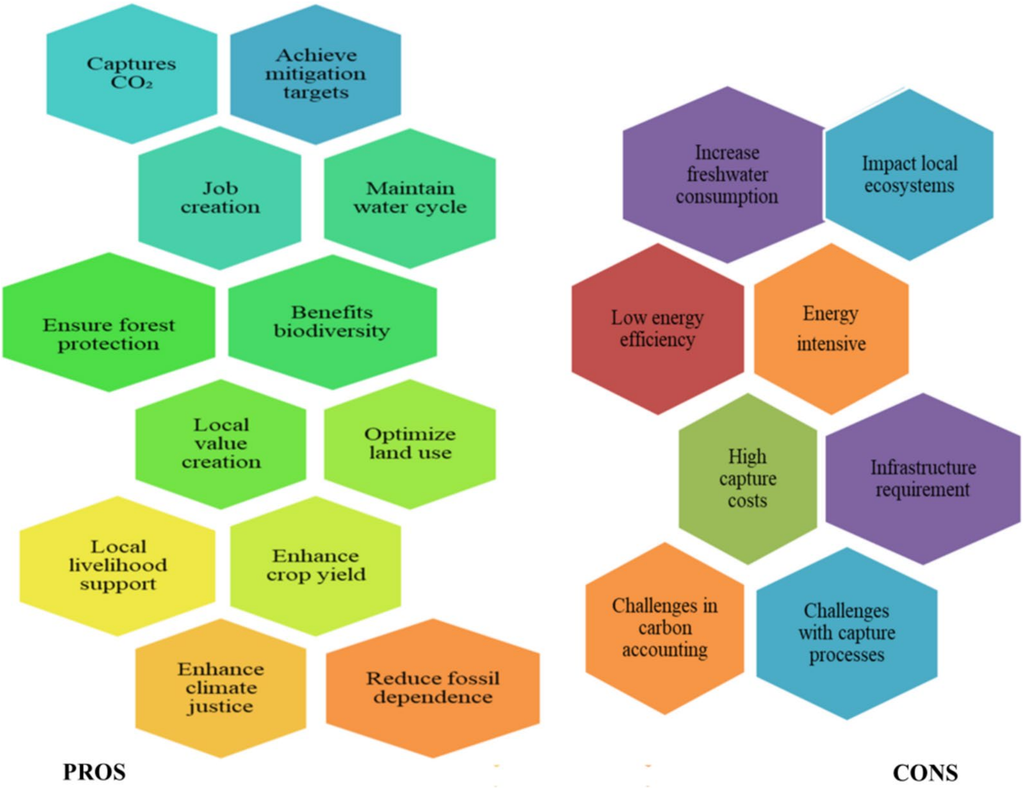


Fig. 2 Pros and cons of BECCUS technology

are needed for carbon capture technologies to guarantee context-specific effectiveness. Apart from economic and technical hurdles, the issues related to land use change have posed questions on the sustainability of the BECCUS system. Furthermore, the competition between the food and energy crops for soil, nutrients, and water has a substantial influence on food security and biological diversity, suggesting sustainable biomass sourcing can address such issues and maintain ecological balance [189]. Adoption of these measures will lead to the development of supportive policies such as research investment and public engagement, which can encourage BECCUS deployment in carbon reduction strategies [106]. BECCUS marks a significant development in the pursuit of a sustainable solution for energy [145]. BECCUS is an important route to shift toward carbon-negative emissions through bioenergy production and the use of CO_2 for the biomanufacturing of diverse products [57]. However, harnessing BECCUS's potential requires familiarity with issues that accompany the adoption of the BECCUS system. It is necessary to overcome obstacles to ensure the contribution of BECCUS to energy security and environmental sustainability.

The review focused on techno-economic innovation and policy changes necessary to boost BECCUS techniques for climate change mitigation with emphasis on market competitiveness and sectoral integration. Furthermore, the high degree of ambiguity associated with carbon pricing, emissions trading systems, as well as certification mechanisms was the driving force to compare policies and technological advancements made in the BECCUS sector by distant countries. As the existing literature discussed BECCUS in terms of emission reduction, the present work emphasized the interplay between technological advancement, policy framework, and market dynamics, which can play a critical role in determining the BECCUS feasibility. The novelty of the present review is based on integrated BECCUS assessment from diverse perspectives, which is different from existing literature mainly focusing on different techniques of carbon capture. The review highlights the unexplored gaps such as fragmented regulatory frameworks, certification systems, carbon pricing, sectoral integration, and harmonized economic models. Furthermore, the review examined the global and Indian perspectives, their support mechanisms, and policy and regulatory framework for BECCUS advancement and deployment. Therefore, by systematically connecting gaps with probable solutions, this work enhances BECCUS system understanding as the strategy not only to reduce carbon emissions, but also to boost biomanufacturing and circular bioeconomy. This review puts forward the need for a strong harmonized policy framework, technological innovation, and collaboration to overcome the challenges encountered in climate change mitigation. By aligning research, market-based solutions, and regulatory support, BECCUS can play a transformative role in achieving the goals of the Paris Agreement and advancing global sustainability.

The review begins with an introduction that highlights the background, significance, and major objectives of the review. After the introduction, the BECCUS and BECCS techniques are compared in a detailed manner including key concepts, advantages, and their relevance for carbon capture and mitigation. The section is followed by global and Indian perspectives in terms of policy modification and financial support, along with different carbon utilization pathways and prospects of different products produced using CO_2 as a substrate. The subsequent section deals with economic analysis by focusing on the different concepts having a role in decreasing capital expenditure, market dynamics, policy framework, and technological innovation necessary to enhance the adoption of the BECCUS technique. Finally, the challenges in the BECCUS implementation along with probable solutions are presented, followed by the conclusion of the review offering the future direction for policy and technological modification necessary for practical BECCUS development and deployment.

Methodology

The literature for the present review was collected from different scientific databases (Scopus, Web of Science, Google Scholar) using keywords such as carbon-negative techniques, sustainable carbon reduction, bioenergy, microalgae-based carbon capture, bioenergy with carbon capture and storage, bioenergy with carbon capture utilization and storage, biosequestration, and circular bioeconomy. The articles selected for the study were from peer-reviewed journals and books with major emphasis on articles from the last two decades to capture the recent advancements, policies, and technological advancements. However, the earlier work related to mechanisms of carbon capture and different industries involved in carbon utilization for the production of different biocompounds was also included. The selection of the papers for the study was based on their relevance toward technological development in BECCUS, policy formulations, market-based solutions, and cross-sectoral integration. The strategies adopted ensured the balanced examination of available literature and presented the challenges encountered, and future prospects of the BECCUS technique.

BECCS vs BECCUS

Carbon storage and utilization are the basis of the BECCUS system, and how efficiently the BECCUS system works is dependent upon its resource availability, implementation strategy, and objectives. BECCUS is an essential instrument to achieve net-zero and climate goals as delineated in the Paris Agreement. However, a lot of resources are required to create the necessary infrastructure needed to transform biomass into energy and capture the emitted CO_2 released during biomass combustion. Additionally, huge financial resources are required for the construction of a BECCUS system in contrast to that of a conventional fuel-based plant. As the BECCUS system requires sophisticated technologies, Bui et al. [25] estimated that the capital cost for the construction of BECCUS facilities can be three times more than that of conventional plants.

In the BECCS system, bioenergy production with carbon storage is an exceptional choice to achieve negative emissions and attain climate stability in the long term. The BECCS system guarantees that CO_2 is stored permanently for centuries [6] in geological formations such as saline aquifers or depleted oil and gas reservoirs [50]. Permanent storage is critical to not only reduce the atmospheric concentrations of CO_2, but also address underlying factors stimulating climate change and eventually decrease climate change intensity. The technique of BECCS is a flawless way to help bioenergy plants to reduce CO_2 emissions, and with its incomparable scalability, it can assist difficult-to-abate industries like steel and cement to decrease emissions in a significant manner. Moreover, carbon pricing policy, emissions trading schemes, and the incentives from the government for decarbonization-related systems can directly benefit BECCS and encourage its secure implementation. The safety of the storage system has been improved by stringent monitoring, verification, and excellent site selection technology despite issues related to leakage and ocean acidification. However, the adoption of the BECCS technique as a feasible technology for carbon reduction is impeded by several issues, such as difficulty in finding suitable locations for carbon storage, huge infrastructure requirements for carbon capture and transportation, enormous initial investment, as well as concerns related to leakage and ocean acidification [108]. Moreover, BECCS does not produce any by-products or economic benefits apart from carbon reduction; thus, it is a less attractive system in low-carbon price markets. The prospects of BECCS are highly dependent upon reducing capital expenditures and simultaneously developing economical technology and optimizing processes responsible for CO_2 separation, compression, and transport to the storage location.

Conversely, the process of BECCUS entails the conversion of captured CO_2 into valuable products such as biofuel, green chemicals, and construction materials [129]. The strategy of BECCUS is in alignment with the circular economy, and this approach also generates revenue to overcome the huge capital expenses involved in the operation of BECCUS. The primary benefits of carbon utilization are to boost market-driven incentives and innovation in biomanufacturing [160]. Moreover, it also resulted in the creation of solutions that are scalable across different sectors. For example, utilizing CO_2 for manufacturing of biofuel and biobased chemicals (biopolymer, lysine, succinic acid, and lactic acid) can help to decarbonize the hard-to-abate industries and also reduce dependence on fossil fuel and their derived products [3, 4]. The industrial and public acceptance of carbon utilization projects is an additional advantage of BECCUS as it directly endorses waste utilization and economic growth, boosts biomanufacturing, strengthens cross-sectoral collaboration, generates employment, and eventually promotes circular bioeconomy and sustainable development. Moreover, the integration of carbon utilization into BECCS systems guarantees that carbon capture techniques produce immediate and noticeable advantages [172] even though they do not permanently eliminate CO_2 from the atmosphere. These factors make carbon utilization a superior choice in situations where market-driven incentives, industrial integration, and economic challenges are the prime concerns. Carbon utilization can reduce the costs of carbon capture, avoid economic challenges, and increase the financial sustainability of BECCUS systems by producing marketable products, particularly in areas with few subsidies or carbon pricing mechanisms [129, 172]. Additionally, carbon utilization plays a critical role in promoting sustainable development and extending the objectives of a bioeconomy and circular economy by converting waste carbon emissions into useful resources. This supports economic growth in a sustainable way by lowering GHG emissions and offering a renewable substitute for industries based on petrochemicals, improves resource efficiency, and helps low-carbon economies grow and shift toward bioeconomy and circular economy. Overall, carbon capture and utilization (CCU) techniques are actually better than carbon capture and storage (CCS) because they can convert absorbed CO_2 into useful products, providing cleaner and more energy-efficient solutions without requiring large storage facilities [57]. Additionally, the financial gain from the conversion of CO_2 to chemicals and fuels is possible in the case of CCU, but CCS is merely a waste mitigation technology [151]. As a result, CCU has drawn a lot of attention from the perspective of chemical engineering in an effort to reduce emissions, mitigate climate change, and achieve a society that is carbon neutral. Thus, carbon utilization strategies need to be planned in such a manner that the released CO_2 from bioenergy plants and industries is captured and reused in a manner that can augment the biorefinery and circular economy model.

Global perspective and support for carbon capture and storage system

The method of CCS necessitates removing CO_2 from different sources, treating, compressing, and eventually storing it in appropriate geological formations [155]. CCU technology can help a number of industries that emit a large amount of CO_2 during the production or processing of natural gas, electricity [40], hydrogen [162], iron and steel [114], ammonia, and fossil fuels [212]. CCS is a fundamental aspect in the recent Ten Point Plan of the United Kingdom (UK) for a Green Industrial Revolution and the Climate Change Act 2008, which both aim to attain zero emissions by 2050. The UK has also made commitments to reach net-zero emissions by 2050, which is evidenced by its complex BECCS advancement program. The government has made significant financial commitments (£800 million) in the budget of 2020 to support the BECCS technique after recognizing it as a crucial system for lowering carbon emissions [195]. The decentralized BECCS systems have the potential to benefit the entire region of the UK and make a substantial contribution toward CO_2 removal goals. The UK's BECCS policies are made to strike a balance between socio-economic and environmental objectives, encouraging innovation as well as public support for decarbonization initiatives. Similarly, the United States of America (USA) has proposed to allocate huge financial resources ($2.4 billion) to encourage CCS-based projects, and research efforts in the CCS field have increased dramatically during the past few decades. The USA aims to reduce industry-level emissions by 26% by implementing the CCS technology [86]. The USA has also put in place financial incentives for CCS projects, such as the 45Q tax credit. Nevertheless, the possibility of incorporating bioenergy solutions into the nation's strategy for capturing carbon is constrained by the lack of clear BECCUS-focused regulations [35]. The approach of the USA toward BECCS is distinguished by a combination of state-level and federal programs. The investment in infrastructure development and substantial incentives provided for BECCS further emphasize the commitment to utilize the CCS-based technology for carbon capture [49]. Furthermore, California strengthens this assistance through programs like the low carbon fuel standard, which encourages the use of these fuels and indirectly helps the BECCS plants [170].

The transportation and storage of CO_2 are the central points of the majority of policies developed for the deployment of CCS technology. The European Union (EU) has shown interest in the implementation of CCS technology [98]. The EU is also demonstrating a significant commitment toward CCS technology development to address climate change. A legal framework for the advancement of CCS has been introduced in the EU [47]. The European Commission (EC) views CCS as the future technology and a potential remedy for emissions from fossil fuel-based projects. The directives related to geological carbon storage were put into effect by the EC in 2008, which ultimately evolved into a legal document for geological CO_2 storage. The policy mandated that newly established power plants must facilitate CO_2 capturing and that mainly coal-fired plants must be fitted with CCS technology by 2020. Although the EU has formulated numerous policies for CCS technology, challenges still prevail, as the EU encounters several difficulties in managing storage sites. The policy also states that the license of any organization will be cancelled in the event of a CO_2 leak; however, the policy document does not specify the steps taken to prevent the leakage. Problems with storage locations show that CO_2 capture, transport, and storage cannot be assured, which lowers the prospect that CCS will be commercialized [202].

The policy of Japan on BECCS advancement in the Asia–Pacific area is connected to its energy security and climate goals. The decarbonization of Japan's strategy incorporates the BECCS system within its Strategic Energy Plan. With a focus on integrated assessment models and sustainable biomass to meet climate targets, BECCS is essential for the climate strategy of Japan [100]. BECCS is also acknowledged by the Chinese government as an essential technology for accomplishing its objectives related to climate change. There have been a number of BECCS projects; however, CCS for fossil fuels has received more attention [218]. Countries like China have enormous bioenergy production potential; however, there is a need to strengthen regulations and incentives to promote the use of BECCS commercially. Effective governmental incentives are necessary to align with the interests of various stakeholders in the BECCS integration model [67, 68]. A novel BECCS strategy called coal bioenergy with carbon capture and storage (CBECCS), associated with the coal industry, has been implemented to reduce emissions in China. CBECCS incorporates CCS technology with biomass co-firing in coal-based power stations in contrast to typical BECCS. A 10% biomass co-firing ratio combined with the carbon capture system can absorb the majority (90%) of emissions that might reduce the emissions generated from the coal-supplemented power plants [90].

Australia has established different levels of assistance to BECCS and CCS through regulatory actions, direct financial resource supplementation, and collaboration with prominent organizations at the international level [148]. Australia has also launched a CCS flagship project, through which two billion dollars were allocated to encourage research and development in the CCS sector. This initiative eventually led to the establishment of the Global CCS Institute, whose prime aim is to promote research and progression in CCS technology [36]. A notable change in policy was observed in Australia with more focus on regulation rather than direct incentives [91].

In underdeveloped countries like Africa and Latin America, the adoption of BECCS is not common due to the requirement of huge infrastructure and financial systems. However, these countries have huge bioenergy potential due to the plentiful bioresources [70]. To boost the bioenergy sector in these countries, international financing and technical support are indispensable instruments underscoring the necessity of knowledge transfer, financial aid, and capacity building for BECCS technology development. Moreover, climate funding will play a substantial role in underdeveloped countries to overcome different impediments and implement successful BECCS solutions for energy production and carbon reduction [48].

Reduced CO_2 emissions are made possible by coupling CCS technology with bioenergy production operations [32]. Until now, the issue associated with the scaling-up of CCS technology to meet energy and CO_2 reduction targets is hampering their extensive adoption [43]. For instance, the Illinois Industrial Carbon Capture and Storage (IICCS) project shows potential for carbon sequestration and simultaneously identifies important technical issues including controlling CO_2 leakage and guaranteeing long-term storage integrity [96]. Similar issues with the effectiveness and dependability of CO_2 collection and storage procedures exist at the Drax Power Station (UK) [84]. Furthermore, several technologies used in the deployment of the BECCUS are still in a premature stage as reflected by the low technology readiness levels (TRL). Owing to their early stage of development, the performance of technologies, scalability, and viability from an economic standpoint are all highly unclear. Advanced biomass conversion technologies and innovative CO_2-based pathways are examples of components that need extensive development and necessitate significant research and demonstration efforts [57].

Status of carbon capture-based projects in India

Approximately, 26% of the world's emissions are contributed by China, followed by the USA (13.7%), India

(7.0%), and Russia (4.8%) [211]. An estimated 51×10^3 million tons of greenhouse gases from diverse sectors are released into the environment each year and the objective is to reduce emissions to zero [59]. The average emission per person in India would increase twofold in the upcoming ten years, which will pose serious challenges if the increase in CO_2 emissions is not controlled. The present challenge is to deal with these problems while steadily raising the production and use of energy in a sustainable manner [181]. In 2030, coal would still account for over 60% of India's electricity, despite the increasing emergence of renewable alternatives such as solar and wind [183]. Therefore, carbon capture, utilization, and storage need to be implemented on an immediate basis considering the efficiency and emission reduction potential of technology. India has not yet made substantial advancements in the field of such technologies. However, some noteworthy steps have been taken by several institutions in India for carbon capture, sequestration, and storage [181].

India has joined the Energy Carbon Sequestration Leadership Forum as a founding member in 2003 [63]. There has been a lot of interest from European governments, particularly the UK, which is working with India to develop CCS technologies. DST organized international workshops at the National Geophysical Research Institute on challenges in the implementation of CCS technology in 2006–2007 [178]. This field observed substantial advancements between 2006 and 2008, as in 2006/2007, DST created the National Program on Carbon Sequestration. To boost the extraction of crude oil, the Oil and Natural Gas Corporation showed their interest in establishing an EOR project in the Ankleshwar oil field, in Gujarat [101]. CO_2 was transported from the Hazira processing plant to Ankleshwar to improve oil recovery [192]. At the Hazira processing plant, a pilot reactor was established to use CO_2 to grow microalgae, and eventually the algal biomass formed was used for the production of biogas [181]. NTPC (National Thermal Power Corporation) has started studying carbon sequestration through one of its schemes, "NTPC Energy Technology Research Alliance" (NETRA). Under this scheme, a plant for capturing CO_2 will be installed, and the feasibility study for the establishment of the plant was carried out by Carbon Clean Solutions Limited and IIT Bombay. The CO_2 is extracted and utilized to make different products such as urea, methanol, and soda ash [63]. Additionally, NETRA and ONGC signed a Memorandum of Understanding to establish a carbon capture facility in Gujarat. ONGC's Jhanor oil field uses the gathered CO_2 for EOR [84]. Similarly, the oilfields in Kamalapuram and the Cauvery basin use the captured CO_2 from the power plant to enhance oil recovery [152].

With its coal-powered facility in Odisha, the National Aluminium Corporation is working toward bio-sequestration. Indo-Can Technology Solutions (ICTS), a prestigious biotechnology company, has been involved in accomplishing these goals. The algae used for the bio-sequestration is grown in a pond (0.18 acres) and flue gas is injected into the pond after cooling to promote the growth of algae and utilize the biomass to produce biofuel. In the Murugappa Chettiar Research Centre, a 7-year pilot research was carried out on the capacity of *Scenedesmus* for bio-sequestration. The waste stream of the sugar mill's liquid waste and a distillery's CO_2-rich gaseous waste were used and resulted in 6000 m^3 of CO_2 consumption and huge biomass production (300–500 $g/m^3/day$). Scaling up the method might result in 100 tons per hectare of biomass production and sequestration of 1500 tons of carbon per hectare annually [177]. Similarly, IIT Bombay has been studying cyanobacteria in an effort to create cell factories that can transform atmospheric CO_2 into beneficial biobased products like biofuel [192]. However, further research is required as this type of work is still in its infancy stage [133]. Viswanaathan and Sudhakar (2019) reached the conclusion that microalgae have enormous potential for bioremediation, wastewater treatment, and biofuel production after reviewing their potential in CCUS. These possibilities for biofuel manufacturing will be particularly beneficial in sustaining India's fuel demand and crucial in assisting India to reach its INDC targets [154].

An Indian company "CarbonClean" has developed an inventive method that turns the released CO_2 into baking soda. The company is founded by two IIT Kharagpur chemists. The system, which can use 60,000 tons of CO_2 annually, is presently deployed at Tuticorin Alkali Chemicals, and the recent advancement to introduce steam boilers resulted in zero emission of CO_2 [71]. Furthermore, the global CCS Institute reported that Dalmia Cement was the first to announce a progressive strategy to become "carbon-negative by 2040" [62]. They have declared their intention to construct a carbon capture facility in Tamil Nadu with the help of technology provided by a UK-based company [166]. Recently, a demonstration facility next to the Panipat refinery, Haryana, is also being built by Indian Oil Corporation Limited. This facility would absorb CO_2 from the industry and convert it into 2,3-butanediol (2,3-BDO) and ethanol [154]. Carbon capture is the most expensive component of CCS as it accounts for three-fifths to four-fifths of the total cost of the system [83]. However, in India, no similar studies have been carried out to examine CCS viability; however, a simulation has been conducted to determine the cost of retrofitting capture systems into existing coal power stations.

Carbon utilization pathways

Apprehension related to global warming and the importance of economical industrial methods have led to an increase in scientific interest in using CO_2. Utilizing CO_2 is frequently marketed as a means of boosting revenue or decreasing net costs related to emissions [171] or eliminating CO_2 from the environment which can help to enhance mitigation [153]. The soil and land change, enhanced weathering, forestry practices, soil carbon sequestration, the production of biochar, and CO_2-based production are a few pathways for the utilization of carbon/greenhouse gases [72, 77, 78]. Direct air capture for geological storage and BECCS are also operational to reduce the concentration of CO_2; however, they are heavily dependent upon the planned transport and storage network [72]. Depending on the situation, these routes can be characterized as either "open" or "cycling" [28]. The pathways must be significant in relation to the net flows of CO_2 for consumption to successfully contribute toward decreasing atmospheric CO_2 concentrations. Flue gases, if collected during fuel combustion, can be repurposed by industries that use concentrated CO_2 to make different by-products [14]. Additionally, the utilization of the captured CO_2 from different sources will also help to improve the process economy, financial stability, and environmental sustainability [41]. Thus, the extraction of CO_2 from the environment and the closure of the cycle are necessary for long-term net-zero emissions [58].

Several processes have been documented over the past 50 years for CO_2 conversion [116] and the main ways to utilize CO_2 are through direct use and its conversion into value-added compounds. Over the course of several billion years, nature has developed extremely sophisticated mechanisms for the fixation and utilization of carbon. There are several bacteria and archaea that can assimilate CO_2, along with photosynthetic organisms like plants and algae [102, 193]. Numerous prokaryotic chemolithotrophic organisms are known to fix inorganic carbon to stimulate growth and ensure survival by utilizing it as an energy source under limited light conditions. The process by which chemolithotrophs fix inorganic carbon has been a significant phenomenon exhibited by microbes in harsh environments [193, 219]. Prokaryotic organisms have been found to contain six autotrophic pathways for CO_2 fixation [102]. The CO_2 fixing autotrophic mechanisms, including the Wood–Ljungdahl (WL) pathway, reductive TCA (rTCA) cycle, Calvin–Benson–Bassham (CBB), 3-hydroxypropionate cycle, 3-hydroxypropionate/4-hydroxybutyrate cycle, and 4-hydroxybutyrate cycle, are found in many natural species [193]. The 3-hydroxypropionate and Calvin cycles (Fig. 3) are two routes tolerant to oxygen for CO_2 fixation [19, 213]. Organisms with

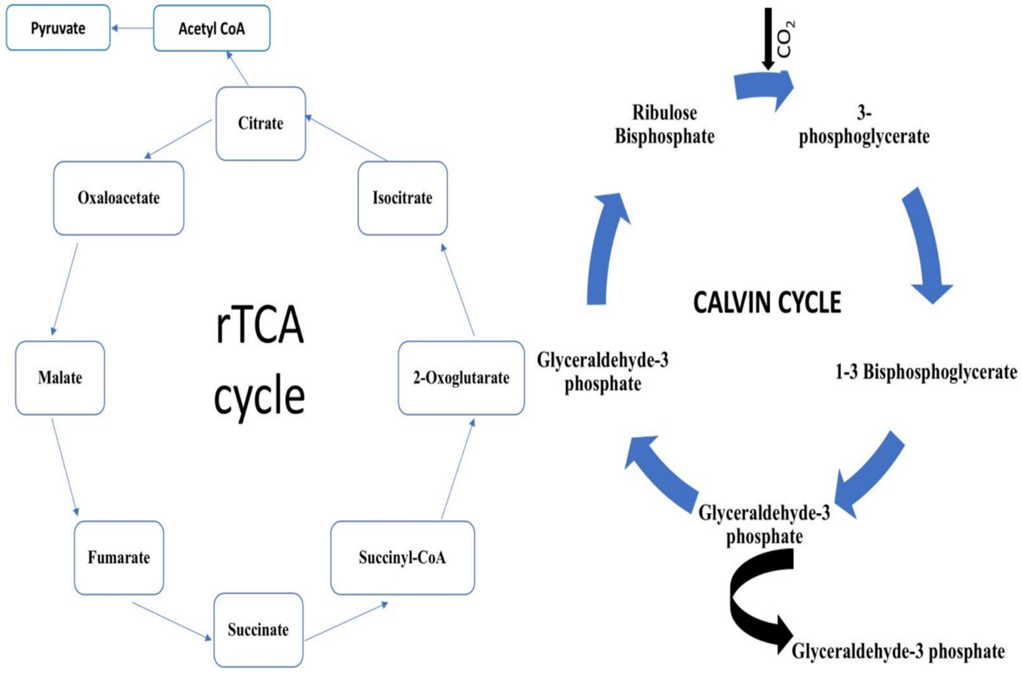


Fig. 3 Calvin and reductive TCA (rTCA) cycles

the above-mentioned pathways either use the process of photosynthesis or the electron transport chain to oxidize reducing equivalents with the help of terminal electron acceptors to generate the energy molecule for CO_2 fixation [55].

CO_2 is incorporated into organic molecules via a variety of biochemical routes as a part of the metabolic mechanism of carbon absorption which permits the production of biomass and useful by-products [93] (Fig. 4). The main photoautotrophs such as plants, microalgae, and blue-green algae employ the CBB cycle to fix CO_2 by Rubisco to form 3-phosphoglycerate (3-PGA) [188]. Of the two molecules, one 3-PGA is involved in key metabolic pathways, while the remaining molecule of 3-PGA is used to continue the cycle. This 3-PGA as an intermediate is then converted to form glyceraldehyde-3-phosphate (G3P) using ATP and NADPH [174], which acts as a precursor to stimulate the biosynthesis of different biomolecules like triacylglycerol [30]. The CBB pathway converts three CO_2 molecules into one G3P, and carbon fixation in autotrophic organisms is accomplished with the help of 11 enzymes [208].

Similarly, the WL pathway, mostly found in acetogens and methanogens, facilitates CO_2 conversion to acetyl-CoA under anaerobic conditions using the enzymatic processes and several cofactors [150]. The WL pathway is non-cyclic in contrast to the Calvin and rTCA cycles. The WL pathway's low ATP cost enables acetogens to conserve carbon from glucose to acetate, enabling the utilization of surplus NADH generated during glycolysis for CO_2 fixation [55]. It is considered the most efficient pathway in terms of energy for carbon fixation [156] In this pathway, CO_2 is transformed into formate, and this formate is reduced to methyl-H4 folate [123, 125]. The methyl group of folates is then transferred to iron–sulfur protein and eventually acquires methylated corrinoid protein. Through the WL route, CO_2 is assimilated, and in the carbonyl chain, it is converted to carbon monoxide and eventually to acetyl-CoA [184]. The two enzymes, namely acetyl-CoA synthase and CO dehydrogenase on the CO route, have a critical role in the WL pathway, as acetyl-CoA synthase facilitates CO formation after the reduction of CO_2, while CO dehydrogenase stimulates acetyl-CoA formation by combining CO and the methyl group [27, 150, 184]. The acetyl-CoA produced serves as the essential intermediary to promote the biosynthesis of valuable biocompounds like acetate and ethanol [37, 180].

The fixation of carbon is made possible by the rTCA cycle in chemoautotrophs. In anaerobic organisms (bacteria and archaea), the rTCA cycle converts CO_2 to organic acids such as malate, fumarate, and succinate by using reducing agents as the electron donors [16, 93]. This process is alternative to the Calvin cycle for the

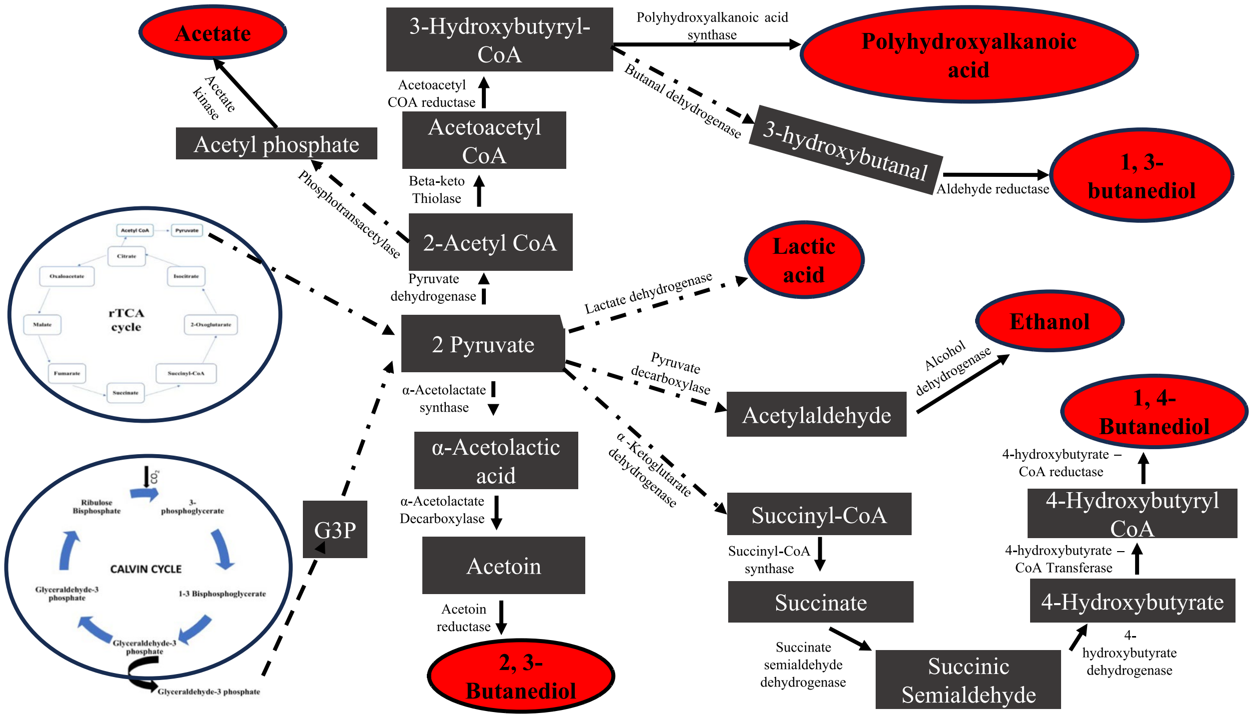


Fig. 4 CO_2-based formation of chemicals via Calvin and reductive TCA (rTCA) cycles

fixation of inorganic carbon in a variety of microorganisms, which also yields organic compounds. In the rTCA cycle, citrate lyase is an important enzyme that plays a central role in converting citrate to form oxaloacetate and acetyl-CoA. In the 3-hydroxypropionate/4-hydroxybutyrate cycle, three enzymes play a vital role in carbon assimilation. Acetyl-CoA is converted to malonyl-CoA, propionyl-CoA, and methylmalonyl-CoA through mediation of different enzymes in the first phase of the cycle [81]. In the second phase, methylmalonyl-CoA formed is then converted to succinyl-CoA through isomerization rearrangement, which is further converted to 4-hydroxybutyrate [184]. The 4-hydroxybutyrate, after a series of reactions with the aid of enzymes, yields acetyl-CoA [16], which, after assimilating carbon, is converted to 3-phosphate glyceraldehyde [184]. Overall, the abovementioned pathways either use CO_2 or bicarbonate as a carbon source, and the presence of different enzymes in each pathway is necessary to facilitate conversion reactions in the cell. However, switching pathways associated with carbon fixation with specific growth conditions in different organisms can assist in improving productivity. Furthermore, utilization of heterotrophic microbes under autotrophic mode through genetic engineering is a potential alternative for the production of different products, reducing the dependency on costly feedstock [73]. Therefore, the efficiency of carbon assimilation pathways is improved by ongoing developments in metabolic engineering, which will boost the generation of distinct bioproducts, improve carbon sequestration, and support efforts to slow down climate change.

Utilization of carbon dioxide via gas fermentation

Globally, climate change presents serious environmental, economic, and social issues due to increased emissions of greenhouse gases into the atmosphere and oceans [2]. The concentration of CO_2, the primary greenhouse gas, has sharply increased during the past century due to energy, fuel, and chemical demand [158]. The need for carbon-negative, ecologically friendly chemical and material manufacturing has increased due to climate change [175, 197]. By facilitating a new circular carbon economy, strategies that ensure carbon capture and production of valuable products by CO_2 conversion will not only promote biomanufacturing [33, 215], but also assist in resolving issues associated with climate change [9]. Fermentation is a biological process that uses biomass-derived renewable and fermentable carbon as the main energy source [113]. In gas fermentation, chemolithoautotrophic bacteria ferment a gaseous carbon substrate to useful by-products [203]. Acetogens transform CO_2 and CO, which are C1 carbons, into C2 carbons, with minimal CO_2 emissions [205]. The gaseous feedstocks available in significant quantities can be either as an industrial exhaust or synthesis gas, which is produced by gasifying biomass and municipal waste streams [12]. Syngas and CH_4 can also be used as carbon sources by microbial catalysts via gas fermentation. Fermentation-based biomanufacturing uses “above-ground” C1 carbon sources to produce desired compounds in a sustainable manner. Using reduced C1 compounds as electron donors is a suitable and effective strategy to strengthen carbon fixation through microbes. It provides energy necessary to drive the process of carbon biosequestration in chemolithoautotrophic organisms [31]. Thus, transformation of GHGs such as CO_2 generated through the process of fermentation or acquired from additional sources through catalytic and biological pathways could be an attractive approach for sequestering of GHGs [159].

Microbial cell factories have been employing renewable feedstocks for a long time, transforming them into metabolites with a wide range of uses and commercial potential [187]. Anaerobic acetogens are promising because they use the most effective known CO_2 fixation route and do not need light as a source of energy. At least 10^{32} tons of acetate are produced annually in nature by acetogens, which are essential for the global acetate cycle [46]. Ethanol, amino acids, or organic acids are examples of traditional fermentation using renewable sugar as a substrate and have been conducted on an industrial scale over several decades [3, 4]. Nowadays, fermentation is also being used to scale up the production of a number of novel compounds that were previously exclusively generated commercially through petrochemical means [122]. Several industrially important compounds are being produced from biological feedstock, and to boost the productivity of valuable compounds, organisms can also be genetically modified to improve biomanufacturing. Moreover, synthetic biology has expanded the product base to include numerous other native as well as non-native metabolites, such as ethanol, acetate [76], 1,3-propanediol [221], 2,3-BDO, and 1,4-butanediol (1,4-BDO) [103].

Fermentation products and by-products are some of the carbon sinks that can be formed from the oxidized molecule known as CO_2 [23]. The quality and purity of CO_2 are essential for gas fermentation to succeed [122, 156]. High-quality CO_2 from biological sources can be readily combined with gas fermentation to produce different products. As the raw material for microbes is biogenic, CO_2 is recycled back into the environment through the breakdown and oxidation of these products. Additionally, biogenic CO_2 captured during the fermentation process is distinct from BECCS systems because it does not require an expensive CO_2 separation technology [128]. Fermentation yields high-purity exhaust gases that are composed of CO_2 (99%), H_2O, and sulfur and organic molecules in trace amounts [207]. Additionally, the capturing and compressing of CO_2 from fermentation is estimated to cost approximately \$30/t CO_2 and is among the least expensive of all CO_2 point sources [15]. Other technologies like soil carbon (\$28–285/tCO_2), BECCS (\$94–270/tCO_2), and direct air capture (\$608/tCO_2) are costly to store carbon for climate change mitigation [72]. CO_2 generated from biogenic processes like during bioenergy production needs to be captured and transformed into distinct products and by-products. Moreover, it is very important to understand that directly releasing CO_2 after biomass combustion into the atmosphere intensifies climate change, while BECCUS utilizes CO_2 to form fuel and by-products which release less carbon into the atmosphere and help to reduce reliance on conventional fossil-based refineries [220]. The fuel produced from biogenic CO_2 will eventually assist in replacing fossil fuel and ensuring carbon circularity with no further addition of carbon into the atmosphere. Additionally, the environmental outcome of the BECCUS depends strongly on the durability of the carbon stored through different metabolic pathways. Products such as biochar, PHA, PHB, fatty acid, and succinic acid produced from CO_2 offer long-term storage in comparison to that of fuel like ethanol and butanol [77, 78, 115]. Therefore, BECCUS should integrate both short-term and durable carbon retention pathways.

Different compounds produced via gas fermentation using CO_2 as feedstock

LanzaTech has developed microbes with the potential to transform waste exhaust gases emitted from a steel plant into ethanol and other important compounds [131]. The commercial interest in acetogens that have promising potential to convert C1 feedstocks (CO_2 and CO) to acetyl-CoA was restored by LanzaTech Technologies. The capability of these bacteria to convert C1 feedstock to different products can be due to the WL pathway and acetyl-CoA synthase. LanzaTech has established commercial ethanol production plants in China [206] and Belgium [11]. A novel process of fermentation has been developed by LanzaTech for the production of fuel and valuable chemical products by the transformation of CO and gases from different sources containing hydrogen. LanzaTech has demonstrated its technology at a plant with a capacity of 300 TPA in collaboration with Baosteel and another plant with Shougang Steel in China using mill gases as feedstock for fermentation [69]. Additionally, three more commercial plants in South Africa [110, 111], India [112], and California [22] use the waste gases from different industries. In Japan, LanzaTech has also established one plant at a commercial scale by employing syngas generated from mixed municipal waste [110, 111] (Table 1). LanzaTech also collaborates with Global Bioenergies for isobutylene production and Evonik for plastic manufacturing [109] and 2-hydroxyisobutyric acid from syngas [191]. Additionally, the ethanol production through the fermentation process developed by LanzaTech produced less greenhouse gases (60%) in comparison to that of gasoline as per the life cycle assessment carried out by Handler et al. [69] This shows that gas fermentation techniques can serve as a feasible alternative for next-generation biofuel production by utilizing industrial exhaust or biomass-based emissions with a minimal emission footprint.

Succinic acid (SA) is a platform chemical produced through petrochemical processes. Several biobased facilities for SA production have demonstrated superiority in terms of environmental sustainability in the past decade. The potential process to convert CO_2 to SA is through non-photosynthetic microbes, enabling large-scale utilization of CO_2. To achieve SA fermentation, CO_2 is fixed into succinate during the fermentation of glucose, through which oxaloacetate is formed after the incorporation of CO_2 in phosphoenolpyruvate [138, 216, 217]. The experiment performed by Zhang et al. [216, 217] using *Actinobacillus succinogenes* revealed that employing glucose (50 g/L) along with fermentative CO_2 (92–94%) resulted in 25.8 g/L of SA production after carrying out the experiment for 27 h. However, it was also observed that CO_2 removal efficiency was maximum at 18 h, while the productivity of SA was maximum at 24 h of fermentation (23.5 g/L·d). Gunnarsson et al. [66] reported that substantial CO_2 emissions can be saved (4.5–5 tons/ton) by using a biological process for SA production rather than a fossil-based production system. SA produced by Reverdia through biological routes has a less carbon footprint (0.9 kg CO2e/kg) as opposed to a petrochemical process (1.9 kg CO2e/kg) [161]. The majority of current research on SA production through biological routes has concentrated on increasing the yield as well as productivity through parameter optimization [139], operating pressure [10], metabolic engineering [118], configuration of the reactor [119], and CO_2 and H_2 availability [66].

The synthesis of polyhydroxybutyrate (PHB) and polyhydroxyalkanoate (PHA) polymers has a long history of employing H_2 and CO_2 in aerobic gas fermentations using hydrogen-oxidizing bacteria [95]. The competent organism for the production of PHB using CO_2 is *C. necator* [199], as it has been reported that the content of PHB in the cells of *C. necator* varies from 0 to 65 wt% [126]. For long-chain lipid production, a two-stage system was constructed using *M. thermoacetica*. In the first stage, *M. thermoacetica* was supplied with syngas to produce

Table 1 Different companies at global level responsible for sustainable production of different products using carbon dioxide

Company	Product	Technique	Advantages	References
Solar Foods (Finland)	Solein (protein)	Captures CO_2 from atmosphere	Contains protein, carbohydrates, dietary fibers, iron vitamin B_{12}, and essential amino acids	https://solarfoods.com/solein/
Carbon Recycling International (Iceland)	Methanol	Emissions to liquid technology	Helps to generate alternative energy source from waste, Serves as aviation and automative fuel	https://carbonrecycling.com/technology
LanzaTech (USA)	Ethanol	Gas fermentation for constant generation of ethanol from steel mill emissions	This facility in China started functioning in 2018; ethanol: 40 million gallons; CO_2 reduction: 2 Mt	[24, 39]
	Acetone, isopropanol	Recombinant strain of *Clostridium autoethanogenum* to demonstrate continuous acetone and isopropanol production	LCA analysis revealed that both products had negative carbon footprints	[121]
LanzaTech and Evonik	Evonik	Developed technology for plastic manufacturing from syngas	–	[109]
Tate & Lyle Group and the Genomatica (US-based company)	1,4-BDO	Modified *E. coli*; Glucose	Licensed their technology to Novamont in 2018; 56% reduction in GHG emissions through biobased production; Prevents 7 million tons of GHGs emissions annually	[61]
Genomatica (US-based company)	1,3-BDO	Fermentation method based on sugar	Used in cosmetic, medical, and personal care products; currently marketed as BrontideTM and AlveaTM	[143]
Newlight Technologies (US-based company)	Polyhydroxybutyrate (PHB)	For PHB production, naturally occurring microbes utilized air and CO_2 as substrates	Carbon-negative PHB production; PHB produced is marketed under the AircarbonTM	[97]
Air Protein (US-based company)	Protein	Microbes using carbon dioxide, oxygen, and hydrogen as substrate to perform fermentation	High production, less time consuming and climate independent production	https://foodplanetprize.org/initiatives/air-protein-making-meat-out-of-air/
Evonik (Brazil)	Lysine	Corn-derived glucose utilizing *Corynebacterium*	Contains 77% ratio of lysine HCl; per kg products generate only 0.1 kg CO_2 equivalent	[124]
Coskata	Ethanol	Used syngas from the gasification of biomass; now, reformed CH_4 for ethanol production	–	[21]
White Dog Labs, a start-up company (2012)	Acetone and isopropanol	Mixotrophic fermentation using feedstock like sugars and syngas	Used syngas for the production of different compounds; envisages to develop a wider range of products from acetyl-CoA	[201]
LanzaTech and Global Bioenergies	Isobutylene	–	Synthesis of fuels	[109]

acetate as the end product, and the broth was fed to *Yarrowia lipolytica*, a genetically modified yeast. This system with modified yeast in an aerobic reactor produced 18 g/L of long-chain fatty acid (C16–C18), reflecting the efficacy of the system to use carbon from syngas to produce different products in a multi-stage system [80]. Similarly, scientists employed an interesting strategy in which *Synechococcus elongatus* was genetically engineered to export CO_2 in the form of sucrose, which was then ingested by *Halomonas boliviensis*, a bacterium that produces PHB. In addition to achieving high productivity, this consortium demonstrated improved resistance to different contaminants produced by the microbial community [117].

For butanol production, several companies are working on the microbial organisms that have promising potential to convert sugar into butanol. "Gevo" has developed a fermentation process and collaborated with ICM to retrofit a system capable of producing butanol in ethanol production units in a cost-effective manner [130]. *Clostridium* genus has substantial potential to enhance biobutanol synthesis due to the presence of some specific enzymes necessary to overcome carbon monoxide toxicity by converting it into CO_2, and eventually into acetyl-CoA [75]. The different species of *Clostridium* can assist in converting gases into ethanol (CO and CO_2) and butanol through the WL pathways [165]. Early work is also underway to produce 1,3-butanediol (1,3-BDO) along with 2,3-BDO by LanzaTech in collaboration with Invista [20] (Table 1). The production of biobased chemicals is not only possible through biological processes, but also the production of some chemicals can be enhanced through the integration of biobased and chemical processes, which are rarely found in biological systems. A process was also developed by LanzaTech in association with Invista and SK Innovation, which involves both biological and chemical steps, for 1,3-butadiene production [85]. The precursors (2,3-BDO and 1,3-BDO) responsible for butadiene production are produced mainly from biological routes via fermentation of syngas, and eventually butadiene is produced through thermo-catalytic dehydration of 2,3-BDO and 1,3-BDO. Additionally, studies are ongoing to produce 1,3-butadiene in one step through the use of a modified biological catalyst. However, both processes are still in the development phase, but it reflects that integrating biological and chemical processes can expand the production of different compounds as well as products derived from syngas [156].

Microbial fermentation is also used to commercially manufacture additional food-grade compounds like lysine. Several chemicals like 1,3-propanediol, 1,4-butanediol, isobutanol, lactic acid, and succinic acid have made it to the commercial level; however, these chemicals need significant human and financial resources [114]. The synthesis of commodity chemicals using sugar fermentation is still challenging, even with recent advancements in fermentative processes [168]. The important point that permits discussion is the numerous attempts to produce products that can be obtained through sugar-based pathways, and some, like lactic acid, 1,3-PDO, and ethanol, are already commercialized [191]. The most significant disruption is still to come, as advancements in synthetic biology and metabolic engineering can help to modify microbes to improve the yield of the system. Through these techniques, more than 50 compounds have been produced, even now, by the reprogramming of the gas-fermenting microbes [120]. Therefore, CO_2-based biochemical technologies can still be improved by creating reliable industrial processes and upgrading microorganisms. Furthermore, the companies investing in carbon utilization technologies can adopt a variety of strategies such as utilizing distinct biochemical platforms, diversifying product portfolios, emphasizing platform chemicals, infrastructure facilities, licensing of the technologies, and forming strategic partnerships to aid not only in development, but also deployment of the technologies. It is important for researchers and innovators to pay attention to different biochemical pathways and employ genetic engineering for strain improvement to offset harmful greenhouse gases, increase product portfolios, and drive economic benefits from these feedstocks. Overall, gas fermentation is one of the desirable platforms for carbon recycling or carbon capture and utilization; thus, it promotes a circular economy because of its feedstock and product flexibility benefits.

The environmental performance of carbon capture and utilization pathways differs significantly because of its dependence upon the mechanism of conversion, energy input, and end use of the product. Different gas fermentation technologies developed by LanzaTech exhibited a substantial reduction in carbon emission in comparison to gasoline as per the life cycle assessment [69]. CO_2-derived succinic acid and PHB reflected robust competence for carbon reduction with the additional benefit of co-product generation [10]. Products such as biopolymer and succinic acid are more relevant in the BECCUS framework due to durable carbon storage, while fuels like ethanol and butanol ensure short-term benefits in terms of carbon storage [115]. Moreover, for BECCUS development and deployment, fair life cycle accounting is needed to examine the performance of each pathway responsible for carbon utilization. As different processes and pathways are being used to capture CO_2 and convert it into valuable products, they differ significantly in terms of feedstock, energy, land, nutrients, transportation systems, technology, and reactor requirements. Therefore, applying standardized frameworks globally that incorporate transparent and equitable evaluation of processes and products can inform the policy mechanism that carbon-negative and resource-efficient technologies are being favored and incentivized through BECCUS. The fair assessment will help to delineate and differentiate products produced through BECCUS, which assist in achieving the target of net-negative emissions in comparison to products that only recycle carbon. This system-level monitoring and evaluation is very crucial to develop policies and direct investment towards sustainable carbon utilization through BECCUS.

Economic analysis

BECCUS is promising pathway to decrease atmospheric CO_2 levels, but it is still economically not viable [57] (Table 2). High capital and operational costs are involved in BECCUS technologies, which makes it a hard solution to deploy on a large scale without external incentives or market mechanisms like EOR or carbon credit trading systems [53]. This is especially true in situations where financing via fossil fuel-related incentives, such as applying captured CO_2 in EOR is not available. The capital expenditure also increases due to huge costs involved in the capture and compression of the gas. Once the gas is captured and compressed, the issues related to transportation arise. The establishment of a pipeline system, its cost, maintaining pressure through the pipeline and energy required for compression eventually increases the cost of transportation. Further, the contaminants in the gas may pose damage to the pipeline which may results in an explosion [57]. The potential of BECCS is also dependent upon the biomass availability, cost, and its quantity. A steady source of sustainable biomass feedstock needs to be established for BECCUS systems to become more economical and viable. The cost of biomass production varies significantly as it depends on the type of biomass and other input factors like availability of land, fertilizers and their use, productivity, harvesting technique as well as transportation system. The uncertainties in feedstock pricing are the issues that negatively affect the profitability of BECCUS plants. As per the supply curve derived by Perlack et al. [147] for different scenarios revealed that the biomass cost varies from 40 to 60 \$/oven-dry ton and almost similar price were observed by IRENA (2012) (40–55 \$/ODT) and Kyle et al. [107] (35 and 65\$/ODT). Supply chain complexity in biomass is influenced by logistical challenges most prominently in decentralized BECCUS systems using local feedstocks such as wheat straw, forest residues, and waste wood [7, 8]. Additionally, biomass sourcing that does not promote significant land use changes while conserving food production further adds complexity to the financial decision-making process. Retrofitting CCS system into the existing plants increases the cost of the end product as different equipment used add production cost to the output. The study carried out by Rubin et al. [164] showed that cost of electricity production increased by 46–69% in pulverized coal plant during post-combustion capture, while it was increased by 60–84% in oxy-combustion plants. Other aspects that affect the economics of BECCUS is transportation cost of CO_2. Rubin et al. [164] reported that transporting 10 Mt CO_2/year over a distance of 250 km can cost 2.2–3.7 \$/tCO_2 in the case of an onshore pipeline and 3.4–4.8 \$/tCO_2 for an offshore pipeline. Similarly, the transport of CO_2 via ships is approximately \$15/t for a 500 km distance, which reflects less correlation with distance, as the majority of the cost was related to shipping fees and the port establishment [54].

The total CAPEX for integrating carbon capture and storage with biogas upgrading is \$3 million, with a payback time that exceeds 10 years. Additionally, the inclusion of carbon capture increases the final cost of biogas production by about 10% [104]. Furthermore, the operation of such systems requires energy, transport, and maintenance of CO_2, which must be balanced by market revenues, especially from carbon credits [142]. Carbon credits and pricing mechanisms are considered important alternatives for making the BECCUS technique profitable. Ganeshan et al. [57] underline that carbon taxes between \$1 and \$137 per ton of CO_2 have already been implemented in 54 countries. Such studies should also assess the economic impacts of these initiatives and explain what optimal structures are for carbon markets worldwide. BECCUS systems usually cannot cover their high operational costs without a well-functioning market for carbon credits or substantial carbon taxes [210]. At this stage, BECCUS cannot become economically viable without appropriate and significant market incentives, government subsidies, or improved carbon prices. A broader perspective indicates that though several nations have announced multiple commercial CCUS projects, their efficiency will depend strictly upon a carbon price that remains highly variable across the world [1] (Fig. 5). Brazil is a strong example of how BECCUS might become economically viable even if it remains very dependent upon external factors such as EOR and carbon pricing. Silveira et al. [185] suggested that the introduction of CO_2 captured from BECCUS into EOR represents one model that can offset large capital and operational expenditures of BECCUS systems in Brazil. However, the economic feasibility of BECCUS in Brazil and its similar regions is not definitely ensured by the use of EOR or other external incentives. Although the Brazilian biofuel industry has succeeded in integrating BECCUS with EOR, this model is not easy to replicate in other regions

Table 2 Economics of bioenergy-based carbon capture plant

Carbon capture technology	Different scenario/assumption/operating conditions	Output	References
CO_2 capture in biogas plants	Three scenarios: upgrading of biogas using amine scrubbing; biogas upgradation using amine scrubbing; and CO_2 is directed toward bio-methanation; Assumptions: continuous process, MEA ($HOC_2H_4NH_2$)-30% wt.; feedstock: grass silage (3.2 wwt) and diary slurry (3.5 wwt) CSTRs—mesophilic temperature (38 °C); HRT-40 (CSTR-1), 30 (CSTR-2); Time period: 20 years Interest rate 8%	Injecting biogas directly to the bio-methanation system is financially viable instead of biogas upgrading and then bio-methanation. Methane production: Scenario 1–3.44 Mm^3 Scenario 2–6.63 Mm^3 Scenario 3–6.64 Mm^3	[198]
CO_2 separation and methanation	Coal-fired plant with capacity of 1000 MWe and 47.9% efficiency was chosen as reference plant Equipment cost: CCU 338.04 M€; ICCU is 211.44 M€, total capital cost: CCU: 507.08 M€; ICCU: 317.17 M€, fixed beds are adopted so flue gas is automatically separated. Cost related to gas compression and energy for transportation of CO_2 are taken into account while cost-related transport of gases and end product are not considered	Calcium looping-based integrated carbon capture utilization (ICCU) and methanation. The process of ICCU-methanation is carried out at low temperature environment reflecting sorbent attrition is not the problem and sorbent deactivation rate is also much lower. ICCU CH_4 cost—443.26 € t^{-1} (considering carbon tax also) Natural gas cost 429 € t^{-1} CO_2 avoided: CCU 182.68€ t^{-1}; ICCU 68.59€ t¯1. Efficiency to recover waste heat is crucial in reducing the cost of both technologies (CCU and ICCU)	[127]
Membrane CO_2 separation	Plant capacity 1000 Nm^3/,h cost of the raw biogas 0.087 \$/Nm^3. Total costs (including raw biogas value for the upgraded biogas): 0.17 \$/Nm^3. Assumptions Membrane life time—5 years, Material of compressors—stainless steel, Interest rat- 6%, operating cost 1.1% of capital investment (CI), maintenance cost 2.3% of CI, insurance 2% CI	Polyvinyl amine membrane was used for separation. PVA membrane and 2-stage recycled process exhibit high separation efficiency and resulted in 99% CH_4 recovery at very low cost and competed with the conventional technologies that are being currently used. The total cost of upgraded biogas is approximately 0.17 \$/Nm^3, much less than that of natural gas	[42]
Amine scrubbing	Five different amines monoethanolamine (MEA), diethanolamine (DEA), diisopropanolamine (DIPA), methyldiethanolamine (MDEA), aminomethyl propanol (AMP) were used to upgrade biogas. Target was to reach 91% biomethane mass fraction Working time: 8760 h/year Capital cost was higher for MEA (110.72 MUSD) and lowest for AMP (64.56 MUSD)	Operating profit was much higher for AMP (17.44 M USD/year) and lowest for MEA (18.55 M USD/year). Biomethane production: 7,190 tons/year CO_2 production: 17,280 tons/year Biomethane price: 1404.8 USD/ton CO_2 price: 380 USD/ton Profit; biomethane: 11.82 M USD/year CO_2: 6.26 M USD/year, AMP serve as the suitable and economical alternative for biogas upgradation, offers superior efficiency, with minimum consumption of energy, and very less or negligible methane slippage	[88]
	Solvents: diglycolamine (DGA); methyldiethanolamine (MDEA) with diethanolamine (DEA). Operating time period: 8000 h/year Flow rate: 1600 Nm^3/h Pressure for DGA—1.5 bar and 1.7 bar MDEA-DEA 2.0 bar and 2.5 bar	Diglycolamine-based upgrading route: 99% CO_2 removal and generates biomethane (91% methane).Biomethane sale price: US\$0.38/m^3 Natural gas sale price: US\$0.23/m^3–US\$0.37/m^3	[29]
Biogas upgrading and CCS	Scenario 1: base case cellulosic biorefinery; Scenario 2: biogas upgrading to RNG; Scenario 3: biogas upgrading and partial CCS; Scenario 4: RNG in addition to full CCS A base case biorefinery of lignocellulosic biomass using sorghum as feedstock pretreated with ionic liquid followed by bio-conversion of sugar into ethanol. As this biorefinery does not capture CO_2, it was compared with facilities that upgrade biogas and simultaneously capture CO_2	Minimum ethanol selling price (MSEP) for biogas onsite combustion: \$1.34/LGE. MSEP FOR biogas upgrading to RNG: \$1.38/LGE (liter gasoline equivalent) MESP for full carbon capture and storge including pre- and post-combustion: ~\$0.43/LGE MESP for partial carbon capture and storage involving only precombustion: ~\$0.03/LGE. Mitigation costs/ ton CO_2e avoided: Scenario 1: \$67, Scenario 2: \$64, Scenario 3: \$53, Scenario 4: \$52	[209]

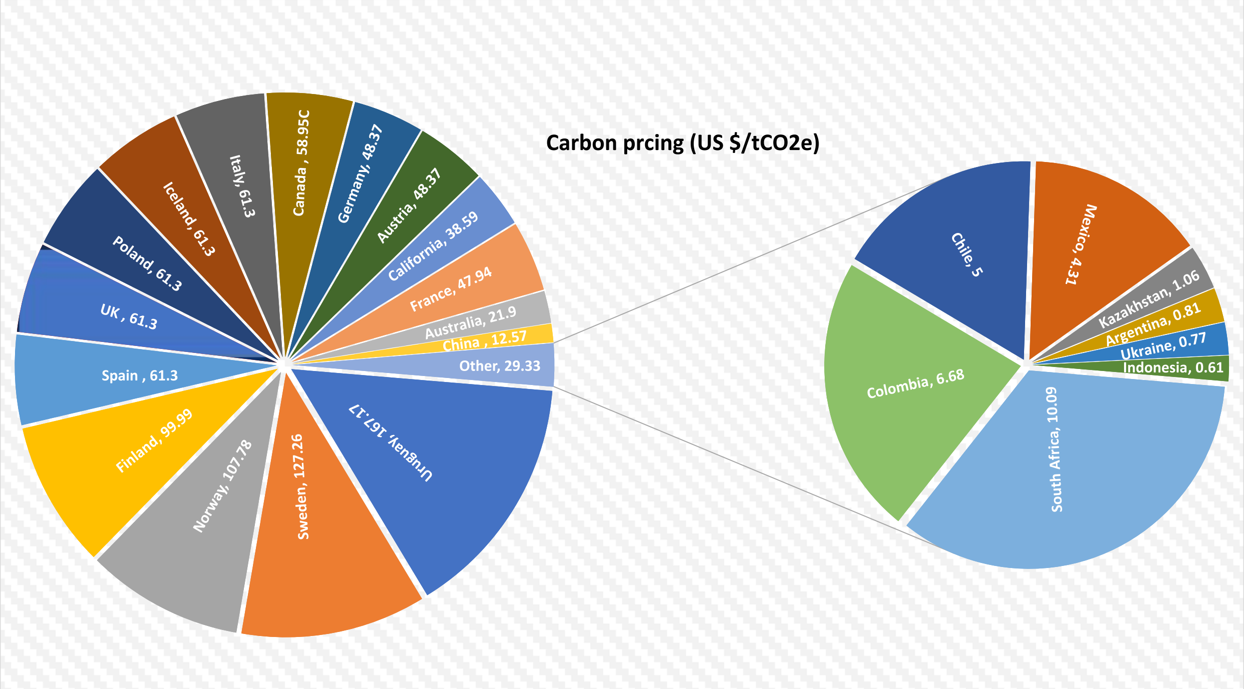


Fig. 5 Carbon taxes in different countries (Source: https://carbonpricingdashboard.worldbank.org/compliance/price)

due to differences in infrastructure, biomass availability, and carbon pricing mechanisms [185]. This will depend mainly on the combination of factors such as technological advancement, robust carbon pricing mechanisms, and policy frameworks supporting carbon removal and renewable energy initiatives. Therefore, substantial improvements in CCS in terms of cost and performance are needed to reduce deployment expenses. The implementation of a carbon price can help to make CCS a profitable technology; thus, the price should be set in such a way that enables this technology to evolve and mitigate climate change.

Market dynamics

There are several critical factors decisive in determining the dynamics of BECCUS, namely pricing models, particularly carbon pricing on a fixed price or fluctuating carbon credit price based on prevailing market demand and regulatory conditions. However, the economic feasibility of BECCUS depends heavily on the price of carbon credits, as higher carbon prices typically improve project viability. For example, an Indian study is very indicative of the decentralized approach utilizing carbon credits to offset uncertainties in the bioenergy sector, resulting in carbon savings of up to 90.38% [65]. Research on China indicates the importance of managing regulatory risks and strategies to ensure that BECCUS could sustainably be financed through carbon credit systems. In Vietnam, interest remains mixed from local community-based carbon schemes in purchasing carbon credits, thereby explaining regional differences in demand [140, 141]. Such results clearly explain the factors influencing the financial feasibility of projects BECCUS, especially in developing countries, where market adjustments and uncertainties in bioenergy markets are most common. One more critical factor for project-level analysis of BECCUS is the levelized cost of energy, the unit cost of building and running an energy generation plant. LCOE also provides a critical input toward the competitiveness assessment of BECCUS in the overall energy landscape, including capital costs, O&M costs, as well as capacity factors. Biomass-based energy is estimated between \$0.172 and \$0.370 per kWh in 2050 [210]. Government incentives include specifically the EU innovation fund and the US 45Q tax credit as these mechanisms reduce the effective pricing that developers and consumers will have to pay in making the BECCUS projects financially more viable. Such subsidies play a significant role in promoting deployment, making BECCUS much more economically competitive than other sources of renewable energy [210]. In terms of market structure, BECCUS projects compete with other renewable technologies like wind and solar, which generally have lower operational cost and lower capital requirements.

In this context, regulatory frameworks and market competition should heavily weigh on BECCUS deployment. Vertical integration within the BECCUS supply chain as represented by the China model can also enhance the competitiveness of these projects by reducing operational risks and streamlining approaches to biomass production and carbon storage [67, 68]. It is critical to enable its adoption globally to understand the interplay of market dynamics, competition, and regulatory frameworks.

Policy frameworks for BECCUS implementation

BECCUS implementation is heavily impeded by policies, particularly regional policy inconsistencies, limited incentives, and overall inadequate government and public engagement [5, 56]. The current literature focuses on integrated cross-sectoral approaches for policy formulation (Table 3) based on local perspectives as well as human impacts on deployment for the effective implementation of BECCUS. The current regulatory framework is inadequate to support high levels of deployment for BECCUS because it deals with an interdisciplinary technology across the energy, environmental, and agricultural sectors. The most probable move to realize climate goals considering the Paris Agreement is to focus on bioenergy and other negative emission technologies. However, BECCUS remains a highly controversial and immature technology because the extant policy framework fails to provide space for significant uptake and operation [186].

Financial incentives are among the most crucial factors that must reduce the costs associated with BECCUS. Yeung et al. [210] stated that the idea of economic incentives like carbon credits and government subsidies is crucial for BECCUS feasibility, especially at an early stage in the technology. Addressing barriers related to the deployment of BECCUS will require filling knowledge gaps between market needs and research priorities [186]. Additionally, stakeholder engagement, greater collaboration among market players, academia, and policymakers, and increased social acceptability will play a significant role in BECCUS adoption. However, Thornley and Mohr [194] have pointed out that the governance model must break through the shell of present policies as envisaged under the climate ambition of the Paris Agreement. More policies like renewable energy certificate schemes and contracts for difference between renewable and fossil products would further expand BECCUS deployment [99]. Market frameworks need to be established that create demand for biogenic CO_2 and incentivize the environmental benefits. The CO_2 released during biological processes such as AD, bioethanol production, and fermentation should be considered a renewable resource substitutable for fossil-based CO_2, and therefore, it would benefit from preferential treatment in carbon accounting systems and carbon markets. Establishing a reliable certification system for carbon removals will facilitate trade in carbon credits that enhance transparency, offering financial incentives to utilize and store biogenic CO_2 in construction materials or underground storage. Additionally, harmonized policy frameworks are essential for the widespread uptake of the bioenergy-based carbon capture technology in addressing climate change. There is a fragmented approach to life cycle assessments and

Table 3 Summary of policy models

Policy model	Details	References
State guarantees	Long-term contracts funded by taxpayers.Sweden's model involves reversed auctions, distributing funds to lowest-cost NE providers (starting 2026).Increases predictability for BECCS operators	[214]
Quota obligations	Emitters finance BECCS by purchasing NEs proportional to emissions. Initial obligation: ~ 10% of fossil emissions, increasing over time. Proven cost-effective with demand-side measures, enabling pathways toward net-zero	[89, 214]
EU ETS integration	NE credits integrated with or linked to EU ETS. Residual emissions offset through NEs as ETS cap tightens to zero by 2050. Certification framework is being developed by EU for CDR credits to enable accounting and voluntary trading	[47, 157, 214]
Voluntary carbon markets (VCMs)	NE credits sold to entities voluntarily offsetting emissions. Key players: Microsoft, Stripe, Shopify.Challenges: non-permanence risks, lack of unified NE accounting practices. Standardized practices could strengthen VCMs	[79, 214]
International credit transfers	Credits traded between nations under Article 6. Article 6.2: voluntary transfers of mitigation outcomes. Article 6.4: market mechanisms engaging private corporations.Challenges: avoiding double counting	[173, 214]

techno-economic analyses, which prevents uniform assessment of BECCUS projects. Regions need standardized methodologies to assess carbon emissions and economic feasibility and stabilize the decision-making processes [134]. Globally harmonized carbon taxes or emissions trading schemes [92], harmonized approaches to biomass sourcing, transportation, and its storage [51] will provide predictable markets for carbon offsets generated by BECCUS, incentivizing investment. Importantly, international cooperation is needed in managing cross-border impacts, such as trade in biomass or cross-boundary CO_2 storage facilities. Lastly, bioenergy policies need to be put in line with major renewable energy and climate objectives as BECCUS is effectively considered one of the effective global decarbonization strategies.

Technological innovation

Innovations in BECCUS are essential to achieve global climate goals because it combines carbon reduction with renewable energy production [74, 160]. A key focus of BECCUS is capturing CO_2 from bioenergy processes, converting it into value-added products [210]. Emerging carbon management strategies (Table 4) incorporate a range of solutions**,** including chemical looping combustion (CLC), CO_2 liquefaction, and microalgae cultivation [176]. Capturing CO_2 integrated with biogas upgrading is gaining momentum due to the benefits of sustainable production of energy and carbon capture. Moreover, global initiatives such as the Carbon-Negative Shot of the US Department of Energy highlight innovation at gigaton scales across sectors, indicating the need for cross-sector collaboration to accelerate deployment [45]. Through these technological innovations, BECCUS will make an extraordinary contribution toward net-zero emissions while creating valuable pathways for industrial carbon management.

Economic models for deployment and challenges of BECCUS

BECCUS offers an immediate dual benefit of energy production coupled with carbon sequestration. Economic models, in detail, explore the interdependencies of technology, resource availability, carbon pricing, and policy incentives that will shape the future of BECCUS [57]. Studies on the integration of BECCUS with polygeneration systems, such as co-electricity and methanol production, have demonstrated that cost optimization and efficiency gains can be enhanced. Babin et al. [13] pointed out that the integration of BECCUS with combined heat and power systems can offset energy penalties, thereby improving its economic viability. Pyrolysis-based BECCUS systems can provide cost parity with fossil-based systems only at carbon prices above \$51–\$212 per ton of CO_2, depending on system configurations. In addition, methane sales and government incentives can further augment economic feasibility [204]. Technological innovation is needed to improve the methods of capturing, purification, and utilization of biogenic CO_2 in a

Table 4 Overview of carbon management start-ups and technologies by category

Category	Subcategories	Examples of start-ups/companies
Carbon Capture, Utilization, and Storage (CCUS)	BECCS	Drax, Beks Stockholm
	Concrete	Solidia, CarbonCure, CarbiCrete
	CO_2 chemicals	Econic, Covalent, CleanO2
	CO_2-based fuels	RedoxNRG, Twelve, Lanzatech
	CO_2 enhanced oil recovery	Denbury
	storage	Vault 44.01, AGR, Vaulted
	Capture technology	Entropy, Carbon Clean, Svante, CarbonCapture
Reduction services	Carbon markets/credits	C-ZR, Carbon Trade Exchange, Patch, Puro.Earth
	Monitoring/analysis	Genvision, Climeworks, MyCarbon, Satelytics
Carbon removal	Biochar	CO2Co, PyroCCS, PYREG
	Microalgae	AlgiCell, Carbonwave, Algenol
	Oceans	Captura, Ebb Carbon
	Mineralization	Cella, Blue Planet, CarbonBuilt
	Land management/soil	Indigo, Yara Soya, Regen Network
	Direct air capture	Climeworks, Carbon Engineering, Global Thermostat
	Enhanced weathering	Undo, Sequest
	Forestry/Biomass	Airfix, Climate Partner
Support services	Carbon management platforms	Cbamboo, Climate Partner, The Climate Choice

Source: https://climateinsider.com/2024/06/13/carbon-management-market-map/

cost-effective manner in various sectors. Agricultural and forestry residues should be used to avoid existing land use conflicts [13]. Carbon leakage penalties and ladder-type pricing mechanisms within the European Union have demonstrated an incentivizing effect on BECCUS adoption. BECCUS systems that produce useful by-products, such as biochar or synthetic fuels, can balance out costs and increase profitability. Woolf et al. [204] reported that biochar systems are cheaper to deploy due to lower carbon prices and enhance soil fertility benefits. Similarly, Werner et al. [200] proposed Pyrogenic Carbon Capture and Storage as a sustainable and land-neutral alternative capable of capturing 0.44–2.62 Gt of CO_2 annually while mitigating food production impacts. Furthermore, a circular economy model that includes biogenic CO_2 as a valuable resource needs to be developed. Setting targets for the use of biogenic CO_2 and incentivizing it through pricing mechanisms or mandatory disclosure of origin would encourage its adoption more broadly across industries, particularly for renewable fuels and industrial processes. Moreover, economic and environmental metrics need to be optimized for large-scale deployments, as pointed out by Geissler et al. [60]. Although BECCUS is a technology with enormous potential to contribute toward achieving global carbon reduction targets, success depends on cost competitiveness as well as effective coordination of policies and societal acceptance. Continued innovation alongside robust policy frameworks and international cooperation will be necessary to tap the full potential of BECCUS's technology. Thus, research into BECCUS should focus on improving market mechanisms, advancing technology for carbon capture and utilization, and enhancing cross-sector integration. The use of biogenic CO_2 will drive the development of climate mitigation strategies and promote an accelerated transition to a circular economy.

Challenges and solutions for BECCUS implementation

A key approach for addressing climate change is BECCUS, which combines the generation of bioenergy with CO_2 capture, utilization, and storage. Despite its potential, widespread implementation is hampered by a number of technological and financial factors. The effectiveness and dependability of CO_2 capture systems, their integration with other technologies, and the research and development uncertainties arising from the early stages of the majority of the technologies are the major areas of concern. The major challenges encountered by the BECCUS system are mentioned below:

Restricted supply of biomass

The main challenge is the restricted supply of sustainable biomass, brought on by competition with food production, biodiversity loss, and changes in land use. However, prioritizing non-food biomass sources such as forestry waste, algae, and agricultural leftovers is essential to increase biomass availability. Additionally, policies for sustainable land use and residue management need to be developed, and integrated systems like agroforestry and intercropping must be encouraged.

High transportation cost

Transportation of captured CO_2 and biomass to the treatment site is expensive. However, high costs associated with the transportation can be decreased by creating a decentralized system close to the biomass source, increasing investment in logistics optimization, and using low-carbon transportation fuel.

High operating and maintenance expenses

The BECCUS system encounters significant obstacles in the form of constant operating and maintenance expenses, which go beyond the initial investment. The BECCUS plant needs ongoing financial support for equipment maintenance, electricity for operations, and biomass purchase. BECCUS plant maintenance expenses account for 10–15% of the total annual capital cost, covering the cost of regular maintenance, replacement parts, and technology advancements [179]. Research into increasing energy efficiency, the use of cutting-edge materials for carbon capture, and integration of the BECCUS system with sustainable and renewable energy can undoubtedly increase revenue streams.

Market competitiveness

Lack of market competitiveness is a major obstacle to BECCUS technology development. Both traditional and renewable energy sources compete with BECCUS. The increased expenses linked to BECCUS exacerbate this competition and reduce the interest of investors and customers in BECCUS technology. The decision by investors and stakeholders is also complicated by the uncertainties surrounding BECCUS technologies. The deployment of BECCUS technology is also hampered by the high capital expenditures involved in biomass processing and storage infrastructure.

Lack of storage sites

The persistent storage of carbon is impeded by the scarcity of suitable geological sites. Thus, it is imperative to use alternate techniques for storage, map storage locations, and also collaborate with other organizations that support cross-border CO_2 storage to tackle the problems associated with storage sites. Additionally, serious concerns related to storage safety, land use change, and environmental impacts are affecting the adoption of BECCUS technology. Hence, problem-specific awareness campaigns that highlight the role of BECCUS in carbon reduction and climate change mitigation, involve local communities in planning, execution, and decision-making, as well as open deliberation regarding environmental and safety precautions can certainly assist in addressing the challenges impeding BECCUS adoption.

Measurement, transparency and regulatory issues

Currently, it is difficult to precisely quantify the carbon captured, used, and ultimately stored in the BECCUS system. Thus, there is a need to develop standardized procedures and methods for precise measurement and apply contemporary technologies such as blockchain and satellite-based monitoring for enhanced transparency and third-party monitoring, evaluation, and certification of BECCUS projects. Furthermore, insufficient and irregular carbon pricing, enigmatic regulatory measures, and absence of supportive policies are further restricting the BECCUS economic viability, adoption, and implementation. Thus, it is important for the global community to support BECCUS technology through strong but encouraging regulations. Additionally, homogenous carbon pricing systems must be implemented to enhance market competitiveness. Simultaneously, cross-border collaboration for carbon management must be encouraged for effective carbon capture, utilization, and eventual storage.

Low technology readiness level (TRL)

The technology involved in the BECCUS deployment has limited commercial application owing to several immature technologies. In order to increase TRL, it is important to improve cooperation between different stakeholders including the government, industry, and academia. Moreover, allocating sufficient financial resources to scale up new technologies can improve TRL and play a critical role in the adoption and deployment of BECCUS [167]. As evidenced by their low TRL, many of the technologies used in BECCS are still in their infancy stage. Technologies such as innovative biomass conversion and CO_2 utilization pathways necessary for BECCUS deployment and adoption are still in their initial stage of development. Thus, it necessitates substantial research and demonstration efforts to reach an advanced stage of development [57].

Lack of policy support

Policy framework is an important pillar in the deployment of BECCUS, as it directly affects the economic feasibility of the system. At present, there is a scarcity of financial resources at both the national and global levels that are necessary to ensure the commercial implementation of BECCUS. Thus, subsidies, tax breaks, incentives, and ultimately government support can help overcome obstacles encountered in the implementation of BECCUS. Additionally, promoting public–private partnerships to share financial risks and innovations in scalable and modular technologies can reduce the costs of BECCUS technology.

Policy recommendations

BECCUS is an important enabler of net-negative emission strategies and has the potential to adequately offset climate change. Some of the key findings and actionable recommendations that emerge from this review are outlined below.

Technological feasibility

Carbon capture methods currently employed, such as post-combustion and direct air capture, have dominated the landscape but require further optimization for large-scale deployment [57]. New developments in CHP systems and microalgae-based CCU are opening new avenues for scalable solutions [140, 141]. However, the roadmap to improve the technological feasibility of BECCUS must prioritize pilot project demonstrations integrating carbon capture and storage, policies on financial incentives prioritizing carbon removal instead of plant capacity, a transparent global monitoring framework for BECCUS evaluation along with third-party monitoring of the system. Establishing stringent and harmonized regulations for site selection at a global level must be developed to ensure safe BECCUS system deployment. Furthermore, the BECCUS technologies enable the production of several products while reducing the carbon footprint of different energy industries. Replacing fossil fuel with biomass (1 ton) in the case of the cement industry resulted in mitigation of CO_2 (0.94 tons) [44]. Similarly, replacement of coal with biomass in boiler can reduce electricity generation costs and CO_2 emission [132]. Additionally, a system utilizing biomass, when fitted with the CCS technique, can lead to net-negative emissions as long as biomass is produced sustainably.

Economic and market opportunities

Carbon captured can generate revenue ranging from $36 to $235 per ton, allowing it to be used for biofuels, beverages, and enhanced oil recovery [57]. However, it still lacks optimal carbon pricing and financial incentives. The countries should implement policies such as carbon taxation, tradable credits, and subsidies to attract investors and large-scale BECCUS deployment. The policy must be designed in such a manner that it reduces the risk associated with the BECCUS system, derisks investors, and develops a durable supply and value chain to unlock the economic and market competitiveness. The time-bound incentives to bridge current economic gaps hampering BECCUS deployment must be kept in place until the technology improves its readiness, scale, and competence. Further, the procurement of products derived from the BECCUS system requires continuous demand followed by public–private investment, and international cooperation on carbon credits can expand the market base and provide a necessary boost to improve the economic feasibility of BECCUS deployment.

Carbon tax has been implemented by several countries; however, it must be implemented globally in a stringent manner. It can provide the necessary stimulus to the industries to implement CCS. The global carbon tax also varies with the country, and approximately 54 countries have implemented it; yet, several countries have not taken the steps for its implementation [57]. Thus, the BECCUS system, considered to play a critical role in achieving a carbon-neutral society, must be implemented globally with a common framework of implementation, site selection, carbon tax, carbon credit, and biomanufacturing. It is also suggested that institutional, sectoral, and global collaboration must be promoted to address the gaps hampering the success of the BECCUS technique.

Policy and regulatory framework

This process is integral because policy frameworks and regulations are key drivers of BECCUS technology adoption [99]. Expansion of regulations regarding biogenic carbon emissions and provision of financial incentives for carbon-negative technologies are also necessary for BECCUS. Countries like the UK provide significant financial support to the BECCUS project, which has increased their deployment for carbon mitigation. Replicating such strategies in other countries, especially India, can assist in reducing carbon emissions and attaining the carbon-neutral goal by 2070. Furthermore, due to the low TRL of several technologies associated with BECCUS deployment, their scalability and feasibility are unclear; therefore, BECCUS-specific research and development grants must be provided to improve their TRL levels [57]. Countries should clearly permit strategies for carbon capture, transport, and storage by setting rules for environmental impact assessment as well as site selection for BECCUS systems. It is also essential to clearly fix the responsibility for stored carbon after project completion. Integrating such strategies into actionable plans for climate change mitigation is crucial to ensure that BECCUS systems complement the carbon reduction strategies instead of competing with them. Incorporating and adopting such strategies in the policy framework will not only reduce the social, financial, and environmental risks, but also improve BECCUS deployment at a commercial scale.

Furthermore, developing a biomass atlas of different crops with seasonal production and availability at the regional level at regular intervals can demonstrate the feasibility of the projects and even improve the confidence of the investors in the BECCUS sector. The integrated studies determining the carbon footprint of the biomass supply chain, biomass processing to valuable products as well as carbon capture, transport, utilization, and storage must be carried out to identify the processes and factors responsible for enhancing the economic feasibility and sustainability of the system [52]. In the USA, the CCS sector is much advanced in terms of financial support, construction, and engineering techniques compared to other countries while regions like Columbia and Scandinavia are excellent in thermochemical conversion of the biomass [137]. Thus, research collaboration among countries and cross-sector collaboration in the CCUS field must be prioritized. Moreover, international policies for the success of BECCUS are necessary as countries plentiful in biomass resources may not have abundant sites for the storage of carbon. For example, the UK lacks adequate sustainable biomass resources, while Sweden lacks suitable geological sites for carbon storage, and vice versa [17, 18]. Investors and industries must identify regions enriched with biomass that can sustain the long-term demand of the BECCUS system as well as the utilization and storage system for carbon utilization for biomanufacturing. Policies should be designed to provide long-term support for BECCUS deployment to attract investment. Therefore, policies should address these issues and promote collaboration among stakeholders to accelerate the implementation of BECCUS systems for carbon mitigation.

Environmental and social impacts

Public perception issues, along with challenges related to land use and water availability, are major constraints for BECCUS. Public acceptance of the technology for carbon capture and storage is very crucial. Public opposition has affected the deployment of BECCUS plants, as seen in several European cases. This technology also suffers due to criticism because it is perceived as prolonging the use of fossil fuels and preventing action responsible for carbon mitigation [135]. Therefore, an awareness program regarding the importance of utilizing emitted carbon as a substrate for biomanufacturing through techniques like gas fermentation must be promoted and supported with scientific research and evidence. A special research project on carbon waste carbon utilization to product creation through biological pathways to enhance the production of ethanol, butanol, polyhydroxybutyrate (PHB), polyhydroxyalkanoate (PHA), long-chain fatty acid, 1,3-BDO, and 2,3-BDO, along with subsidies on using such products, could help to change public perception. Furthermore, using residues and algae as feedstock sources could reduce environmental impacts [169]. Integrating captured carbon with microalgae will improve the biomass yield, reduce carbon emissions, and promote the process of biomanufacturing, biorefinery, and the circular bioeconomy.

Conclusion

Climate change poses serious environmental, economic, and social issues due to increased emission of greenhouse gases, especially CO_2. This has created an urgent need for carbon-negative, ecologically friendly, chemical and material biomanufacturing to utilize CO_2 as feedstock. Gas fermentation processes are being used to utilize CO_2 to scale up production of novel compounds that were previously generated commercially through petrochemical means. However, the efficiency of carbon assimilation pathways is being improved by ongoing developments in metabolic engineering, which will enhance the production of diverse bioproducts, improve carbon sequestration, and support efforts to slow down climate change. Synthetic biology has expanded the product base to include both native as well as non-native metabolites such as ethanol, acetate, polyhydroxybutyrate, and polyhydroxyalkanoate, long-chain fatty acid, 1,3-propanediol, 2,3-BDO, and 1,4-butanediol. Gas fermentation retrofitted onto CO_2 emitting plants can be one of the desirable platforms for carbon capture and utilization, thus promoting a circular economy. Additionally, setting targets for biogenic CO_2 utilization and incentivizing it through pricing mechanisms would promote its adoption more broadly across industries, particularly for renewable fuels and industrial processes. Moreover, there is a need to develop standardized procedures and methods for precise measurement along with contemporary technologies to enhance transparency and third-party monitoring, evaluation, and certification of BECCUS projects. BECCUS can be a transformative approach to combat climate change with a substantial prospect for global greenhouse gas abatement and becoming a cornerstone of global climate strategy through a holistic approach. However, the realization of this potential requires positive inputs in research, policy, and partnerships. Future studies should focus on market-based solutions, technological advancement, and cross-sectoral integration to overcome existing hurdles. Policymakers must enforce robust frameworks that provide financial and regulatory support while ensuring environmental sustainability. BECCUS could serve as a game changer in mitigating global warming, provided that technical, economic, and social challenges are addressed. Investments in pilot projects, stakeholder engagement, and international collaboration are vital to scaling BECCUS and achieving the goals of the Paris Agreement.

Acknowledgements
We do not have any acknowledgment to make.

Author contributions
DVS and SN: conceptualization, writing—original draft, reviewing and editing; CHL and BI: writing—original draft, reviewing and editing; RPS and GP: reviewing and editing; GK and VK: conceptualization, writing—original draft, reviewing and editing, and project management.

Data availability
No datasets were generated or analyzed during the current study.

Declarations

Competing Interests
The authors declare no competing interests.

Author details
[1]Biochemical Conversion Division, Sardar Swaran Singh National Institute of Bioenergy, Punjab, India. [2]Feng Chia University, No. 100, Wenhwa Rd. Seatwen Dist, Taichung City 407102, Taiwan. [3]Faculty of Chemistry, Nicolaus Copernicus University in Toruń, Gagarina 7, 87-100 Toruń, Poland. [4]GPCHEM. Laboratory of Biogas Research and Analysis and Technology Incubator, GPCHEM, Ul. Legionów 40a/3, 87-100 Toruń, Poland. [5]Institute of Chemistry, Bioscience, and Environmental Engineering, Faculty of Science and Technology, University of Stavanger, Stavanger, Norway 8600. [6]Magan Centre for Applied Mycology, Faculty of Engineering and Applied Sciences, Cranfield University, Cranfield MK43 0AL, UK. [7]Department of Engineering Technology, College of Technology, University of Houston-Sugarland, Houston TX 77479, United States of America.

Received: 17 July 2025 Accepted: 27 November 2025

References

1. Adam Baylin-Stern, Former Energy Analyst. . Is carbon capture too expensive?—Analysis—IEA. IEA. 2024. https://www.iea.org/commentaries/is-carbon-capture-too-expensive
2. Adedeji O, Reuben O, Olatoye O. Global climate change. J Geoscience Environ Prot. 2014;2(2):114–22.
3. Agrawal D, Awani K, Nabavi SA, Balan V, Jin M, Aminabhavi TM, et al. Carbon emissions and decarbonisation: the role and relevance of fermentation industry in chemical sector. Chem Eng J. 2023. https://doi.org/10.1016/j.cej.2023.146308.
4. Agrawal D, Awani K, Nabavi SA, Balan V, Jin M, Aminabhavi TM, et al. Carbon emissions and decarbonisation: the role and relevance of fermentation industry in chemical sector. Chem Eng J. 2023;475:146308.
5. Alizadeh SM, Khalili Y, Ahmadi M. Comprehensive review of carbon capture and storage integration in hydrogen production: opportunities, challenges, and future perspectives. Energies. 2024;17(21):5330.
6. Alkan H, Burachok O, Kowollik P. Geologic carbon storage: key components. In: Surface Process, Transportation, and Storage. Gulf Professional Publishing; 2023. p. 325–422.
7. Almena A, Thornley P, Chong K, Röder M. Carbon dioxide removal potential from decentralised bioenergy with carbon capture and storage (BECCS) and the relevance of operational choices. Biomass Bioenergy. 2022;159:106406.
8. Almena A, Thornley P, Chong K, Röder M. Carbon dioxide removal potential from decentralized bioenergy with carbon capture and

storage (BECCUS) and the relevance of operational choices. Biomass Bioenergy. 2022;159:106406.

9. Alsarhan LM, Alayyar AS, Alqahtani NB, Khdary NH. Circular carbon economy (CCE): a way to invest CO_2 and protect the environment, a review. Sustainability. 2021;13(21):11625.
10. Amulya K, Kopperi H, Mohan SV. Tunable production of succinic acid at elevated pressures of CO_2 in a high-pressure gas fermentation reactor. Bioresour Technol. 2020. https://doi.org/10.1016/j.biortech.2020.123327.
11. ArcelorMittal. Towards a Circular Economy Breakthrough: Our Partnership with LanzaTech. 2018. http:// corporate.arcelormittal.com/news-and-media/our-stories/ourpartnership-with-lanzatech. Accessed 10 May 2018.
12. Asadullah M. Biomass gasification gas cleaning for downstream applications: a comparative critical review. Renew Sustain Energy Rev. 2014;40:118–32.
13. Babin A, Vaneeckhaute C, Iliuta MC. Potential and challenges of bioenergy with carbon capture and storage as a carbon-negative energy source: a review. Biomass Bioenergy. 2021;146:105968.
14. Baena-Moreno FM, Leventaki E, Riddell A, Wojtasz-Mucha J, Bernin D. Effluents and residues from industrial sites for carbon dioxide capture: a review. Environ Chem Lett. 2023;21(1):319–37.
15. Bains P, Psarras P, Wilcox J. CO_2 capture from the industry sector. Prog Energy Combust Sci. 2017;63:146–72.
16. Bar-Even A, Noor E, Milo R. A survey of carbon fixation pathways through a quantitative lens. J Exp Bot. 2012;63(6):2325–42.
17. Bellamy R, Fridahl M, Lezaun J, Palmer J, Rodriguez E, Lefvert A, et al. Incentivising bioenergy with carbon capture and storage (BECCUS) responsibly: comparing stakeholder policy preferences in the United Kingdom and Sweden. Environ Sci Policy. 2021;116:47–55.
18. Bellamy R, Fridahl M, Lezaun J, Palmer J, Rodriguez E, Lefvert A, et al. Incentivising bioenergy with carbon capture and storage (BECCS) responsibly: comparing stakeholder policy preferences in the United Kingdom and Sweden. Environ Sci Policy. 2021;116:47–55.
19. Berg IA, Kockelkorn D, Buckel W, Fuchs G. A 3-hydroxypropionate/4-hydroxybutyrate autotrophic carbon dioxide assimilation pathway in Archaea. Science. 2007;318(5857):1782–6.
20. Biofuels Digest. LanzaTech, INVISTA Find Direct Pathway to Bio-based Butadiene. 2015. http:// www.biofuelsdigest.com/bdigest/2015/12/01/lanzatechinvista-find-direct-pathway-to-bio-based-butadiene/. Accessed 13 April 2018.
21. Biofuels Digest. Coskata's Technology Re-emerges as Synata Bio. 2016. http://www.biofuelsdigest.com/ bdigest/2016/01/24/coskatas-technology-re-emerges-assynata-bio/. Accessed 13 April 2018.
22. Biofuels Digest. Commercial Time: Aemetis Embarks on $158 Million Cellulosic Ethanol Project in California. 2018. http://www.biofuelsdigest.com/bdigest/2018/03/08/ commercial-time-aemetis-embarks-on-158-million-cellulosicethanol-project-in-california/. Accessed 10 May 2018.
23. Bommareddy RR, Wang Y, Pearcy N, Hayes M, Lester E, Minton NP, et al. A sustainable chemicals manufacturing paradigm using CO_2 and renewable H2. iScience. 2020. https://doi.org/10.1016/j.isci.2020.101218.
24. Bruton, F. Commercial CCU Plant using Lanza Tech Technology receives RSB Advance products certification. 2021. https://renewable-carbon.eu/news/commercial-ccu-plant-using-lanzatech-technology-receives-rsb-advanced-products-certification/. Accessed 1Sep 2023.
25. Bui M, Adjiman CS, Bardow A, Anthony EJ, Boston A, Brown S, Fennell PS, Fuss S, Galindo A, Hackett LA, Hallett JP. Carbon capture and storage (CCS): the way forward. Energy Environ Sci. 2018;1(5):1062–176.
26. Cabello A, Abad A, de las Obras Loscertales M, Domingos Y, Mendiara T. Techno-economic analysis of chemical looping processes with biomass resources for energy production and CO2 utilization. Comparison of CLC and CLOU technologies. Energy Convers Manage. 2024;310:118476.
27. Can M, Armstrong FA, Ragsdale SW. Structure, function, and mechanism of the nickel metalloenzymes, CO dehydrogenase, and acetyl-CoA synthase. Chem Rev. 2014;114(8):4149–74.
28. Can M., Gozgor G. Dynamic relationships among CO_2 emissions, energy consumption, economic growth, and economic complexity in France. Energy Consumption, Economic Growth, and Economic Complexity in France. 2016.
29. Cavaignac RS, Ferreira NL, Guardani R. Techno-economic and environmental process evaluation of biogas upgrading via amine scrubbing. Renew Energy. 2021;171:868–80.
30. Chen HH, Xue LL, Liang MH, Jiang JG. Effects of triethylamine on the expression patterns of two G3PDHs and lipid accumulation in *Dunaliella tertiolecta*. Enzyme Microb Technol. 2019;127:17–21.
31. Chistoserdova L. Applications of methylotrophs: can single carbon be harnessed for biotechnology? Curr Opin Biotechnol. 2018;50:189–94.
32. Choi YY, Patel AK, Hong ME, Chang WS, Sim SJ. Microalgae bioenergy with carbon capture and storage (BECCS): an emerging sustainable bioprocess for reduced CO2 emission and biofuel production. Bioresour Technol Rep. 2019;7:100270.
33. Claassens NJ, Sánchez-Andrea I, Sousa DZ, Bar-Even A. Towards sustainable feedstocks: a guide to electron donors for microbial carbon fixation. Curr Opin Biotechnol. 2018;50:195–205.
34. Clarke L.E, Jiang K, Akimoto K, Babiker M, Blanford G.J, Fisher-Vanden K, Hourcade J.C, Krey V, Kriegler E, Loschel A. and McCollum D. Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (No. PNNL-SA-102686). 2015.
35. Congressional Research Service. The Tax Credit for Carbon Sequestration. 2021.
36. Coninck H, Flach T, Curnow P, et al. The acceptability of CO_2 capture and storage (CCS) in Europe: an assessment of the key determining factors. Int J Greenhouse Gas Control. 2008;3(3):344–56.
37. Correa SS, Schultz J, Lauersen KJ, Rosado AS. Natural carbon fixation and advances in synthetic engineering for redesigning and creating new fixation pathways. J Adv Res. 2023;47:75–92.
38. Creutzig F, Erb KH, Haberl H, Hof C, Hunsberger C, Roe S. Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments. Global Change Biology Bioenergy. 2021;13(4):510–5.
39. D. Salazar. This company ferments industrial carbon emissions into useful products. 2023. https://www.fastcompany.com/90850275/lanzatech-industrial-carbon-emissions-products. Accessed 1 Sep 2023.
40. Damen K, van Troost M, Faaij A, Turkenburg W. A comparison of electricity and hydrogen production systems with CO_2 capture and storage—Part B: chain analysis of promising CCS options. Prog Energy Combust Sci. 2007;33(6):580–609.
41. Dehjalali FR, Avami A. A design procedure for the assessment of carbon capturing and utilization of flue gas from power plant using experimental data. Chem Eng Res Des. 2018;131:393–405.
42. Deng L, Hägg MB. Techno-economic evaluation of biogas upgrading process using CO2 facilitated transport membrane. Int J Greenhouse Gas Control. 2010;4(4):638–46.
43. Detz RJ, van der Zwaan B. Transitioning towards negative CO_2 emissions. Energy Policy. 2019;133:110938.
44. Dit, M. Palm kernel shell (PKS) is more than biomass for alternative fuel after 2005. In: Proceedings of chemistry and technology conference. 2007.
45. DOE. Carbon Negative Shot initiative. 2024.
46. Drake H.L, Küsel K and Matthies C. Acetogenic prokaryote. 2006.
47. EC (European Commission). Green paper: a European strategy for sustainable, competitive and secure energy. COM (2006) 105 Final. Commission of the European Communities. 2006.
48. EFI Foundation. Surveying the BECCS Landscape [WWW Document]. EFI Foundation. 2022. https://efifoundation.org/reports/surveying-the-beccs-landscape/.
49. EFI Foundation, E.D. Taking Root: A Policy Blueprint for Responsible BECCS Development in the United States [WWW Document]. EFI foundation. 2023. https://efifoundation.org/topics/carbon-management/taking-root-a-policy-blueprint-for-responsible-beccs-development-in-the-united-states/.
50. Eigbe PA, Ajayi OO, Olakoyejo OT, Fadipe OL, Efe S, Adelaja AO. A general review of CO_2 sequestration in underground geological formations and assessment of depleted hydrocarbon reservoirs in the Niger Delta. Appl Energy. 2023;350:121723.
51. El-Kady AH, Amin MT, Khan F, El-Halwagi MM. Analysis of CO2 pipeline regulations from a safety perspective for offshore carbon capture,

utilization, and storage (CCUS). J Clean Prod. 2024. https://doi.org/10.1016/j.jclepro.2024.140734.
52. Emenike O, Michailos S, Finney KN, Hughes KJ, Ingham D, Pourkashanian M. Initial techno-economic screening of BECCS technologies in power generation for a range of biomass feedstock. Sustain Energy Technol Assess. 2020;40:100743.
53. Erbay, Y., Joos, M., and Durusut, E. Global future role of power CCUS technologies. SSRN Electronic Journal. 2020
54. ETP [European Technology Platform for Zero Emission Fossil Fuel Power Plants]. The Costs of CO2 Capture - Post-Demonstration CCS in the EU: 81. 2011. http://web.mit.edu/sequestration/costing/pdfs/2011_ZEP_CO2_Capture_Report.pdf
55. Fast AG, Schmidt ED, Jones SW, Tracy BP. Acetogenic mixotrophy: novel options for yield improvement in biofuels and biochemicals production. Curr Opin Biotechnol. 2015;33:60–72.
56. Fridahl M, Bellamy R, Hansson A, Haikola S. Mapping multi-level policy incentives for bioenergy with carbon capture and storage in Sweden. Frontiers in climate. 2020;2:604787.
57. Ganeshan P, Vigneswaran VS, Gowd SC, Mishra R, Singh E, Kumar A, et al. Bioenergy with carbon capture, storage and utilization: potential technologies to mitigate climate change. Biomass Bioenergy. 2023;177:106941.
58. Gardiner SM. A perfect moral storm: climate change, intergenerational ethics and the problem of moral corruption. Environ Values. 2006;15(3):397–413.
59. Gates, B. How to avoid a climate disaster: the solutions we have and the breakthroughs we need. Vintage. 2021.
60. Geissler B, Werner C, Stecher K, Hildebrandt J. Revisiting BECCUS: assessing the sustainability and economic viability of bioenergy with carbon capture and storage. Renew Sustain Energy Rev. 2022;156:111976.
61. Genomatica. Leading a transition to more sustainable products. 2019. https://www.brontidebg.com/wp-content/uploads/2020/10/Genomatica-Sustainability-and-Social-Responsibility-2019.pdf. Accessed 1 Sep 2023.
62. Global CCS Institute (Global Carbon Capture and Storage Institute). The global status of CCS: 2019. Melbourne, Australia (2019).
63. Goel M, Pal R. and Sharma A. An assessment of co 2 reduction potential from carbon sequestration versus renewable energy targets in India. Climate Change and Green Chemistry of CO2 Sequestration. 2021
64. Goeppert A, Czaun M, Jones JP, Prakash GS, Olah GA. Recycling of carbon dioxide to methanol and derived products–closing the loop. Chem Soc Rev. 2014;43(23):7995–8048.
65. Gumte, K., Akram, V., and Rath, B. N. Handling bioenergy sector uncertainties with carbon credit revenue in developing nation's economy: an Indian case study. Environment, Development and Sustainability. 2024.
66. Gunnarsson IB, Alvarado-Morales M, Angelidaki I. Utilization of CO2 fixating bacterium Actinobacillus succinogenes 130Z for simultaneous biogas upgrading and biosuccinic acid production. Environ Sci Technol. 2014;48(20):12464–8.
67. Guo J, Zhong M, Chen S. Analysis and simulation of BECCS vertical integration model in China based on evolutionary game and system dynamics. Energy. 2022;252:124000.
68. Guo J, Zhong M, Chen S. Analysis and simulation of BECCUS vertical integration model in China based on evolutionary game and system dynamics. Energy. 2022;252:124000.
69. Handler RM, Shonnard DR, Griffing EM, Lai A, Palou-Rivera I. Life cycle assessments of ethanol production via gas fermentation: anticipated greenhouse gas emissions for cellulosic and waste gas feedstocks. Ind Eng Chem Res. 2016;55(12):3253–61.
70. Hansson A, Fridahl M, Haikola S, Yanda P, Pauline N, Mabhuye E. Preconditions for bioenergy with carbon capture and storage (BECCS) in sub-Saharan Africa: the case of Tanzania. Environ Dev Sustain. 2020;22:6851–75.
71. Harrabin R. Indian firm makes carbon capture breakthrough. The Guardian. https://www. theguardian. com/environment/2017/jan/03/indian-firm-carbon-capture-breakthrough-carbonclean. 2017.
72. Haszeldine S., Cavanagh A., Scott V., Sohi S., Masek O. and Renforth P. Greenhouse gas removal technologies: Approaches and implementation pathways in Scotland. University of Edinburgh & Heriot-Watt University. 2019
73. Hawkins AS, Han Y, Lian H, Loder AJ, Menon AL, Iwuchukwu IJ, et al. Extremely thermophilic routes to microbial electrofuels. ACS Catal. 2011;1(9):1043–50.
74. Hayat MA, Alhadhrami K, Elshurafa AM. Which bioenergy with carbon capture and storage (BECCS) pathways can provide net-negative emissions? Int J Greenhouse Gas Control. 2024;135:104164.
75. He Y, Kennes C, Lens PN. Enhanced solventogenesis in syngas bioconversion: role of process parameters and thermodynamics. Chemosphere. 2022;299:134425.
76. Heijstra BD, Leang C, Juminaga A. Gas fermentation: cellular engineering possibilities and scale up. Microb Cell Fact. 2017;16:1–11.
77. Hepburn C, Adlen E, Beddington J. The technological and economic prospects for CO_2 utilization and removal. Nature. 2019;575:87–97.
78. Hepburn C, Adlen E, Beddington J, Carter EA, Fuss S, Mac Dowell N, et al. The technological and economic prospects for CO2 utilization and removal. Nature. 2019;575(7781):87–97.
79. Honegger M, Poralla M, Michaelowa A, Ahonen HM. Who is paying for carbon dioxide removal? Designing policy instruments for mobilizing negative emissions technologies. Fronti Clim. 2021;3:672996.
80. Hu P, Chakraborty S, Kumar A, Woolston B, Liu H, Emerson D, et al. Integrated bioprocess for conversion of gaseous substrates to liquids. Proc Natl Acad Sci U S A. 2016;113(14):3773–8.
81. Hügler M, Fuchs G. Assaying for the 3-hydroxypropionate cycle of carbon fixation. Methods Enzymol. 2005;397:212–21.
82. Hunter T.S., Pettit J. and Taylor M. Implications of 'Net-Zero Emissions by 2050'for the Hydrocarbon Industry: A Case Study of Selected Mature Petroleum Jurisdictions. 2022.
83. IEA. CO2 Capture in the Cement Industry. 2008.
84. IEA. Carbon Removal through BECCS and DACS in the Sustainable Development Scenario and IPCC SR1.5 Scenarios, 2030–2100. Paris, France, 2020. Updated 23 September 2020. 2020. https://www.iea.org/data-and-statistics/charts/carbon-removal-through-beccs-and-dacs-in-the-sustainable-development-scenario-and-ipcc-sr1-5-scenarios-2030-2100
85. Invista. INVISTA and LanzaTech Make Breakthrough for Bio-derived Butadiene Production. 2015. http://www.invista.com/en/news/ pr-invista-and-lanzatech-make-breakthrough-for-bio-derived-butadiene production.html. Accessed June 2016.
86. IPCC. In: McCarthy, J.J., et al. (Eds.), Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. 2001.
87. IPCC. Summary for Policymakers. In Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty; Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., et al., Eds.; in press; Intergovernmental Panel on Climate Change: Geneva, Switzerland. 2018.
88. Jabraeelzadeh A, Gharehghani A, Saray JA, Andwari AM, Borhani TN. Techno-economic analysis of biogas upgrading through amine scrubbing: a comparative study of different single amines. Fuel. 2025;381:133662.
89. Jenkins S, Mitchell-Larson E, Ives MC, Haszeldine S, Allen M. Upstream decarbonization through a carbon takeback obligation: an affordable backstop climate policy. Joule. 2021;5(11):2777–96.
90. Jiang K, Ashworth P, Zhang S, Liang X, Sun Y, Angus D. China's carbon capture, utilization and storage (CCUS) policy: a critical review. Renew Sustain Energy Rev. 2020;1(119):109601.
91. Johnstone R. From carrot to stick–the impact of a changing landscape of CCS policy and funding in Australia since 1999. Australian Energy Prod J. 2024;64(2):S139–42.
92. Kalkuhl M, Edenhofer O, Lessmann K. The role of carbon capture and sequestration policies for climate change mitigation. Environ Resource Econ. 2015;60:55–80.
93. Karishma S, Kamalesh R, Saravanan A, Deivayanai VC, Yaashikaa PR, Vickram AS. A review on recent advancements in biochemical fixation and transformation of CO2 into constructive products. Biochem Eng J. 2024. https://doi.org/10.1016/j.bej.2024.109366.

94. Kemper J. Biomass and carbon dioxide capture and storage: a review. Int J Greenhouse Gas Control. 2015;40:401–30.
95. Khosravi-Darani K, Mokhtari ZB, Amai T, Tanaka K. Microbial production of poly (hydroxybutyrate) from C 1 carbon sources. Appl Microbiol Biotechnol. 2013;97:1407–24.
96. Koenig, J., Trabucchi, C., McKaskle, R. and Whittaker, S. CCS Business Development Case Study for CarbonSAFE Illinois-Macon County (Task 4.1) (No. DOE-FE0029381–4). Univ. of Illinois at Urbana-Champaign, IL (United States). 2020.
97. Koller M, Mukherjee A. A new wave of industrialization of PHA biopolyesters. Bioengineering. 2022;9(2):74.
98. Koukouzas N, Christopoulou M, Giannakopoulou PP, Rogkala A, Gianni E, Karkalis C, et al. Current CO2 capture and storage trends in Europe in a view of social knowledge and acceptance. A short review. Energies. 2022;15(15):5716.
99. Koytsoumpa EI, Magiri–Skouloudi D, Karellas S, Kakaras E. Bioenergy with carbon capture and utilization: a review on the potential deployment towards a European circular bioeconomy. Renew Sustain Energy Rev. 2021;152:111641.
100. Kraxner F., Fuss S., Krey V., Best D., Leduc S., Kindermann G., Yamagata Y., Schepaschenko D., Shvidenko A., Aoki K. and Yan J. The role of bioenergy with carbon capture and storage (BECCS) for climate policy. Handbook of Clean Energy Systems. 2015.
101. Kumar A, Sucharita P, Shrivastava JP. Contemporary researches and issues related to the Deccan volcanism. Proc Indian Natn Sci Acad. 2020;86(1):245–61.
102. Kumar M, Sundaram S, Gnansounou E, Christian Larroche C, Thakur IS. Carbon dioxide capture, storage and production of biofuel and biomaterials by bacteria: a review. Bioresour Technol. 2017. https://doi.org/10.1016/j.biortech.2017.09.050.
103. Kumar P, Park H, Yuk Y, Kim H, Jang J, Pagolu R, et al. Developed and emerging 1, 4-butanediol commercial production strategies: forecasting the current status and future possibility. Crit Rev Biotechnol. 2024;44(4):530–46.
104. Kumar S, Patel A. The role of carbon capture in biogas upgrading: a comprehensive economic review. Renew Sustain Energy Rev. 2020;51(5):395–409.
105. Kuuskraa VA, Godec ML, Dipietro P. CO_2 utilization from "next generation" CO_2 enhanced oil recovery technology. Energy Procedia. 2013;37:6854–66.
106. Kwakye, J. M., Ekechukwu, D. E., and Ogundipe, O. B. Reviewing the role of bioenergy with carbon capture and storage (BECCUS) in climate mitigation. Engineering Science & Technology Journal. 2024.
107. Kyle P., P. Luckow K. Calvin W. Emanuel M. Nathan and Y. Zhou. GCAM 3.0 Agriculture and Land Use : Data Sources and Methods." Agriculture (December): 58. 2011.
108. Lane J, Greig C, Garnett A. Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. Nat Clim Chang. 2021;11(11):925–36.
109. LanzaTech, LanzaTech and Global Bioenergies Announce New Collaboration Agreement. [Online]. (2016). Available: http://www.lanzatech.com/lanzatech-global-bioenergies-announce-new-collaboration-agreement/ [13 April 2018].
110. LanzaTech. From Trash to Tank: Upcycling of Landfill to Fuel Demonstrated in Japan. 2017. http://www. lanzatech.com/trash-tank-upcycling-landfill-fuel-demonstrated-japan/. Accessed 10 May 2018.
111. LanzaTech. Swayana Brings Carbon Recycling to South Africa. 2017. http://www.lanzatech.com/swayanabrings-carbon-recycling-south-africa/. Accessed 10 May 2018.
112. LanzaTech. IndianOil and LanzaTech Sign a Statement of Intent to Construct World's First Refinery Off Gas-to-Bioethanol Production Facility in India. 2018. http://www.lanzatech.com/indianoil-lanzatech-signstatement-intent-construct-worlds-first-refinery-gas-bioethanol-production-facility-india/. Accessed 10 May 2018.
113. Lee JY, Lee SE, Lee DW. Current status and future prospects of biological routes to bio-based products using raw materials, wastes, and residues as renewable resources. Crit Rev Environ Sci Technol. 2022;52(14):2453–509.
114. Leeson D, Mac Dowell N, Shah N, Petit C, Fennell PS. A techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. Int J Greenhouse Gas Control. 2017;61:71–84.
115. Leung DYC, Caramanna G, Maroto-Valer MM. An overview of current status of carbon dioxide capture and storage technologies. Renew Sustain Energy Rev. 2022;138:110490.
116. Leung DY, Caramanna G, Maroto-Valer MM. An overview of current status of carbon dioxide capture and storage technologies. Renew Sustain Energy Rev. 2014;39:426–43.
117. Li H, Opgenorth PH, Wernick DG, Rogers S, Wu TY, Higashide W, et al. Integrated electromicrobial conversion of CO_2 to higher alcohols. Science. 2012;335(6076):1596–1596.
118. Li J, Li Y, Cui Z, Liang Q, Qi Q. Enhancement of succinate yield by manipulating NADH/NAD+ ratio and ATP generation. Appl Microbiol Biotechnol. 2017;101(8):3153–61.
119. Li X, Zhang M, Luo J, Zhang S, Yang X, Igalavithana AD, et al. Efficient succinic acid production using a biochar-treated textile waste hydrolysate in an in situ fibrous bed bioreactor. Biochem Eng J. 2019;149:107249.
120. Liew F, Martin E, Tappel R, Heijstra B, Mihalcea C, Kopke M. Gas fermentation – a flexible platform for commercial scale production of low carbon fuels and chemicals from waste and renewable feedstocks. Front Microbiol. 2016;7:694.
121. Liew FE, Nogle R, Abdalla T, Rasor BJ, Canter C, Jensen RO, et al. Carbon-negative production of acetone and isopropanol by gas fermentation at industrial pilot scale. Nat Biotechnol. 2022;40(3):335–44.
122. Liew F.M., Köpke M. and Simpson S.D. Gas fermentation for commercial biofuels production. Liquid, Gaseous and Solid Biofuels-Conversion Techniques, pp.125–173. 2013.
123. Ljungdahl LG, Andreesen JR. Formate dehydrogenase, a selenium-tungsten enzyme from Clostridium thermoaceticum. Method Enzymol. 1978;53:360–72.
124. Locher, A. Carbon neutral fermentation. Elements, the innovation magazine by Evonik. 2022. https://elements.evonik.com/research-and-innovation/carbon-neutral-fermentation/. Accessed on 1 Sep 2023.
125. Lovell CR, Przybyla A, Ljungdahl LG. Primary structure of the thermostable formyltetrahydrofolate synthetase from *Clostridium thermoaceticum*. Biochemistry. 1990;29(24):5687–94.
126. Lu Y, Yu J. Comparison analysis on the energy efficiencies and biomass yields in microbial CO_2 fixation. Process Biochem. 2017;62:151–60.
127. Lv Z, Du H, Xu S, Deng T, Ruan J, Qin C. Techno-economic analysis on CO2 mitigation by integrated carbon capture and methanation. Appl Energy. 2024;355:122242.
128. Makepa DC, Chihobo CH. Sustainable pathways for biomass production and utilization in carbon capture and storage—a review. Biomass Convers Biorefin. 2024. https://doi.org/10.1007/s13399-024-06010-5.
129. Makepa DC, Chihobo CH. Sustainable pathways for biomass production and utilization in carbon capture and storage—a review. Biomass Convers Biorefin. 2025;15(8):11397–419.
130. Manzer, L.E. The role of startup companies in the conversion of biomass to renewable fuels and chemicals. Catalysis for the conversion of biomass and its derivatives. Max Planck Research Library for the history and development of knowledge, Proc, 2. 2013.
131. Mihalcea C, Burton F, Conrado R, Simpson S. R&D&I and Industry examples: LanzaTech's gas fermentation. In: CO2 and CO as Feedstock: Sustainable Carbon Sources for the Circular Economy. Cham: Springer International Publishing; 2024. p. 333–43.
132. Mo W, Du K, Sun Y, Guo M, Zhou C, You M, Xu J, Jiang L, Wang Y, Su S, Hu S. Technical-economic-environmental analysis of biomass direct and indirect co-firing in pulverized coal boiler in China. Journal of Cleaner Prod. 2023;426:139119.
133. Mondal M., Goswami S., Ghosh A., Oinam G., Tiwari O.N., Das P., Gayen K., Mandal M.K. and Halder G.N. Production of biodiesel from microalgae through biological carbon capture: a review. 3 Biotech, 7 1–21. 2017.
134. Müller, L.J., Bardow, A., Koß, H.J. and Sick, V. Harmonized life cycle assessment of technologies for carbon capture and utilization (No. RWTH-2022–08250). 2022.
135. Muratori M, Calvin K, Wise M, Kyle P, Edmonds J. Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). Environ Res Lett. 2016. https://doi.org/10.1088/1748-9326/11/9/095004.

136. Muthuraj R, Mekonnen T. Recent progress in carbon dioxide (CO_2) as feedstock for sustainable materials development: co-polymers and polymer blends. Polymer. 2018;145:348–73.
137. National Research Council, 2015. Climate intervention: carbon dioxide removal and reliable sequestration, Clim. Interv. Carbon Dioxide Remov. Reliab. Sequestration, 1–154, https://doi.org/10.17226/18805.
138. Nghiem NP, Hicks KB, Johnston DB. Integration of succinic acid and ethanol production with potential application in a corn or barley biorefinery. Appl Biochem Biotechnol. 2010;162:1915–28.
139. Nghiem NP, Kleff S, Schwegmann S. Succinic acid: technology development and commercialization. Fermentation. 2017;3(2):26.
140. Nguyen H, Harper RJ, Dell B. Examining local community understanding of mangrove carbon mitigation: a case study from Ca Mau province, Mekong River Delta, Vietnam. Mar Policy. 2023;148:105398.
141. Nguyen LN, Vu MT, Vu HP, Johir MAH, Labeeuw L, Ralph PJ, et al. Microalgae-based carbon capture and utilization: a critical review on current system developments and biomass utilization. Crit Rev Environ Sci Technol. 2023;53(2):216–38.
142. Nicolas C, Chen Y-HH, Morris J, Winchester N, Paltsev S. Bioenergy with carbon capture and storage: key issues and major challenges. Environ Res Lett. 2017;12(5):055001.
143. Pacheco R, Huston K. Life cycle assessment (LCA) of naturally-sourced and petroleum-based glycols commonly used in personal care products. SOFW J. 2018;144:12–5.
144. Pacific Northwest National Lab (PNNL), Richland, WA (United States), Karlsson S, Eriksson A, Normann F, Johnsson F. Large-scale implementation of bioenergy with carbon capture and storage in the Swedish pulp and paper industry involving biomass supply at the regional level. Front Energy Res. 2021;9:738791.
145. Palmer J, Carton W. Carbon removal as carbon revival? Bioenergy, negative emissions, and the politics of alternative energy futures. Front Clim. 2021;3:678031.
146. Pelissari M.R., San Martín Cañas S.J., Ciotta M.R. and Tassinari C.C.G. BECCUS: a digital approach for a bioethanol plant in Brazil. In Rio Oil & Gas Expo and Conference. 2020.
147. Perlack R., B. Stokes L. Eaton and A. Turnhollow. 2011. US Billion-Ton Update. Biomass Supply for a Bioenergy and Bioproducts Industry. Energy Efficiency and Renewable Energy. https://doi.org/10.1089/ind.2011.7.375. https://bioenergykdf.net/.
148. Pour N, Webley PA, Cook PJ. Opportunities for application of BECCS in the Australian power sector. Appl Energy. 2018;224:615–35.
149. Quader MA, Ahmed S. Bioenergy with carbon capture and storage (BECCS): Future prospects of carbon-negative technologies. In: Clean energy for sustainable development. Academic Press; 2017. p. 91–140.
150. Ragsdale SW. Enzymology of the Wood-Ljungdahl pathway of acetogenesis. Ann N Y Acad Sci. 2008;1125(1):129–36.
151. Rahman FA, Aziz MMA, Saidur R, Bakar WAWA, Hainin MR, Putrajaya R, et al. Pollution to solution: capture and sequestration of carbon dioxide (CO2) and its utilization as a renewable energy source for a sustainable future. Renew Sustain Energy Rev. 2017;71:112–26.
152. Ranjan. Carbon capture, utilization and storage (CCUS) – a roadmap for India, Technology Information Forecasting and Assessment Council Ministry of Science and Technology, Government of India. 2018.
153. Ravanchi MT, Sahebdelfar S. Catalytic conversions of CO_2 to help mitigate climate change: recent process developments. Process Saf Environ Prot. 2021;145:172–94.
154. Ray A. Carbon capture and sequestration: Implications and opportunities for India. *Climate Change and Green Chemistry of CO_2 Sequestration*. 19–25. 2021.
155. Raza A, Gholami R, Rezaee R, Rasouli V, Rabiei M. Significant aspects of carbon capture and storage–a review. Petroleum. 2019;5(4):335–40.
156. Redl S, Diender M, Jensen TØ, Sousa DZ, Nielsen AT. Exploiting the potential of gas fermentation. Ind Crops Prod. 2017;106:21–30.
157. Rickels W, Proelß A, Geden O, Burhenne J, Fridahl M. Integrating carbon dioxide removal into European emissions trading. Front Clim. 2021;24(3):690023.
158. Ritchie H. and Roser M. CO_2 and other greenhouse gas emissions. Our world in data. 2017.
159. Rodgers S, Conradie A, King R, Poulston S, Hayes M, Bommareddy RR, et al. Reconciling the sustainable manufacturing of commodity chemicals with feasible technoeconomic outcomes: assessing the investment case for heat integrated aerobic gas fermentation. Johnson Matthey Technol Rev. 2021;65(3):375–94.
160. Rogieri Pelissari M, Gomes Relva S, Peyerl D. Possibilities for carbon capture, utilization, and storage in Brazil. In: Energy Transition in Brazil. Cham: Springer Nature Switzerland; 2023.
161. Roquette Brochure. BIOSUCCINIUM® Enabling sustainable materials. 2021. https://www.roquette.com/-/media/documentation/biosuccinium/roquette-brochure-biosuccinium-general-enabling-sustainable-materials.pdf Accessed 1 Sep 2023.
162. Rosa L, Mazzotti M. Potential for hydrogen production from sustainable biomass with carbon capture and storage. Renew Sustain Energy Rev. 2022;157:112123.
163. Rosa L, Becattini V, Gabrielli P, Andreotti A, Mazzotti M. Carbon dioxide mineralization in recycled concrete aggregates can contribute immediately to carbon-neutrality. Resour Conserv Recycl. 2022;184:106436.
164. Rubin E, Davison J, Herzog H. The cost of CO2 capture and storage. Int J Greenhouse Gas Control. 2015;40:378–400.
165. Rückel A, Hannemann J, Maierhofer C, Fuchs A, Weuster-Botz D. Studies on syngas fermentation with *Clostridium carboxidivorans* in stirred-tank reactors with defined gas impurities. Front Microbiol. 2021;12:655390.
166. Rumayor M, Fernández-González J, Domínguez-Ramos A, Irabien A. Deep decarbonization of the cement sector: a prospective environmental assessment of CO2 recycling to methanol. ACS Sustain Chem Eng. 2021;10(1):267–78.
167. Rycroft L, Wildenborg T, Bolscher H, Opinska LG, Yearwood J, Parmiter P, Jordal K, Reyes-Lúa A, Whiriskey K, Andreas J, Kraemer D. CCUS projects network: European knowledge sharing and communication to support project development. In: Proceedings of the 15th Greenhouse Gas Control Technologies Conference, vol. 24, pp. 15–18 (2021).
168. Salinas A, McGregor C, Irorere V, Arenas-López C, Bommareddy RR, Winzer K, et al. Metabolic engineering of *Cupriavidus necator* H16 for heterotrophic and autotrophic production of 3-hydroxypropionic acid. Metab Eng. 2022;74:178–90.
169. Samoraj M, Çalış D, Trzaska K, Mironiuk M, Chojnacka K. Advancements in algal biorefineries for sustainable agriculture: Biofuels, high-value products, and environmental solutions. Biocatal Agri Biotechnol. 2024;58:103224.
170. Sanchez DL, Fingerman K, Herbert C, Uden S. Policy options for deep decarbonization and wood utilization in California's low carbon fuel standard. Front Clim. 2021;3:665778.
171. Saravanan A, Vo DVN, Jeevanantham S, Bhuvaneswari V, Narayanan VA, Yaashikaa PR, et al. A comprehensive review on different approaches for CO2 utilization and conversion pathways. Chem Eng Sci. 2021;236:116515.
172. Saxena A, Prakash Gupta J, Tiwary JK, Kumar A, Sharma S, Pandey G, et al. Innovative pathways in carbon capture: advancements and strategic approaches for effective carbon capture, utilization, and storage. Sustainability. 2024;16(22):10132.
173. Schneider L. Using International Carbon Credits to Achieve National Mitigation Targets of EU Member States–Options for Accounting under Article 6 of the Paris Agreement. Öko Institut eV, available here https://www.oeko.de/publikation/usinginternational-carboncredits-to-achieve-national-mitigation-targets-of-eu-member-statesoptions-for-accounting-under-article-6-of-the-paris-agreement. 2023; 9
174. Schwander T, von Schada Borzyskowski L, Burgener S, Cortina NS, Erb TJ. A synthetic pathway for the fixation of carbon dioxide in vitro. Science. 2016;354(6314):900–4.
175. Scown CD. Prospects for carbon-negative biomanufacturing. Trends Biotechnol. 2022;40(12):1415–24.
176. Selvan ST, Velramar B, Chandrasekaran RK, Ramamurthy D, Natarajan PM. Phototrophic Carbon Capture Using Natural Microalgal Whole-Cell Support: An Eco-Technological Approach. In: Whole-Cell Biocatalysis. Palm Bay: Apple Academic Press; 2024.
177. Seshadri S, Sashirekha V. Prospects and limitations in establishing integrated carbon capture and wastewater treatment facility using algal and bacterial consortia. In: Workshop on Awareness and Capacity Building in Carbon Capture and Storage and Utilization. GOI; 2018.
178. Shackley S, Verma P. Tackling CO_2 reduction in India through use of CO_2 capture and storage (CCS): prospects and challenges. Energy Policy. 2008;36(9):3554–61.

179. Shahbaz M, AlNouss A, Ghiat I, Mckay G, Mackey H, Elkhalifa S, Al-Ansari T. A comprehensive review of biomass based thermochemical conversion technologies integrated with CO_2 capture and utilisation within BECCS networks. Resour Conserv Recycl. 2021;1(173):105734.
180. Sharma M, Datta R, Kedia VK, Brtnicky M. Microbial Potential for Carbon Fixation and Stabilization. In: Datta R, Meena RS, editors. Soil Carbon Stabilization to Mitigate Climate Change. Singapore: Springer; 2021. p. 125–68.
181. Shaw R, Mukherjee S. The development of carbon capture and storage (CCS) in India: a critical review. Carbon Capture Sci Technol. 2022;2:100036.
182. Shcherbyna YM, Novoseltsev O, Evtukhova T. Overview of carbon capture, utilization and storage technologies to ensure low-carbon development of energy systems. Sys Res Energy. 2022. https://doi.org/10.15407/srenergy2022.02.004.
183. Shearer C, Fofrich R, Davis SJ. Future CO_2 emissions and electricity generation from proposed coal-fired power plants in India. Earths Future. 2017;5(4):408–16.
184. Shi J, Jiang Y, Jiang Z, Wang X, Wang X, Zhang S, et al. Enzymatic conversion of carbon dioxide. Chem Soc Rev. 2015;44(17):5981–6000.
185. Silveira BHM, Costa HKM, Santos EM. Bioenergy with carbon capture and storage (BECCUS) in Brazil: a review. Energies. 2023;16(4):2021.
186. Stavrakas V, Spyridaki N-A, Flamos A. Striving towards the deployment of bio-energy with carbon capture and storage (BECCUS): a review of research priorities and assessment needs. Sustainability. 2018;10(7):2206.
187. Straathof AJ. Transformation of biomass into commodity chemicals using enzymes or cells. Chem Rev. 2014;114(3):1871–908.
188. Sun H, Zhao W, Mao X, Li Y, Wu T, Chen F. High-value biomass from microalgae production platforms: strategies and progress based on carbon metabolism and energy conversion. Biotechnol Biofuels. 2018;11:1–23.
189. Talei S, Soleimani Z. An overview of bioenergy with carbon capture and storage process as a negative emission technology. ALKHAS; J Environ, Agr Biol Sci. 2020;3:1.
190. Tanzer SE, Blok K, Ramirez A. Decarbonising industry via BECCS: promising sectors, challenges, and techno-economic limits of negative emissions. Curr Sustain/Renew Energy Rep. 2021;8:1–10.
191. Teixeira LV, Moutinho LF, Romão-Dumaresq AS. Gas fermentation of C1 feedstocks: commercialization status and future prospects. Biofuels Bioprod Biorefin. 2018. https://doi.org/10.1002/bbb.1912.
192. TERI. India CCS Scoping Study: Final Report, the Energy and Resources Institute, New Delhi. 42 2013.
193. Thakur IS, Kumar M, Varjani SJ, Wu Y, Gnansounou E, Ravindran S. Sequestration and utilization of carbon dioxide by chemical and biological methods for biofuels and biomaterials by chemoautotrophs: opportunities and challenges. Bioresour Technol. 2018;256:478–90.
194. Thornley P, Mohr A. Policy Frameworks and Supply-Chain Accounting. In: Gough C, Thornley P, Mander S, Vaughan N, Falano T, editors. Bioenergy with Carbon Capture and Storage. Hoboken: Wiley; 2018.
195. Turner K, Katris A, Race J. and Stewart J. How is Planned Public Investment to Enable CCS Likely to Impact the Wider UK Economy?. 2020.
196. Van Der Giesen C, Kleijn R, Kramer GJ. Energy and climate impacts of producing synthetic hydrocarbon fuels from CO2. Environ Sci Technol. 2014;48(12):7111–21.
197. Vanholme B, Desmet T, Ronsse F, Rabaey K, Breusegem FV, Mey MD, et al. Towards a carbon-negative sustainable bio-based economy. Front Plant Sci. 2013;4:174.
198. Vo TT, Wall DM, Ring D, Rajendran K, Murphy JD. Techno-economic analysis of biogas upgrading via amine scrubber, carbon capture and ex-situ methanation. Appl Energy. 2018;212:1191–202.
199. Volova TG, Kiselev EG, Shishatskaya EI. Cell growth and accumulation of polyhydroxyalkanoates from CO_2 and H_2 of a hydrogen-oxidizing bacterium, *Cupriavidus eutrophus* B.-10646. Bioresour Technol. 2013;146:215–22.
200. Werner C, Schmidt H-P, Gerten D. Pyrogenic carbon capture and storage (PyCCS): a novel land-neutral solution for carbon sequestration. Environ Sci Technol. 2022;56(10):6874–84. https://doi.org/10.1021/acs.est.1c08552.
201. White Dog Labs. Inc, Start-up white dog labs wins doe grant for technology that could dramatically increase biochemicals yield while decreasing carbon dioxide emissions. 2016. https://www.whitedoglabs.com/pressrelease-june62016/.
202. Wilberforce T, Baroutaji A, Soudan B, Al-Alami AH, Olabi AG. Outlook of carbon capture technology and challenges. Sci Total Env. 2018;657:56.
203. Woern C, Grossmann L. Microbial gas fermentation technology for sustainable food protein production. Biotechnol Adv. 2023;1:108240.
204. Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S. Sustainable biochar to mitigate global climate change. Nat Commun. 2016;1:56. https://doi.org/10.1038/ncomms106.
205. Wu C, Lo J, Urban C, Gao X, Yang B, Humphreys J, et al. Acetyl-CoA synthesis through a bicyclic carbon-fixing pathway in gas-fermenting bacteria. Nat Synth. 2022;1(8):615–25.
206. Xia, C. Beijing Iron Maker to Turn Waste Gas into Biofuels. 2018. http://www.china.org.cn/ china/2018–02/27/content_50616460.htm. Accessed 10 May 2018.
207. Xu Y, Isom L, Hanna MA. Adding value to carbon dioxide from ethanol fer-mentations. Bioresour Technol. 2010;101:3311–9.
208. Yang CH, Liu EJ, Chen YL, Ou-Yang FY, Li SY. The comprehensive profile of fermentation products during in situ CO 2 recycling by Rubisco-based engineered *Escherichia coli*. Microb Cell Fact. 2016;15:1–10.
209. Yang M, Baral NR, Anastasopoulou A, Breunig HM, Scown CD. Cost and life-cycle greenhouse gas implications of integrating biogas upgrading and carbon capture technologies in cellulosic biorefineries. Environ Sci Technol. 2020;54(20):12810–9.
210. Yeung FD, Sammarchi S, Wang E, Gao Q, Li J. Interdisciplinary challenges in bio-energy carbon capture utilization & storage deployment: a review. Carbon Capture Sci Technol. 2024;13:100283.
211. Yoro KO, Daramola MO. CO_2 emission sources, greenhouse gases, and the global warming effect. In: Advances in carbon capture. Cambridge: Woodhead Publishing; 2020.
212. Zakkour P, Cook G. CCS Roadmap for Industry: High-purity CO_2 sources. UK: Carbon Counts Company Ltd; 2010.
213. Zarzycki J, Brecht V, Müller M, Fuchs G. Identifying the missing steps of the autotrophic 3-hydroxypropionate CO_2 fixation cycle in *Chloroflexus aurantiacus*. Proc Natl Acad Sci USA. 2009;106(50):21317–22.
214. Zetterberg L, Johnsson F. Policy mechanisms for accelerating BECCUS deployment in Europe: a review. Energy Strategy Rev. 2021;35:100638. https://doi.org/10.1016/j.esr.2021.100638.
215. Zhang C, Fei Q, Fu R, Lackner M, Zhou YJ, Tan T. Economic and sustainable revolution to facilitate one-carbon biomanufacturing. Nat Commun. 2025;16(1):1–10.
216. Zhang Q, Cheng CL, Nagarajan D, Chang JS, Hu J, Lee DJ. Carbon capture and utilization of fermentation CO2: integrated ethanol fermentation and succinic acid production as an efficient platform. Appl Energy. 2017;206:364–71.
217. Zhang Q, Nurhayati C, Nagarajan CL, Chang D, Hu J JS, Lee DJ. Carbon capture and utilization of fermentation CO 2: Integrated ethanol fermentation and succinic acid production as an efficient platform. Appl Energy. 2017;206:364–71.
218. Zhang X, Yang X, Lu X. CCS Progress in China - A status report the administrative center for China's Agenda 21, Global CCS Institute. Tsinghua: Tsinghua University; 2023.
219. Zhao X, Li L, Zhang S, Fu X, Xie L, Wang L. Efficient chemoautotrophic carbon fixation in controlled systems: influencing factors, regulatory strategies and application prospects. Crit Rev Environ Sci Technol. 2025. https://doi.org/10.1080/10643389.2024.2449328.
220. Zhou W, Lin R, Murphy JD. Biogenic CO_2 utilization for biofuels: balancing carbon circularity and negative emissions. Renew Energy. 2022;185:1228–41.
221. Zhu F, Liu D, Chen Z. Recent advances in biological production of 1, 3-propanediol: new routes and engineering strategies. Green Chem. 2022;24(4):1390–403.

Publisher's Note

Terms and Conditions

Springer Nature journal content, brought to you courtesy of Springer Nature Customer Service Center GmbH (“Springer Nature”).

Springer Nature supports a reasonable amount of sharing of research papers by authors, subscribers and authorised users (“Users”), for small-scale personal, non-commercial use provided that all copyright, trade and service marks and other proprietary notices are maintained. By accessing, sharing, receiving or otherwise using the Springer Nature journal content you agree to these terms of use (“Terms”). For these purposes, Springer Nature considers academic use (by researchers and students) to be non-commercial.

These Terms are supplementary and will apply in addition to any applicable website terms and conditions, a relevant site licence or a personal subscription. These Terms will prevail over any conflict or ambiguity with regards to the relevant terms, a site licence or a personal subscription (to the extent of the conflict or ambiguity only). For Creative Commons-licensed articles, the terms of the Creative Commons license used will apply.

We collect and use personal data to provide access to the Springer Nature journal content. We may also use these personal data internally within ResearchGate and Springer Nature and as agreed share it, in an anonymised way, for purposes of tracking, analysis and reporting. We will not otherwise disclose your personal data outside the ResearchGate or the Springer Nature group of companies unless we have your permission as detailed in the Privacy Policy.

While Users may use the Springer Nature journal content for small scale, personal non-commercial use, it is important to note that Users may not:

1. use such content for the purpose of providing other users with access on a regular or large scale basis or as a means to circumvent access control;
2. use such content where to do so would be considered a criminal or statutory offence in any jurisdiction, or gives rise to civil liability, or is otherwise unlawful;
3. falsely or misleadingly imply or suggest endorsement, approval , sponsorship, or association unless explicitly agreed to by Springer Nature in writing;
4. use bots or other automated methods to access the content or redirect messages
5. override any security feature or exclusionary protocol; or
6. share the content in order to create substitute for Springer Nature products or services or a systematic database of Springer Nature journal content.

In line with the restriction against commercial use, Springer Nature does not permit the creation of a product or service that creates revenue, royalties, rent or income from our content or its inclusion as part of a paid for service or for other commercial gain. Springer Nature journal content cannot be used for inter-library loans and librarians may not upload Springer Nature journal content on a large scale into their, or any other, institutional repository.

These terms of use are reviewed regularly and may be amended at any time. Springer Nature is not obligated to publish any information or content on this website and may remove it or features or functionality at our sole discretion, at any time with or without notice. Springer Nature may revoke this licence to you at any time and remove access to any copies of the Springer Nature journal content which have been saved.

To the fullest extent permitted by law, Springer Nature makes no warranties, representations or guarantees to Users, either express or implied with respect to the Springer nature journal content and all parties disclaim and waive any implied warranties or warranties imposed by law, including merchantability or fitness for any particular purpose.

Please note that these rights do not automatically extend to content, data or other material published by Springer Nature that may be licensed from third parties.

If you would like to use or distribute our Springer Nature journal content to a wider audience or on a regular basis or in any other manner not expressly permitted by these Terms, please contact Springer Nature at

onlineservice@springernature.com