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Natural Allies: Leveraging Biological Systems for Climate Change Mitigation Through CO_2 Removal

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ABSTRACT

This review paper delves into the diverse biological strategies for carbon dioxide removal (BCDR), highlighting their potential to mitigate climate change effectively. Biological systems, ranging from vast forests to microscopic algae, are crucial in capturing atmospheric CO_2 and sequestering it within organic matter or through conversion into bioenergy. The paper begins by discussing the increasing urgency of addressing historical CO_2 accumulations and the complementary role of BCDR to traditional decarbonization efforts. It then explores various biological mechanisms such as photosynthesis and the Calvin-Benson-Bassham cycle, which plants, algae, and microorganisms utilize to convert CO_2 into biomass, thereby contributing to long-term carbon storage. Further sections analyze the role of innovative biological technologies, including genetically engineered microorganisms and hyperaccumulators, in enhancing carbon capture efficiency. The review also addresses the advantages and limitations of these biological strategies, comparing them with mechanical carbon capture technologies. Case studies of successful BCDR projects illustrate the practical implementation and challenges of scaling these approaches. The review concluded that, concerning future directions and policy implications, there is a crucial need for integrated strategies incorporating biological and chemo-physical techniques to mitigate climate change and achieve sustainable carbon reduction. Through a comprehensive analysis of existing and emerging BCDR techniques, this review underscores the importance of biological approaches in the global effort to combat climate change, offering insights into their potential scalability, economic feasibility, and ecological impact. The key finding of the review is that integrating biological carbon dioxide removal (BCDR) strategies with chemo-physical techniques offers a scalable, cost-effective, and sustainable approach to mitigating climate change.

KEYWORDS: Silver, Manganese, nanoparticles, antibacterial, *Escherichia coli,*

INTRODUCTION

This review aims to evaluate effective biological strategies for carbon dioxide removal (BCDR) and assess their potential capabilities to mitigate carbon dioxide emissions compared with chemical ones, which will mitigate climate change. One effective option to achieve BCDR is through sustainable land use anchored in the

United Nations' Agenda 2030, contributing to global food security, biodiversity protection, climate adaptation, resilience, and mitigation. An extensive biological system, e.g., a forest or an agroforestry system, accumulates more carbon than it annually releases to the atmosphere in carbon dioxide, and it is regularly removed from the system as a raw material or as biomass for energy (National Academies of Sciences 2018). Regrowing biological systems can reduce carbon emissions through biological carbon storage, where chronologically old carbon is injected deep underground in the form of bioenergy with carbon capture and storage (BECCS), also known as bio-CCS. Negative emissions are required because achieving zero emissions does not address the historical carbon dioxide accumulations (Udawatta et al., 2022). The principles of this approach are covered through the expression carbon negative by design as per the circular economy philosophy. Active and passive bioenergy carbon dioxide removal approaches could offer a more flexible, less risky, diverse, and sustainable portfolio to combat climate change (Palmer & Carton, 2021).

THE ROLE OF CARBON DIOXIDE IN CLIMATE CHANGE

Climate change has attained critical urgency in the twenty-first century mainly due to increased carbon dioxide (CO_2) emissions, one of the most important greenhouse gases emitted faster than it is removed. Earlier records suggest that atmospheric CO_2 globally averaged about 200 ppm, and the current concentration of CO_2 has exceeded 400 ppm (Nunes, 2023). According to different research organizations, CO_2 is an ideal conserved greenhouse gas as it contributes to around 55% of global warming effects. Though many attempts are being made to slow the increase of carbon dioxide by controlling its release rate, either by extracting naturally or through human influence, little success has been achieved concerning carbon sequestration or elimination. Practical and effective techniques for CO_2 removal are required to protect the climate system (Fawzy et al., 2020).

Significant CO_2 emissions occur from fossil fuel burning in power plant industries and bioenergy systems. CO_2 is also emitted from fossil-related events such as agriculture and deforestation. Various countries and regions have agreed to work together to mitigate average temperature levels in response to these issues. Carbon capture and utilization (CCU) and carbon capture and storage (CCS) are widely received for removing or avoiding CO_2 emissions from significant sources of more than 50,000 tons per year, including power plants, industries, and bioenergy systems (Perera, 2018). Historically, geological storage and mineralization have been widely accepted as physical storage technologies to store CO_2 away from the atmosphere for an extended period. However, these approaches have to overcome mechanical issues and depend upon geological availability in the region, as well as the security of the physical store. Biological systems, including trees, plants, and other ecosystems, use photosynthesis to consume CO_2 and produce oxygen, which is also considered an effective mechanism for removing CO_2 from the atmosphere (Omotoso & Omotayo, 2023). Global efforts to mitigate climate change have been shaped by international agreements such as the United Nations Framework Convention on Combating Climate Change (UNFCCC) and the Paris Agreement. These frameworks establish guidelines for reducing greenhouse gas emissions and emphasize the critical role of carbon capture technologies, including biological carbon dioxide removal (BCDR). The Paris Agreement, in particular, sets ambitious targets for limiting the rise of global temperature and encourages the integration of sustainable carbon sequestration methods. By aligning with these international policies, BCDR strategies can contribute to achieving net-zero emissions while ensuring ecological and economic viability.

BIOLOGICAL CARBON DIOXIDE REMOVAL MECHANISMS

This review will elucidate various mechanisms for biological carbon removal. Diatoms use a unique biological pathway to remove carbon dioxide from the environment, which is also being investigated in research for commercial carbon capture (Sethi et al., 2020). Diatoms, among other biological cellular processes, can remove bioinspired artificial carbon. Thus, exploring and understanding the biological strategies used by diatoms will help further enhance the currently studied carbon dioxide removal techniques.

Plants, algae, and cyanobacteria use the Calvin-Benson-Bassham cycle to convert CO_2 and water into glucose (Santos Correa et al., 2022), which are the necessary and valuable building blocks to maximize their energy for growth. The carbon-containing compounds should remain in the plant for effective carbon dioxide removal. In natural systems, algae and plants convert excess sugars to starch, cellulose, or lipids (Daneshvar et al., 2022). Photosynthesis allows converting CO_2 from the atmosphere into new organic matter. It acts as an ocean sink where marine photosynthesis maintains the delicate balance between marine and atmospheric CO_2, lowering the CO_2 concentration in the surrounding water and enhancing the absorption of CO_2 from the atmosphere (Cooley et al., 2023)). Moreover, phytoplankton convert CO_2 to glucose via oxygenic photosynthesis to perform internal processes such as photorespiration, respiration, and various metabolic pathways to sustain life (Elkelish & Abu-Elsaoud, 2024). Removing CO_2 in biological metabolic processes is fundamental to building and maintaining physical structure and reproduction (Yu King Hing et al., 2021).

PHOTOSYNTHESIS AND CARBON SEQUESTRATION

Photosynthesis is a fundamental biological process that converts light using carbon resources into organic materials in various living systems. The significance of photosynthesis to humanity, however, not only lies in providing food and oxygen for survival and energy for biotic activities but also in the potential of photosynthesis to capture and store CO_2 from the atmosphere, i.e., carbon sequestration (Johnson, 2016). The carbon emitted into the atmosphere, whether of natural or anthropogenic origin, occurs simultaneously, and biochemical activities determine its quantity. However, as a non-conservative element in the atmosphere, CO_2 emission has established global concern for its effects on ecological health, adverse climate conditions, and human survival. With the carbon concentration in the atmosphere continually rising, the effectiveness of photosynthesis in the original CO_2 removal process also becomes a research hotspot with increasing concerns for understanding the biological mechanisms that effectively enhance carbon sequestration (Janssen et al., 2014).

To resolve this problem, fundamental questions must be addressed: how CO_2 is absorbed during biological activities, and how do natural elements continually remove CO_2 from the atmosphere while feeding the Earth's biosphere? (Cooley et al., 2023) Estimating the CO_2 absorption capability and efficiency of the Earth's biosphere thus provides the research of biospheric CO_2 sequestration. Reducing this problem to the simple vision of a carbon reservoir system and an atmospheric carbon reservoir, the capacity of plant photosynthesis to photosynthetically fix CO_2 would play a role as a much more stocked carbon quantification destination, as one of the most straightforward carbon reservoir units estimated (Wang et al., 2021). That surprising fact also poses another question: how much CO_2 are these reservoir systems expected to absorb or fix during capture?

ALGAE AND MICROORGANISMS AS CARBON DIOXIDE ABSORBERS

Exploring algae for carbon dioxide removal is an innovative approach aiming to develop a constant supply of feedstock that can be used as biofuels or in industrial feedstock, which is in huge demand. Microorganisms, including algae, photosynthetic bacteria, and cyanobacteria (blue-green algae), can convert solar energy and carbon dioxide into algal biomass and oxygen through photosynthesis. One ton of algae can produce 1.83 tons of oxygen. In addition, a portion of the absorbed carbon is stored inside the algal biomass. Microbial biomass can store about 40% to 50% of the carbon fixed daily. Therefore, both algal and cyanobacterial biomass can be seen as an effective source for carbon dioxide removal by dissociating oxygen and algal biomass. This enables the natural degradation of the biomass into a microbial cell (Ezhumalai et al., 2024).

Cyanobacteria are one of the most significant contributors to carbon dioxide removal from the atmosphere. Cyanobacteria have various forms, are ecologically and biotechnologically significant, and are grouped into three major kinds and biotypes: gas vesicle-associated, heterocystous, and non-heterocystous. Anabaena, Nostoc, Aphanizomenon, and Cylindrospermum are heterocystous species used in agriculture and are essential in soil fertility replenishment through biological nitrogen fixation. The non-heterocystous forms of spirulina have significantly contributed to the food sector to support the supply of natural colorants, vitamins, and minerals. Unicellular and multicellular species such as Chlorella, Spirulina, Euglena, and Ulothrix are only a few examples of photosynthetic microorganisms, mainly algae and adhered microorganisms (Agarwal et al., 2022; Kumar et al., 2010).

BIOLOGICAL CARBON CAPTURE TECHNOLOGIES

Biological processes can be harnessed for carbon dioxide removal, encompassing various species. For example, trees are well-known for facilitating carbon sequestration, a phenomenon that reduces the concentration of carbon dioxide in the atmosphere (Murphy, 2024). Over the years, however, researchers and entrepreneurs have investigated or developed other applications leveraging these biological processes to capture carbon. This can be illustrated with various approaches, such as manipulation, genetic engineering, or the discovery of new enzymes to enhance the capacity of those species that naturally capture carbon (Rodrigues et al., 2023).

One of the earliest and frequently heard-about carbon-capturing entities is single-celled microalgae. These organisms contain specialized genes and biochemical pathways capable of sequestering and storing large amounts of carbon through photosynthesis (Barati et al., 2022). Though sometimes overlooked, certain microalgae species require large amounts of carbon-rich carbon, to which carbon dioxide contributes, to facilitate exponential growth. While microalgae manifest great promise, there are some challenges associated with their use, such as low growth rate and possibly high energy costs for cultivation (Politaeva et al., 2023). Consequently, another popular application has used a similar carbon sequestration pathway in bacteria. Combining synthetic biology, computational applications, and high-throughput experimentation with biotechnology industry pioneers such as Amyris enabled bacteria to compete as carbon-capturing candidates by providing them with the right carbon-sequestering genes and biochemical pathways (Wongsodiharjo & Masjud, 2024). The advantages of utilizing bacteria and microalgae include, for example, reduced energy requirements for growth and bioconversion. Carbon-capturing microorganisms also have high biological potential as they can prevent environmental degradation while promoting soil fertility. A substantial challenge lies in the development of efficient and robust microbial strains (Li et al., 2023).

Trees and hyperaccumulators naturally remove carbon dioxide from the soil. Hyperaccumulators have high biological potential for soil sequestration and are also used as an effective way to remove heavy metals from the soil (Skuza et al., 2022). For instance, studies suggest that *Vetiveria zizanoides* grown in the land of the breaker of the pharmaceuticals industry are a strong type of phytoextraction plant and are the most efficient accumulator of light and heavy trace metals of all species studied (Rascio & Navari-Izzo, 2011). Selection of tree species may contribute to sequestering carbon beyond that sequestered in wood production and removal from the atmosphere (Siyar et al., 2022). For example, the soil can sequester 3.65-ton CO_2 ha^{-1} yr in poplars and 1.82-ton CO_2 ha−1 yr in intercropped agricultural olive trees. Furthermore, the present review details the currently available biological carbon capture approaches, recent advances, associated challenges, and policy implications (Asare et al., 2023).

ADVANTAGES AND LIMITATIONS OF BIOLOGICAL STRATEGIES

Biological strategies are naturally scalable and tunable to reduce CO_2 to a consumable product with minimal waste. The environmental benefits derived from using photosystems are straightforward in reducing anthropogenic carbon dioxide atmospherically, economically, and in terms of existing infrastructure (Turek et al., 2021). The photosynthetic nature tends to grow and repeat existing non-propagative photosystems, facilitating large-scale carbon fixation of small-unit cost. Both land and retort (i.e., without arable land) systems can be used with more than one optimal gas purification strategy, i.e., either 'in liquid' or the form of 'response products.' However, biological systems can be susceptible to location, land, soil type, nutrients, and even climatic conditions. This review evaluates the advantages and limitations of biological implementation for CO_2 capture (Chiellini & Galli, 2002).

Carbon utilization is, therefore, the most attractive, whether by synthetic catalysts or biological techniques. The rate of inorganic carbon sequestration may be limited by the water solubility of irradiated carbon (I) oxides (CO and CO_2) and their protic gas luminescence, which could potentially be harmful to the active sites of enzymes (Lin et al., 2022). Ozonation eliminates volatile organic compounds (VOC) formation during the synthesis of syngas, which is used to produce lower MW alcohol and formalin and as a reaction intermediate for trioxane and other oxygenated products (Shukla et al., 2019). Though chemical strategies for carbon dioxide capture are generally preferred to bioreaction, social, environmental, and economic pressures for further sustainability and new chemical products are driving research in cheap, selective, and biofactor reallocation. Further spontaneous carbon-squandering reactions catalyze several enzymes discussed in the next section to provide the foundation for this evaluation. The best metabolic habits to improve design are complex metabolic networks/plants adapted to carbon dioxide fixation, sugars, alcohols, and other complex substances in various chemical production scenarios, thereby exploiting C1, C_2, or C_3 assimilation that has already been metabolized twice.

COMPARISON WITH MECHANICAL CARBON CAPTURE TECHNOLOGIES

Here, we analyzed some biological capture and storage technologies that help reduce CO_2 levels (Hochman & Appasamy, 2024). The biological processes for scavenging atmospheric CO_2 are found to be effective in 1) removing CO_2 from fossil fuel exhaust, 2) generating O_2 for highly populated cities, 3) converting atmospheric CO_2 to useful chemicals or polymers, 4) restoring desert ecologies, increasing food crops, and/or 5) increasing the profitability and land values of waste treatment plants (Poblete et al., 2022).

A variety of process biotechnologies are available for this work. Microalgal panels and photobioreactors are the most popular and have been studied for their suitability in various configurations to remove CO_2 from different emissions across a broad range of CO_2 levels (Chanquia et al., 2021). Algal processes are not yet used to treat high-temperature emissions that are near-absolutely free of contaminants. They must be filtered, sterilized, and/or integrated with additional biological and electronic processes to protect the photoreactive organisms from toxic materials and high heat (Shareefdeen et al., 2023). For example, a strain of the cyanobacteria Spirulina has demonstrated tolerance to the heat on the hot side of a TE cooler (Dębowski et al., 2021). Many photophysical technologies developed by chemical engineers and chemists could also be adapted to such systems. These chemocatalytic and nanophotonic systems are only half-commercial and are meant to prevent acid rain associated with burning coal. Consequently, they do not use CO_2 like the photo- and chemoautotrophic approaches. Thus, not only are these mechanical processes more expensive than algal processes, but they are also not as profitable.

CASE STUDIES OF SUCCESSFUL BIOLOGICAL CARBON DIOXIDE REMOVAL PROJECTS

This section aims to determine whether projects designed to capture and store CO_2 using Biological Carbon Dioxide Removal (BCDR) strategies have, at a minimum, proved that capturing and storing carbon is technically feasible. The paragraphs below explore the outcomes of real-world projects that grew biomass and used the profit to finance the recapture of the CO_2 byproduct and, in some cases, to store it or produce carbon offsets for the international market. To learn from these real-world carbon capture projects, we have drawn our data primarily from written case studies in scientific, industry, and governmental publications that provide details of the projects (Sarwer et al., 2022).

The BCDR strategies implemented in these case study projects varied in biological method (afforestation and reforestation, as well as anaerobic digestion of manure, charcoal sequestration, and carbonation of silicates/biocarbonate), size (from less than 1 hectare of growing trees to the manure from herds of more than 160,000 domesticated animals), and capture outcome (from less than 100 metric tons of CO_2 to more than 70,000 metric tons) (Ramachandran Nair et al., 2009). BCDR strategies that seek to store carbon in living organisms have limited temporal horizons, as the carbon can be released over time in many ways (Zaks et al., 2011). Carbon stored in afforestation or reforestation campaigns can be released due to declining tree density or death, whether by natural causes, disease, or logging. Charcoal is less likely to be rapidly mineralized or decomposed, but instead, it might be used as biofuel or pyrolyzed before decomposition occurs. In the end, or even as an intermediate step, the tons of CO_2 captured in the produced carbon could eventually be re-emitted to the atmosphere (Sidi Habib et al., 2024; Žalys et al., 2023). One of the projects is the Bonn Challenge **(**afforestation/reforestation), a global effort restoring over 210 million hectares of degraded land, sequestering significant amounts of CO_2. The Biochar Initiative (charcoal sequestration) determines if applications in agriculture have resulted in long-term carbon storage with improved soil fertility. The Anaerobic Digestion Project in Denmark used processed manure from over 200,000 cattle to generate biogas while capturing CO_2 emissions, removing over 50,000 metric tons of CO_2 annually.

FUTURE DIRECTIONS AND INNOVATION IN BIOLOGICAL CARBON DIOXIDE REMOVAL

Looking to the future, biological carbon dioxide mitigation processes and reduced dependence on carbon provide a cost-effective approach based on nature to increase the rates at which the Earth's excess carbon can be absorbed (Singh et al., 2024). Production of new systems that can reduce or be independent of water use by photorespiration is one of the significant areas of development. Using new non-rubisco strategies to provide bicarbonate for microbial substrates or storage of velvet alga products or double encapsulation as R. T. Hillman (terrestrial), C3-H: dicoma mode (black), molluscum (finger calcareous), Yuzhenka (yellow marine algae), Haliphyma with free formaldehyde production, or purple fungi Spirulina spp, *Chromocantus purpurea*, or formulations of algae with flow-based entities as active fillings such as *Microtrix rubra* algal coolers will benefit from carbon supply under anoxic conditions (Machín et al., 2023; Ray et al., 2022).

For the biotic cultivation of cassava grown under perennial conditions, new varieties and cultivation practices suitable for periodic biological cultivation are required and can be expanded or effectively grown to be grown for more abundant crops (Walker et al., 2021). Research is ongoing, but the first demonstration at a field scale is experimental. Therefore, the practical limitations of the theory behind this proposed industry have not yet been explored by any major power grid with local, regional, or panel distribution. Data enriched with unconventional methodologies and climate simulations will be used to analyze the life cycle analysis of new crops (or use combinations of elements) and networks that do not necessarily depend on the use of oceanic sources.

POLICY IMPLICATIONS AND REGULATION OF BIOLOGICAL CARBON CAPTURE

Adopting and scaling biological carbon removal technologies introduce a suite of opportunities and challenges related to regulation and policy at local, regional, and international scales (Gupta et al., 2023). The promise of new, low-carbon bio-based materials with carbon benefits beyond only the atmosphere is likely to enhance the market value of bio-carbon and develop even more complex inter-commodity markets, potentially introducing extensive regulatory challenges beyond those outlined already. Here, we briefly explore some key implications of using biological carbon-based materials for carbon removal in the context of EU policy and regulation. We gesture towards challenges and questions that are more relevant globally (Singh et al., 2024). These build from the current work on biotechnologies and biomaterials' regulatory challenges and opportunities and the broader integration of ecosystem services and bio-sequestration within evolving policy frameworks and financial systems approaches.

The broader challenge of incorporating these systems within larger decarbonization and ecological protection initiatives may enhance their governance costs while further diverting scarce resources from alternative technologies and innovations. Ultimately, in examining the 'improvement of nature' in an ascribed arena of 'climate governance' and against a baseline of intervention, we are concerned not just with advancing specific techniques and materials but with the nature and policing of the 'bounds' themselves (Liu et al., 2024).

ECONOMIC CONSIDERATIONS AND COST-EFFECTIVENESS

Potential financial aspects and impacts in developing biological strategies for CO_2 sequestration are being considered for roll-out on a larger scale. CDR costs are defined as initial research and development and demonstration costs, costs for implementing and running a technology at the deployment stage, and total economic or social costs, including incentives and subsidy requirements for a full-scale roll-out. The accuracy of these costs is difficult to verify, and direct comparisons among processes should not be regarded as irrefutable.

Biological CDR is relatively competitive compared to non-biological CDR, assuming the required benchmarked volumes of biomass production and processing per unit area are met. Several biomasses are particularly effective in terms of productivity. Our analysis indicates that two of the seven biomasses considered to be most promising show net carbon payback within less than 12 months from deployment. Thus, the sink feature must be cost-effective and show a significant positive return regarding reduced kWh costs, not as a more comprehensive network interconnection at a grid level. Companies and policymakers must avoid following purely interdisciplinary models, which could lead to the unequal sharing of co-benefits in the event of competitive constraints included in these technologies.

ENVIRONMENTAL AND ECOLOGICAL IMPACTS OF BIOLOGICAL CARBON CAPTURE

To counter global warming, methods are being developed to capture CO_2 by photosynthetic organisms. These biological methods are grouped under Biological Carbon Capture and Storage. However, one could also look at the possible negative effects on the ecosystems that would carry out these biological CO_2 removal (BCD) measures. We have argued that the outcome of the BCD measures would disproportionately negatively affect ecosystems because organisms also adapt. Therefore, an adverse outcome may occur due to a significant cumulative impact from individual effects on the BCD ecosystems.

PUBLIC PERCEPTION AND ACCEPTANCE OF BIOLOGICAL CARBON DIOXIDE REMOVAL TECHNOLOGIES

Biological CO_2 removal technologies are increasingly prominent in discussions around climate solutions. However, it is unclear how bioenergy with carbon capture and storage will integrate with anthropogenic greenhouse gas (GHG) emissions reduction measurements. Similarly, will bioenergy crops be used for CO_2 removal in a renewable economy, and is this acceptable to the public? These observations suggest that a combination of technical, ethical, and socio-cultural approaches can help articulate how potential solutions combining harmful emissions can provide sustainable and effective feedback on a regional basis regarding future scenarios and land use practices.

Acceptance of climate change mitigation infrastructure such as nuclear power, large-scale wind or solar technology, and carbon capture and storage are all limited by technology's symbolic meaning (in combination with social, economic, and material constraints). Conceptually, this understanding is built into theories of socio-technology, where even smaller-scale decisions to use environmentally sustainable energy (for home heating or variable inputs into the electricity grid) are informed by adherence to sets of values, social practices, and economic constraints. Attitude is an umbrella term that can help describe and predict behavior. It covers how much an individual knows and endorses a technology, believes that they can control it, is not concerned about risks, and finds the helpful technology. Values are also a significant predictor of environment and technology.

CHALLENGES AND POTENTIAL SOLUTIONS IN SCALING UP BIOLOGICAL CARBON CAPTURE

Biological strategies for carbon dioxide removal, such as the pyrolysis-bioenergy with carbon capture and storage (BECCS), have an order-of-magnitude greater effective land use than natural solutions like afforestation and reforestation. However, many challenges are associated with large-scale biological approaches, such as improving the efficiency of oil-producing algal photobioreactors, minimizing evaporative losses in large-scale phyto-desalination systems, or unintended environmental effects. To a serious scientist in 2022, efforts to scale up carbon-negative agriculture and BECCS that incorporate thousands beyond what can be explored in experiments tend to invoke combinations of derision, disbelief, and tender condescension. However, the cooking-with-gas spatial derivatives needed for scaling exist (just about!) if we can co-locate many megacities on the order of 100-km² semi-circular earth-buffered plots. This conceptual rebranding has implications for the evolution of land use in the Anthropocene, and the possibility of multiple pathways to "grow" carbon-negative land for various reasons - and on a scale relevant to geoengineering - is explored here.

It is a common refrain that "we can, therefore, infer almost nothing about the behavior of the system" from the few studies of data-informed experimental systems in biology. Here, I track implications at each stage for the conditions to incrementally integrate systems into complex ecosystems. We are left with an order-of-magnitude disenchantment from projects that integrate with local systems. Our ability to work with regional players to incorporate a regular mega-scale BECCS (that sequesters carbon and subsidizes a homeland security nation) likely starts and ends with a top-10 rich northeastern US city basin. We have some traction with moving large-scale quantitative work to the global grid-scale, though with complex, evolving challenges.'

INTEGRATION OF BIOLOGICAL CARBON CAPTURE WITH OTHER CLIMATE CHANGE MITIGATION STRATEGIES

Biological carbon capture, in addition to reducing CO_2 emissions, can absorb 48% of the CO_2 emissions by terrestrial, ocean, and hydrological systems. These systems contribute to CO_2 removal and the fight against global warming. Reforestation, afforestation, land restoration, conservation agriculture, and bioenergy are some of the land-based carbon sequestration strategies made by the United Nations to mitigate climate change. 2021 has defined six priority ecosystem-based initiatives in an integrated climate change solution framework to keep global warming below 1.5°C, increasing afforestation, reforestation, and agroforestry, improving forest and land management, climate change mitigation, and land-based carbon removal. Promoting the conservation and restoration of ecosystems, sustainable management of marine and terrestrial ecosystems, and investing in NBS deployment, research, and monitoring.

Research on the concepts and quantification of the synergistic impacts of combining biological removal with other explored climate change mitigation options identified synergy between plant-based carbon removal and direct air capture (DAC), bioenergy, and land use change. Research on oleaginous crops that combine biological removal with direct air carbon capture. Research by Zhao et al., (2024) shows that combining BECCS with land-based carbon sequestration would be more profitable than alone. Special emission reduction targets are needed so that non-CO2 emissions and carbon removal through biological processes are competitive. Furthermore, our aspirations to limit global warming to 1.5°C to 2°C show that negative carbon technologies (NETs) are inevitable. Evaluating the potential synergistic benefits of combining biological removal strategies with other technological processes is essential. In the future, we aim to explore further "the emergence of synergetic CO_2 reduction by combining biological strategies with other approaches in climate change mitigation with demonstrable methods."

CONCLUSION AND KEY FINDINGS

This review has attempted to discuss the possibilities of biological carbon dioxide removal that could be quicker and cheaper than climate engineering. It has focused on increasing the efficiency of existing biological processes and allowing waste to be reused for this purpose, thus making the treatment process even more effective. Additionally, the review has attempted to explore low-cost and effective technologies that might be budding or unfamiliar worldwide.

CONCLUSION

We conclude with a concrete recommendation to expand the discussion toward defining more effective measures to safeguard contemporary ecosystems. We have identified an essential munition of tools and approaches covering various responses and needs. In all cases, the challenge now is to bring them to the desired level of tempo and size. It is also vital to admit that as such measures involve rapid and widespread action, there are no guarantees of success; this can seem somewhat daunting to our mindset. Running these activities in controlled ecosystems will allow assessment and optimization. Aspects concerning prevention measures in living systems depend significantly on our understanding and ability to implement these globally. The appropriate infrastructure might take a few years for a global assembly.

Conflict of interest statement

We declare that we have no conflict of interest.

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