Review On Carbon Negative Innovations Including Biochar Hempcrete and the Next Generation of Sustainable Materials

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Abstract. This review paper aims to synthesize the current state of carbon-negative innovations, with a focused analysis on biochar and hempcrete as paradigm materials, to assess their sequestration mechanisms, applications, and potential for mitigating climate change. Key quantitative findings from the assessed literature reveal that biochar, when incorporated at 50-70 wt.% in particleboard, can achieve flexural strengths exceeding 5.5 MPa. At the same time, hempcrete demonstrates the capacity to sequester up to 38.4% of its initial manufacturing CO_2 emissions and provides thermal insulation with U-values as low as 0.27 W/(m²·K). Biochar-augmented concrete formulations show promise, sequestering approximately 59 kg of CO_2 per tonne. Other emerging materials, such as mycelium-based composites, exhibit compressive strengths up to 1.1 MPa and low thermal conductivity (0.05–0.07 W/m·K). Life cycle assessments consistently indicate the carbon-negative potential of these technologies, with systems like integrated biochar filtration achieving a net impact of -1.41 kg CO_2 e/m³. The major conclusion underscores that while these materials present viable pathways for significant carbon sequestration and sustainable development across construction, agriculture, and energy sectors, their widespread adoption is hindered by challenges related to production cost, scalability, and regulatory frameworks. Future progress hinges on targeted research, supportive policy, and industrial collaboration to integrate these solutions into mainstream applications for a carbon-neutral future.

1 Introduction

Since climate change poses urgent demands for carbon level reduction and sequestration, it is an important agenda item in the global scene. The Intergovernmental Panel on Climate Change has reminded everyone that deep cuts in greenhouse gas emissions are needed to limit global warming to 1.5°C above pre-industrial times. Carbon-negative innovations then become an essential strategy under such circumstances. These materials and technologies

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reduce carbon emissions during production. Still, more importantly, they actively remove and sequester carbon dioxide from the atmosphere, providing a dual benefit in combating climate change. The industrial, construction, and agricultural sectors are among the largest emitters globally and provide an opportunity to apply carbon-negative materials to realize significant environmental impacts. For example, Europe's commitments under the 2015 Paris Agreement to reduce emissions and its long-term goal of a decarbonized economy by 2050 require tighter emissions budgets. This represents the long-term plan of both the EU and the UK (in the Climate Change Act 2008). A sustainable low-carbon future is closely related to the decoupling of economic and emissions growth and the development of a carbon-free energy system. In the same way, if Russia has to decarbonize by 2050, the economy needs to be on an appropriate low-carbon transition path [1].

Negative emissions involve the physical removal of carbon dioxide (CO2) from the atmosphere. NETs include natural climate solutions such as afforestation and soil carbon sequestration to human-driven interventions like bioenergy with carbon capture and storage (BECCS) and direct air capture with carbon storage (DACCS). These technologies directly reduce the atmospheric load of CO2, unlike actions that merely limit or prevent CO2 emissions [2], [3]. Carbon dioxide emissions have risen by more than 90% over the past 50 years, with fossil fuel combustion and industrial processes accounting for about 78% of this increase from 1970 to 2011, peaking at a record high in 2020 [4]. Decarbonization is extremely necessary in all sectors in which risks are applied due to climate change risk that threatens almost every ecosystem [5]. Replacing traditional materials with sustainable materials is a fundamental step to achieving a low-carbon economy. Materials such as Portland cement, steel, and plastics emit a lot of carbon; one reason is that they use a high amount of energy in their manufacture, in addition to using non-renewable resources. Carbon-negative materials that come through biochar, hempcrete, and CO2-infused concrete can be used to potentially clean out this industrial sector. The innovations sequester atmospheric carbon during their life cycle or use waste materials as inputs. They help in creating circular economies, reduce the dependency on fossil fuels, and offer sustainable alternatives to traditional practices. In addition, sustainable materials enhance resource efficiency and environmental resilience-imperatives for both industries and policymakers.

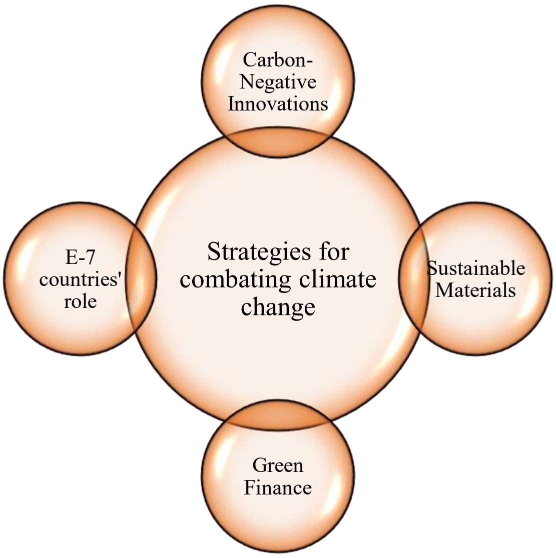

Fig. 1. Strategies for combating climate change

As far back as the industrial revolution, the financial sector has been a critical component of human development through the efficient mobilization and allocation of global savings, for centuries, the failure of financial systems has led to investment in environmentally destructive projects that enhance human-induced climate change. Before, the financial sector remained unconcerned about ecological degradation, which included depletion of habitats, depletion, pollution, and climatic change. Recently, finance has moved towards green investing to foster sustainable growth. Green finance instruments, such as green bonds, green mortgages, and climate credit cards, have been recently developed to achieve environmental goals [6]. E-7 countries, which include China, India, Brazil, Mexico, Russia, Indonesia, and Turkey-are projected to outperform the G-7 economies with a considerable portion of the global economy by 2032. The E-7 economies have been seen to register quite impressive growth in environmental technology and renewable energy investments. According to the past ten years, E-7 countries-china, India, and Brazil-have shown a growth rate of 16% increase in renewable energy investments.

In contrast, developing countries have recorded an overall growth of 30% renewable energy investments [7]. The Fig. 1 represents strategies on how to combat climate change through a central circle surrounded by four interacting elements. The strategies will be Carbon-Negative Innovations at the top, Sustainable Materials on the right side, Green Finance at the bottom, and the role of E-7 countries on the left. Each part outlines one of the most critical foci for the solution to the issue of climate change, which includes: technological development, material resources, financial mechanisms, and input of the E-7. Its form stresses the interconnectedness of those strategies toward achieving climate action objectives.

This is a review study, expanding the overview of carbon-negative materials, focusing on topics of biochar, hempcrete, and other emerging environmental sustainability technologies. Objectives involved were to highlight the science behind sequestration mechanisms of the technology; an overview of the currently accomplished works, along with relevant production methods and applications to the real world, and point out the barriers to adoption, together with relevant economic and technological hurdles. Future directions for scaling up production to maximize global impact are also discussed. This review will integrate scientific insights, case studies, and life cycle analyses to present a holistic perspective on carbon-negative materials using biochar and hempcrete as case studies. It provides a foundation for further research and tries to inform academia, industry, and policymakers about the transformative potential of these materials in addressing climate change.

2 Understanding Carbon-Negative Materials

Carbon-negative materials are those that have zero carbon emissions during their production but sequester carbon dioxide from the atmosphere during their entire life-cycle. These materials are engineered to be more than just sustainable; they actually reduce the overall atmospheric carbon load. Carbon-negative materials characteristics include using renewable resources, reducing fossil fuel dependency, and integrating waste products into the production process. Important enough, low-carbon does not mean carbon-negative, which is a material, in fact, that captures and stores much more carbon than it emits across all processes in its life-cycle. An interesting consideration - carbon-negative materials are net emission negative, and this basically holds some pivotal promise for climate change. The environmental benefits of carbon sequestration in materials are extensive. These materials help lock carbon within their structures for a long time, often decades or even centuries, hence mitigating global warming. They reduce the reliance on traditional materials with a high carbon footprint and integrate waste streams and renewable inputs into circular economies. The introduction of carbon-negative materials can also support ecosystem restoration and resilience by relieving pressure on natural resources and enhancing carbon storage in managed landscapes.

2.1 Types of Carbon-Negative Materials

Biochar: Through the pyrolysis of organic biomass under low-oxygen conditions, biochar is produced, sequestering carbon for hundreds to thousands of years and enhancing the fertility of soil, reduction in fertilizers, and water-holding capacity of the soil. Biochar is also applied in improving soil and water, as a construction material. Particleboard made with 50-70 wt.% biochar exhibited remarkable mechanical properties while meeting all flexural strength standards that exceed 5.5 MPa [8].

Hempcrete: A bio-composite composed of hemp shiv and lime-based binders that absorbs CO_2 through curing. Hempcrete is an insulating and fire-resistant construction material for sustainable construction. It can store up to 38.4% of the manufacturing emissions of CO_2 through the carbonation of binders and biogenic carbon storage; a U-value of 0.27 $W/(m^2 \cdot K)$ for a 1 m^2 wall assembly [9].

Carbon-Infused Concrete: This concrete combines CO_2 capture and mineralization, which makes it emit less than Portland cement. It has an increased compressive strength and durability. LC^2 mix prototype for a green concrete was able to produce a net saving of 72.24 kg CO_2/m^3 with a 6.8% cost reduction per barrier, which is suitable for roadside safety according to the EN 1317 standards [10].

Timber and Engineered Wood: Carbon-storing sustainably harvested wood and engineered wood, such as cross-laminated timber, or CLT, have a significant opportunity to be used for a wide variety of construction and furniture applications and have potential for lowering carbon footprints in buildings. Advanced modifications enhance the mechanical, thermal, and optical properties to support carbon-negative building designs [11].

Bioplastics: Derived from renewable resources such as corn starch or algae, bioplastics are biodegradable and compostable. It has the potential to attain net-zero or negative emissions and can replace up to 80% of the global plastic market. Decarbonization of energy sources and optimizing biomass conversion to minimize feedstock inputs are crucial steps [12].

Algae-Based Materials: Algae-based materials that utilize these rapid growth rates and efficiency in photosynthesis sequester CO_2 and are used in bioplastics, biofuels, textile manufacturing, and cosmetics. Combining these systems that integrate algae production with biochar production obtained 35.1% of carbon storage while stabilizing the biomass for long-term storage [13].

Carbon- Storing Agricultural Products: Methane emissions decreased by using agri-residuals such as straw, rice husk, coconut coir used as insulation; particleboards, bio-composite. Innovations in microbiological infiltration mineralization increased tensile strengths by about 80 – 150 per cent, respectively [14].

Mycelium-based products: These lightweight biodegradable materials absorb CO_2 during growth and could be used for insulation and packaging applications. Mycelium composites were shown to have compressive strengths of up to 1.1 MPa and thermal conductivities of 0.05–0.07 $W/m \cdot K$ [15].

Bio-Based Polymers: Made from plant oils and sugars, bio-based polymers are recyclable and capture carbon at the time of manufacture. Fermentation processes have significantly reduced carbon footprints, making these polymers a sustainable alternative for textiles, automotive parts, and consumer goods [16].

Carbon-Storing Paints and Coatings: These materials contain carbon-sequestering biochar or carbonates, which absorb CO_2 during curing but can provide durable finishes. It is in support of the UN Sustainable Development Goals by reducing construction emissions and enhancing indoor air quality [17].

Graphene and Carbon Nanomaterials: Graphene produced through carbon capture techniques provides stable, high-strength storage of carbon, while simultaneously enhancing composite materials. Examples include electronics and energy storage. New nanodevices were recently demonstrated for energy-efficient carbon storage [18].
Carbon-Negative Fibers: These fibers are derived from natural sources such as bamboo or flax. They are renewable, biodegradable, and carbon-sequestering during growth. They showed better energy storage properties, reaching an initial coulombic efficiency of 82% in sodium-ion batteries [19].

3 Biochar As a Versatile Carbon Sequestration Material

Biochar is the charcoal-like product resulting from the pyrolysis of organic biomass, such as agricultural waste, in a low-oxygen environment. The biomass is thus converted into stable carbon capable of holding carbon dioxide for centuries (Fig. 2).

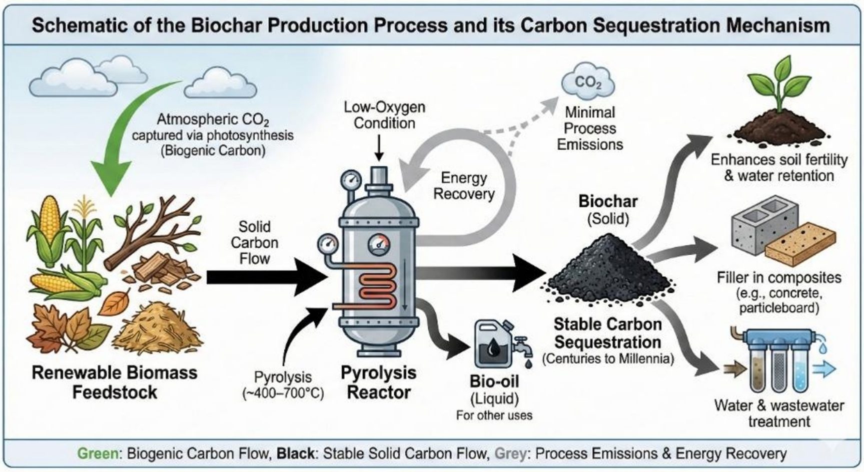

Fig. 2: Schematic overview of the biochar production pathway via pyrolysis of biomass under controlled, low-oxygen conditions

Various methods of producing biochar are applied, such as traditional kilns, rotary kilns, and fluidized bed reactors, with different levels of efficiency and scale of operation [20]. The specific production method greatly affects the physicochemical properties of biochar, including porosity, surface area, and nutrient content, which further dictate its applicability in various fields. Biochar types also differ depending on pyrolysis conditions; high-temperature biochar is often applied for soil amendments, whereas low-temperature biochar is applied in waste management [21]. Biochar is widely used for applications across diverse fields, primarily within agriculture, in terms of increasing water retention and enhancing the nutrient content, as well as improving the activity of microorganisms in soil. Thus, the dependence on synthetic fertilizers decreases due to soil conditions with biochar. Moreover, it also finds great usage within waste management systems to convert organic wastes into useful resource streams [22]. It reduces methane emissions from conventional waste management and aids in the filtration of contaminants in wastewater. Additionally, biochar has emerged as an exciting material in the construction industry, where it is being used as an aggregate in cementitious composites to produce carbon-negative building materials and also as an additive for insulation [23]. Fig. 3 illustrates the biochar derived from the trunk, leaves and seed.

Table 1. Carbon Negative Materials: Their Features and Applications.

Ref. No.	Material	Description	Key Features	Applications	Key Findings	Efficiency	Method Used
[8]	Biochar	Charcoal-like material from the pyrolysis of biomass in low-oxygen conditions.	Sequesters carbon for centuries; enhances soil fertility; improves water retention.	Soil improvement, water filtration, and construction material filler.	50-70 wt.% biochar in Cement showed good mechanical properties.	Up to 5.5 MPa flexural strength.	Pyrolysis of bio-waste in a low-oxygen environment; incorporation into Cement.
[9]	Hempcrete	Bio-composite of hemp shiv and lime-based binder.	Absorbs CO2 during curing; lightweight; insulating and fire-resistant.	Sustainable construction, insulation, retrofitting.	Sequesters up to 38.4% of initial CO2 emissions.	U-value of 0.27 W/(m2K) for wall assembly.	Biogenic carbon storage and binder carbonation.
[10]	Carbon-Infused Concrete	Concrete that captures and mineralizes CO2 during production.	Reduces emissions; durable; high compressive strength.	Infrastructure, buildings, industrial projects.	72.24 kg CO2/mÂ³ net saving.	Comparable to standard concrete strength.	Incorporation of glass aggregate and limestone calcined clay (LCÂ²).
[11]	Timber and Engineered Wood	Sustainably harvested wood like cross-laminated timber (CLT).	Long-term carbon storage; renewable; biodegradable.	Construction, furniture, and interior design.	Significant carbon storage potential.	Dependent on specific design and applications.	Use of sustainably harvested wood; multiscale design principles.
[12]	Bioplastics	Plastics from renewable biological sources like corn starch or algae.	Biodegradable; compostable; reduces fossil fuel dependence.	Packaging, medical devices, consumer goods.	Potential to achieve net-zero or negative emissions.	Depends on the allocation methods and processing.	Fermentation and advanced bioplastic production methods.
[13]	Algae-Based Materials	Materials derived from algae with high photosynthetic efficiency.	Sequesters CO2; versatile; biodegradable.	Bioplastics, biofuels, textiles, cosmetics.	35.1% carbon is distributed to biochar and algae.	Methane outlet purity of up to 85%.	Anaerobic digestion and biogas purification.
[14]	Carbon-Storing	By-products like straw, rice husks, and coconut coir.	Repurposes waste; reduces methane emissions.	Insulation, particleboards, bio-composites.	Significant tensile strength improvement.	80-150% tensile	Microbial infiltration and mineralization reactions.

	Agricultural Products					strength increment.	
[15]	Mycelium-Based Products	Products grown from fungal mycelium using agricultural waste.	Absorbs CO2; lightweight; biodegradable.	Packaging, insulation, structural components.	Practical thermal insulation applications.	Thermal conductivity of 0.05-0.07 W/m*K.	Mycelium cultivation on agricultural substrates.
[16]	Bio-Based Polymers	Polymers from renewable sources like plant oils and sugars.	Biodegradable; recyclable; sequesters carbon.	Textiles, automotive parts, consumer goods.	Low or zero-carbon footprint.	Varies by polymer type and processing.	Microbial fermentation of biomass.
[17]	Carbon-Storing Paints and Coatings	Paints with carbon-sequestering materials like biochar.	Absorbs CO2 during curing; durable; long-lasting finish.	Building interiors, exteriors, and industrial surfaces.	Supports UN SDG goals for sustainability.	Depends on the application methods.	Use of biochar and carbonates in formulations.
[18]	Graphene and Carbon Nanomaterials	Nanomaterials produced using carbon capture techniques.	High-strength, stable carbon storage; enhances composites.	Electronics, energy storage, and advanced composites.	High carbon capture efficiency.	Depends on specific nanomaterial applications.	Graphene nanopore/reduced graphene oxide synthesis.
[19]	Carbon-Negative Fibers	Fibers from carbon-absorbing sources like bamboo or flax.	Renewable; biodegradable; versatile.	Textiles, ropes, bio-composites.	Improved tensile strength and energy storage.	82% initial coulombic efficiency.	Mechanical treatment of soft carbon precursors.

Fig. 3: Trunk, leaves, and seed-derived biochar [51]

Despite its versatility, the large-scale use of biochar is hindered by a number of challenges. First, the production cost is relatively high because of the energy-intensive nature of the pyrolysis process. Moreover, the quality of biochar depends upon the feedstock type and production conditions, and thus it cannot be uniformly applied in various sectors [24]. The regulatory hurdles and lack of standardized guidelines also make its wide-scale use challenging, as there would be no guarantee about its quality and effectiveness. There are other logistical constraints like collection, transportation, and consistent supply of feedstocks. Limited awareness among the stakeholders and a lack of field data regarding long-term environmental impacts are also another issue that creates a hurdle for the adoption and implementation of biochar [25]. Overcoming these challenges requires advancing production technology, reducing costs, and developing standardized industry criteria. Such measures would allow biochar to achieve its full potential as a multifaceted tool for carbon sequestration, sustainable waste management, and the development of eco-friendly materials. With such an approach, the challenges associated with biochar will be overcome, and it can play a vital role in achieving environmental sustainability and mitigating climate change [26].

4 Hempcrete As a Carbon-Negative Building Material

Hempcrete is a bio-composite material composed of mixing the woody core of the hemp plant, commonly referred to as hemp hurds, with a lime-based binder and water. The result is that hempcrete is light, non-structural, and depends on the hemp plant's ability to absorb vast quantities of carbon dioxide during growth (Fig. 4).

The process of production is pretty straightforward. It involves the growth of hemp, processing of hemp fibers, and mixing hurds with a binder to produce a moldable material that hardens and cures with time [27]. Hempcrete presents specific qualities that make it very suited for sustainable construction. Being an excellent insulator with excellent thermal and acoustic performance makes it suitable for energy efficiency in buildings. Breathability reduces indoor humidity, making it an ideal solution against mold formation indoors and improves indoor air quality. Hempcrete is resistant to fire, tough, yet light in weight; therefore, it is convenient for work and application. In fact, being a carbon-negative material, hempcrete absorbs much more carbon dioxide during the production process compared to the carbon dioxide emitted [28]. Fig. 5 illustrates the thermal insulation by hempcrete panels.

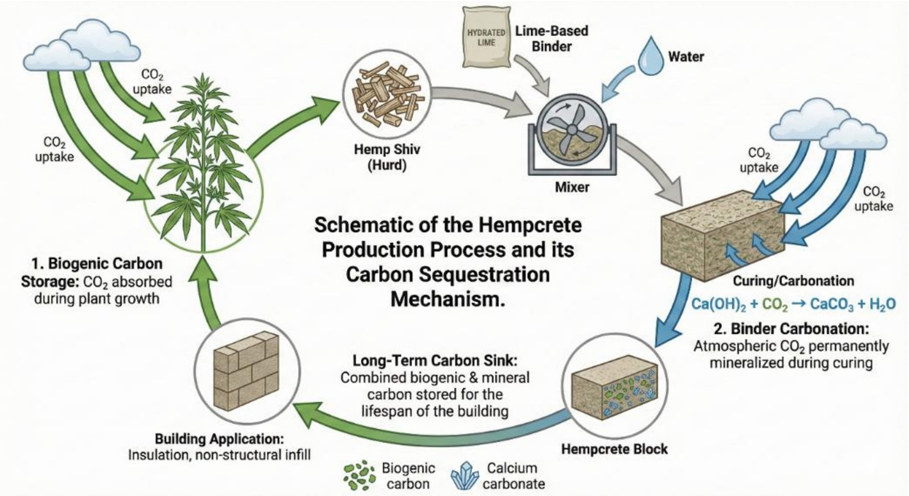

Fig. 4: Schematic overview of the hempcrete life-cycle, illustrating its dual-pathway carbon-negative mechanism

Fig. 5: Thermal insulation by Hempcrete panels and prefabricated Hempcrete panels [52]

Despite its benefits, hempcrete has challenges in scaling up into mainstream construction. Hemp farming, processing, and the binder material are expensive to produce and costlier than conventional materials. Industrial hemp availability limits scalability, as well as widespread infrastructure for hempcrete production. Regulatory barriers, such as building codes and certifications, also affect its adoption [29]. Hempcrete, being a non-structural material, can only be used in combination with load-bearing systems, which makes construction designs complicated. Hempcrete is a carbon-negative building material that possesses enormous potential for environmental and functional benefits. It is now time to overcome cost, scalability, and regulatory challenges that would make hempcrete popular in the construction industry and thereby contribute to sustainable development [30].

5 Emerging Carbon-Negative Materials

5.1 New Technologies in Carbon-Negative Concrete Manufacturing

Carbon-negative concrete is a recent research with a focus on technologies that include CO_2-infused concrete, in which carbon dioxide is captured and injected during the production process. This reduces emissions and even enhances the material strength. Techniques such as mineralization ensure that CO_2 is stored permanently within the concrete. The construction sector is seen as a major player in carbon sequestration.

5.2 Advanced Materials Incorporating Agricultural and Industrial By-Products

New materials are being developed with the use of agricultural residues, such as rice husk ash and hemp hurds, and industrial by-products, such as fly ash and slag, as substitutes for traditional carbon-intensive materials. They offer sustainable alternatives while at the same time reducing waste, lowering embodied carbon, and promoting circular economy principles.

5.3 Bio-Based Polymers and Composites Advance

Emerging alternatives to petroleum-based plastics include low-carbon bio-based polymers and composites derived from renewable resources like plant biomass and algae. Materials such as PLA and bio-resins offer biodegradability, reduced emissions during production, and other favourable properties that make them useful for applications in packaging, construction, and manufacturing.

5.4 Role of Nanotechnology in Enhancing Carbon Sequestration Capabilities

Nanotechnology plays a significant role in carbon sequestration improvement because it makes carbon-negative materials performance better. For instance, nanoparticles are added into the material to add strength and durability and more carbon-absorbing power, for example, nano-silica and carbon nanotubes. More efficient usage of materials, reduced emissions, and novel carbon capture mechanisms at the microscopic level characterize these technologies.

The DE fossilization of energy systems plays an important role in adapting and mitigating climate change and brings to the fore, within the renewable hydrogen platform, an alternative to fossil fuel energy. A major pathway is the climate-neutral production of hydrogen through electrolysis employing renewable electricity. Another innovative strategy comes from biohydrogen that is produced from organic materials that are biogenically produced, combined with the CCS, HyBECCS (Hydrogen Bioenergy with Carbon Capture and Storage). This technology achieves net-negative emissions, which is a capability not found in any Negative Emission Technologies, such as Direct Air Carbon Capture and Post-combustion Carbon Capture. HyBECCS has an annual potential to save CO_2 of 8.49–17.06 $MtCO_2$ annually for Germany by 2030, with the required production costs having to lie within the range of between €4.30 to 10.44/kg [31]. Biochar-enhanced concrete exhibits substantial carbon sequestration potential while strengthening the mechanical properties of the concrete. Biochar accelerates cement hydration and promotes C-S-H gel formation, which diminishes CO_2 emissions in SCMs. LCA showed that the production is carbon-negative, sequestering 59 kg CO_2/tonne, and has economic profit at $35.4 per cubic meter with optimized mixtures [32].

Furthermore, reduced graphene oxide-synthesized graphitic carbon nitride ($g\text{-}C_3N_4$) exhibits superior performance as a negative electrode material in lithium-ion batteries. The composite obtained an outstanding Li-storage capacity of 708.6 mAh/g at 300 cycles, manifesting energy storage performance economically [33]. Optimization of soft carbon electrodes, derived from thermoplastic polymers, through intermediate mechanical treatments has achieved a high initial coulombic efficiency of 82% and energy densities up to 140 Wh/kg [34]. In industrial decarbonization, DSR, integrated with carbon capture technologies (CCT), has managed to achieve remarkable reductions in CO_2 emissions during hydrated lime production. Fully electric DSR kilns operating on renewable energy produced CO_2 emissions cuts as high as 94%, providing carbon-negative outcomes in conjunction with an offset of 149% from natural carbonation [35].

More innovations in waste pyrolysis gas-derived pyrolytic carbon production could be promising for sodium-ion batteries, as the material shows remarkable performance superior to that of commercial hard carbon, holding as much as 105 mAh/g after 2000 cycles owing to optimized defect structures and pore designs [36]. Biochar is now also used in geopolymer composites as part of road subgrades based on fly ash (FA) and slag (S) stabilizers. These composites reached unconfined compressive strengths over 700 kPa, and with cost reductions, were carbon-negative [37]. Biochar admixtures engineered for cementitious materials increase strength, reduce permeability and shrinkage cracking resistance with chemical attacks; 1–2% by weight replacement levels are optimum performance [38]. Finally, a biorefinery process based on biomass pyrolysis efficiently coproducts hydrogen and hard carbon anodes for sodium-ion batteries with 100% carbon utilization efficiency. It sequesters 891 kg of CO_2 per ton of feedstock, with a payback period of about two years and is therefore a commercially attractive solution for affordable energy and green materials [39].

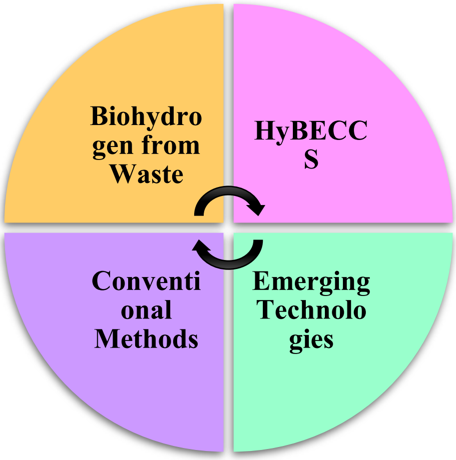

Fig. 6: Comparative Analysis of Hydrogen Production Methods

Carbon-negative hydrogen production [31], biochar-based construction materials [32], [37], [38], energy storage solutions [33], [34], [36], and industrial decarbonization [35], [39] offer promising avenues for carbon-neutrality that go hand-in-hand with economic and environmental sustainability. Novel carbon-negative materials, such as carbon-negative concrete, bio-based alternatives, and nanotechnology, are significant steps toward addressing global carbon emission reduction. Beyond the environmental challenges, the materials open up avenues to sustainable development in different industries, innovative solutions that balance ecological preservation with industrial growth. Fig. 6 compares the hydrogen production methods as per economic viability as well as CO_2 capture efficiency. According to it, four quadrants have been created, i.e., Biohydrogen from Waste has a relatively high economic viability but negligible CO_2 capture efficiency, while HyBECCS provides both aspects with high economic viability as well as high CO_2 capture efficiency. On the other hand, Conventional Methods have low economic viability and low CO_2 capture efficiency, while Emerging Technologies have high CO_2 capture efficiency but low economic viability. This analysis shows the strengths and limitations of each method, with HyBECCS being a potential sustainable and efficient hydrogen production method.

Table 2: Advancements in Carbon-Negative Materials for Composition Findings and Applications.

Ref. No.	**Carbon-Negative Materials**	**Material Composition**	**Key Findings**	**Efficiency**	**Cost Effectiveness**	**Parameters Included**	**Technique/ Approach Used**
31	Carbon-negative Hydrogen (HyBECCS)	Biohydrogen + Carbon Capture and Storage (CCS)	Net-negative hydrogen production with savings of 8.49-17.06 MtCO2 by 2030.	Higher CO2 capture rate than BECCS technologies.	Production cost: 4.30 €-10.44€/kg for market competitiveness.	CO2 savings, economic assessment, energy systems.	Biotechnological/ thermochemical processes with CO2 capture.
32	Biochar-augmented Concrete	Biochar + Supplementary Cementitious Materials (SCMs)	Carbon-negative concrete with 59 kg CO2 sequestered per tonne.	Enhanced hydration and mechanical strength.	Overall profit: $35.4/m3 with LCA benefits.	CO2 sequestration, strength, cost-benefit analysis.	Biochar addition to concrete + SCM incorporation.
33	rGO-g-C3N4 Composite	Graphitic Carbon Nitride + Reduced Graphene Oxide	High lithium storage capacity up to 708.6 mAh/g.	Maintains performance after 10,000 cycles at 15 A/g.	Low-cost electrode preparation.	Electrochemical performance, lithium-ion mobility.	In-situ synthesis method for composite preparation.
34	Soft Carbon Electrode	Thermoplastic Polymer-derived Soft Carbon	Achieved 82% initial coulombic efficiency and 200 mAh/g capacity.	High-rate capability and energy density (140 Wh/kg).	Optimized production through mechanical treatment.	Coulombic efficiency, energy density, and rate capability.	Mechanical treatment during intermediate carbonization.

35	Decarbonized Lime (DSR Kilns)	Hydrated Lime + Renewable Energy + CCS	149% CO2 reduction with fully electrified DSR kilns.	94% emission decrease compared to conventional production.	26% carbon tax reduction enhances economic viability.	CO2 reduction, environmental impact, life-cycle assessment.	Direct Separation Reactors with carbon capture.
36	Pyrolytic Carbon	Waste Pyrolysis Gas-derived Carbon	Improved sodium storage capacity up to 105 mAh/g after 2000 cycles.	Enhanced pore structure for high performance.	Uses waste gas for economical carbon production.	Cycling performance, pore optimization, energy density.	Pyrolysis + post-treatment for pore design.
37	Geopolymer Stabilized Biochar	Olive Stone Biochar + Fly Ash + Slag	Achieved UCS values exceeding 700 kPa for road subgrade materials.	Improved dynamic strength and reduced pavement thickness.	Comparable cost to natural aggregates.	UCS, curing time, temperature, and CBR test.	Geopolymer stabilization with biochar incorporation.
38	Biochar-Cement Composite	Biochar + Cement (1-2 wt%)	Enhanced durability, reduced permeability, and sulfate resistance.	Optimal replacement achieved with 5% wt biochar.	Carbon-efficient and low-cost solution.	Durability, permeability, and hydration characteristics.	Biochar admixture in cementitious applications.
39	Biocarbon + Hard Carbon (HC)	Biomass Pyrolysis Residue + Catalyst (NiAlO)	Co-production of H2 and battery-grade hard carbon.	High energy density (263 Wh/kg) and ICE of 89%.	Payback period of ~2 years; highly profitable process.	Carbon utilization, H2 production, LCA, and economic analysis.	Biorefinery process with tandem catalysts.

6 Life Cycle Assessment and Applications of Carbon-Negative Materials

Since material life cycle assessment (LCA) is a crucial piece of information for understanding what environmental impact carbon-negative materials do pose towards carbon sequestration, and because the LCA methodology calls upon comprehensive measurements of carbon footprints made throughout the entire life-cycle that involves production, use, and end-of-life for the materials, the material will be compared between its carbon-negative counterparts and non-negative materials. These materials show significant net carbon sequestration through integrating carbon capture and resource-efficient processes, thus making them a good solution for mitigating climate change [40].

Carbon-negative materials serve various industries in attaining sustainability and carbon neutrality. Materials, such as biochar-augmented concrete and geopolymer composites, enhance strength but sequester carbon within construction and infrastructure activities. In agriculture, biochar has improved the fertility status of soil, its water-retaining and nutrient-supplying capacities, resulting in sustainable agriculture practices [41]. Energy applications in renewable sources will feature carbon-based electrodes that contribute to better energy storage and carbon capture technologies in productions involving biohydrogen-generating systems. Further, carbon-negative solutions are implemented in consumer goods and packaging industries, where bio-based polymers and composites are used as sustainable substitutes for traditional plastics, reducing waste and emissions. Carbon-negative materials provide a path toward sustainable development and long-term carbon neutrality by coupling rigorous life cycle assessments with widespread industrial applications, thereby addressing global environmental challenges while fostering economic and technological innovation [42].

A study on food waste-based bioethanol production has shown potential to be carbon-negative for use as a vehicle fuel. An integrated hybrid framework combining process simulation, life cycle assessment, and SCN optimization was used in the study to reveal energy efficiency at 16.2% for AD and biorefinery processes. The LCA results revealed a 14.1% decrease in global warming impacts relative to conventional gasoline-fuel vehicles, reaching up to -1.29 kg CO_2/gal of bioethanol in policy-driven scenarios for 2030 [43]. Catalytic pyrolysis using waste-based catalysts, such as Alumina hydroxide nanoparticles (AHNP), was found to be an eco-friendly and cost-effective one. Recycling biochar as a substitute for coal gave higher environmental benefits, where about 0.031 kg CO_2 equivalent could be saved, while the reuse of biochar decreases the cost of operation. The data obtained were reliable since very low uncertainties (<10%) were confirmed by Monte Carlo analysis, and this was the reason why pyrolytic biofuels could be considered as another alternative to petroleum-derived fuel [44]. Parallelly, DAC technologies were evaluated for carbon removal. The TSA and HT-Aq solutions were considered for the comparison. In all the environmental categories, TSA DAC performed better than HT-Aq. It has a net carbon removal of 86% whereas that of HT-Aq was at 73%. However, it used considerable renewable energy and material consumption [45].

Carbon capture potential using steel slag-based aggregates and blocks was found promising. Emissions from CO_2 produced accounted for the major proportion, even though carbonation curing obtained carbon negativity. Sensitivity analyses revealed that long transportation distances and diesel consumption reversed the carbon benefits, calling for energy-efficient processes like horizontal roller milling for saving energy [46]. In like manner, a review of biomass pyrolysis presented that it could generate biochar, bio-oil, and syngas, and while sequestering up to 2.74 tons of CO_2 per ton of biochar. Pyrolysis methods have affected the yield of the product. Biochar applications also presented potential for the removal of atmospheric CO_2, at the rate of 2.75 gigatons yearly [47].

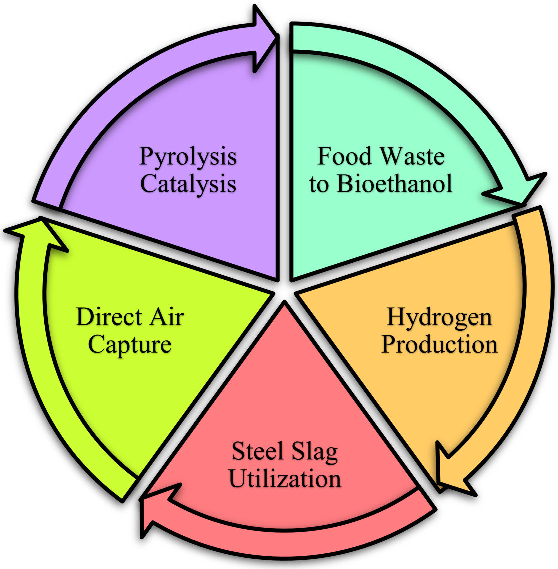

Fig. 7. Carbon – Negative Solutions

In wastewater treatment, through a biochar-integrated reactive filtration (RF) system that includes iron-ozone catalytic oxidation, carbon negative performance was achieved with –1.41 kg CO_2 e/m^3, 90–99% efficiency in removing phosphorus and micropollutant removal. Techno-economic analysis showed that scaling up reduces the cost of treatment to \$0.08/m^3, making it a plausible carbon-negative water treatment standard 48. Lastly, waste concrete powder (WCP) was assessed for recycling into carbonated compacts and as a cement substitute. The best carbonation time reached a sequestration of 42.7 kg CO_2/tonne, while the substitution of 20% of Cement with uncarbonated WCP resulted in a reduction of GWP by 16%, which is in support of its role in carbon footprint reduction [49]. Furthermore, a study on biomass-to-hydrogen pathways with ammonia storage resulted in a negative GWP of -7.55 kg CO_2 eq, which highlights its feasibility in circular economies and renewable fuel systems [50].

The Fig. 7 shown is a circular depiction of five main strategies that show how carbon emissions can be brought down. These include the following: Food Waste to Bioethanol, Hydrogen Production, Steel Slag Utilization, Direct Air Capture, and Pyrolysis Catalysis. All of the above have been represented here through lines where a point is being made through its seamless movement of being continuous in carbon negativity achievement. The circle represents an idea of being integrated and cycle-based. This calls for a multiplicity of technological and resource management strategies to effectively fight the phenomenon of climate change.

Table 3. Comparative Analysis of Carbon-Negative Materials and Technologies

Ref. no.	**Carbon Negative Materials**	**Material Composition**	**Key Findings**	**Efficiency**	**Cost Effectiveness**	**Parameters Included**	**Technique Approach Used**
43	FW-based Bioethanol	Food Waste via Anaerobic Digestion and Biorefinery	Carbon-negative impact: -5.58 kg CO_2/gal bioethanol. 14.1% lower GWP than the conventional scenario.	Overall energy efficiency of 16.2%	Optimized GW impact in SCN; scenarios: -0.69 to -1.29 kg CO_2/gal.	LCA, SCN optimization, well-to-wheel impact	Process simulation, LCA, SCN optimization
44	Catalytic Pyrolysis Biofuel	Waste AHNP-derived catalysts, NCGs, biochar	Max negative emissions of ~0.031 kg CO_2 eq with biochar coal credits.	Higher environmental benefits with Ni/Al catalysts.	Biochar recycling reduces operating costs; Monte Carlo reliability <10%.	LCA, Monte Carlo uncertainty, operating cost	Catalytic/non-catalytic pyrolysis with coproduct recycling
45	Direct Air Capture (DAC)	TSA and HT-Aq DAC technologies	TSA DAC achieves 86% net carbon removal; HT-Aq DAC achieves 73%.	TSA DAC outperforms HT-Aq DAC by 1.3-10x in impact categories.	Material consumption ~5x higher, but energy-efficient.	LCA, renewable energy input, material consumption	Temperature swing adsorption, aqueous solution DAC
46	Steel Slag Blocks/Aggregates	Steel slag + Carbonation curing	Achieves carbon negativity; CO_2 emissions from production: 12-50%.	The horizontal roller mill is determined as the most efficient.	Transport distances impact GWP and cost.	LCA, sensitivity analysis, GWP, grinding efficiency	Carbonation curing, an efficient milling process
47	Algal and Lignocellulosic Biochar	Pyrolysis of algae and lignocellul	Sequesters 2.74 tons CO_2/ton biochar; annual potential: 0.2-2.75 Gt CO_2.	Product yields: biochar (10-41%), oil (9-40%), syngas (11-28%).	Economically feasible with carbon removal credits.	LCA, product yield, carbon sequestration	Pyrolysis with product upgrading techniques

		osic biomass					
48	Biochar-Integrated Reactive Filtration (RF)	Biochar + Iron-ozone catalytic oxidation	Carbon-negative: -1.21 to -1.41 kg CO_2 e/m³; 90-99% phosphorus removal.	Micropollutant destruction >90%; phosphorus recovery.	Treatment cost: \$0.08-0.18/m³ with carbon neutrality.	LCA, TEA, water treatment efficiency	Reactive filtration, catalytic oxidation
49	Waste Concrete Powder (WCP)	Carbonated and uncarbonated WCP	Optimal carbonation: 42.7 kg CO_2/ton; GWP: -4.22 kg CO_2 e.	16% GWP reduction by replacing 20% cement with WCP.	Electricity supply influences carbon footprint.	LCA, GWP, optimal carbonation time	Carbonation curing, cement replacement
50	Biomass-based Hydrogen (Chemical Looping)	Hydrogen stored as ammonia, methane, or methanol	Negative GWP: -7.55 kg CO_2 eq with ammonia storage.	Higher performance with chemical looping technology.	The biomass route has lower GWP compared to power-based routes.	LCA, GWP, energy efficiency	Chemical looping technology for hydrogen production

7 Conclusions

Carbon-negative materials present a transformative opportunity in the global effort to mitigate climate change while advancing sustainability across construction, agriculture, and energy sectors. This review has highlighted the significant potential of paradigmatic materials like biochar and hempcrete, along with emerging alternatives such as bioplastics, algae-based products, and carbon-infused concrete, for sequestering atmospheric CO_2 and enhancing resource efficiency. Key findings demonstrate substantial carbon sequestration capacities, with hempcrete sequestering up to 38.4% of its initial manufacturing emissions and biochar-augmented concrete achieving net sequestration of approximately 59 kg CO_2 per tonne. Furthermore, these materials offer viable mechanical and functional properties, such as the flexural strength of biochar-composites exceeding 5.5 MPa and the excellent thermal insulation of hempcrete (U-value of 0.27 $W/(m^2 \cdot K)$). Despite this promise, widespread adoption is impeded by persistent challenges, including high production costs, scalability limitations of feedstock supply chains, and a lack of comprehensive regulatory frameworks and standardized building codes. Life cycle and techno-economic assessments confirm the environmental benefits and long-term economic viability of these technologies, but also underscore the sensitivity of their net carbon negativity to system boundaries and local conditions. To translate potential into practice, specific research gaps and actionable recommendations must be addressed. Critical research gaps include the need for standardized LCA protocols specific to carbon-negative materials to ensure consistent and comparable environmental claims; further investigation into the long-term durability and structural performance of biochar and hempcrete composites under varied environmental conditions; and the development of efficient, large-scale logistics for sustainable feedstock procurement and consistent material quality. Scaling these innovations requires a multifaceted approach. First, policymakers should establish supportive regulatory environments, including integrating carbon-negative materials into national building codes, creating carbon credit mechanisms, and implementing green public procurement policies. Second, increased public and private investment in R&D is crucial to drive down costs through process optimization, such as advancing pyrolysis techniques and binder formulations. Third, fostering strong industry-academia-government partnerships is essential to pilot commercial-scale applications, develop integrated supply chains, and embed these materials within circular economy models, as demonstrated in biorefinery approaches. By systematically addressing these research gaps and heeding these recommendations, carbon-negative materials can transition from niche innovations to mainstream solutions, playing a pivotal role in achieving a sustainable, carbon-neutral future.

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