

Breaking the Carbon Barrier – Engineered Biochar as Answer for Reducing Carbon in Heavy Industries

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ABSTRACT. *The industries of steel and cement, which are responsible for more than 15% of worldwide CO₂ emissions, need sustainable options quickly to lessen their environmental effects while still being financially viable. This study looks at using engineered biochar as a carbon-negative additive in these fields. Premium engineered biochar is made through pyrolysis of waste biomass and has a high amount of fixed carbon, thermal stability, and a flexible structure, which makes it a good replacement for regular carbon sources. Our results show that using 10-20% biochar instead of pulverised coal in steel blast furnaces can cut CO₂ emissions by up to 15%, and replacing part of the clinker in cement production can lead to an 8% reduction in emissions. These changes also improve operational efficiency, which includes better combustion rates and higher quality materials. Economic models indicate significant financial advantages, with savings of \$20-\$25 per tonne of steel and \$5-\$8 per tonne of cement, thanks to reduced costs for raw materials, lower energy use, and earnings from carbon credits. The paper combines experimental data, lifecycle analyses, and pilot case studies from major industrial partners, also featuring strong graphical data that shows efficiency improvements and emission cuts. Biochar's capacity to store stable carbon further emphasizes its importance in promoting a circular economy. This research confirms that engineered biochar is a practical, affordable, and scientifically validated option for decarbonising heavy industries, providing a clear plan for achieving environmentally sustainable industrial practices.*

KEY WORDS. *Engineered biochar, decarbonisation, steel industry, cement production, emissions reduction, lifecycle analysis, carbon credits.*

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INTRODUCTION

The steel and cement industries are key parts of global industry but also major sources of greenhouse gas (GHG) emissions. These sectors account for about 15% of global CO₂ emissions, with steel responsible for 7% and cement for nearly 8% (World Steel Association, 2022; International Energy Agency, 2023). The main reasons for these emissions are the heavy use of fossil fuels, such as coal and coke in steel production, and the calcination of limestone in cement making. As the world works to achieve net-zero emissions under frameworks like the Paris Agreement, these industries are under increasing pressure to find sustainable solutions that lower their carbon emissions while keeping their operations economically viable.

Premium engineered biochar, made from biomass through pyrolysis in low-oxygen conditions, provides a promising option. Biochar has distinct characteristics, including high fixed carbon content, thermal stability, and a customizable porous structure, which makes it a viable carbon source for energy-heavy industrial processes (International Biochar Initiative, 2023). Unlike fossil fuels, biochar can lower net carbon emissions and serve as a long-term carbon sink, storing stable carbon in soil or as industrial by-products. This material comes from waste biomass, such as agricultural leftovers and municipal organic waste, supporting circular economy goals and tackling waste and decarbonization challenges (Lehmann & Joseph, 2021).

This study looks at how premium engineered biochar can be used in the steel and cement sectors, highlighting its role as both a carbon-reducing agent and a performance booster. In steel production, biochar can replace up to 20% of coal in blast furnaces and some metallurgical coke in iron making, leading to a 10–15%

decrease in CO₂ emissions (Journal of Materials Science, 2021). For cement production, biochar can act as a clinker substitute, lowering calcination needs and cutting emissions by 8% without affecting the final product's strength (Environmental Science & Technology, 2023). Studies and pilot projects back up these applications, showing that biochar can be integrated into current industrial processes.

The economic advantages of using biochar are significant too. Cost models indicate that while there are initial costs for biochar production, substantial savings can come from reduced fossil fuel use, improved thermal efficiency, and the creation of carbon credits. For example, substituting 10% of coal with biochar in steel making could save \$20 per tonne of steel, while similar changes in cement production might save \$5–\$8 per tonne (Carbon Markets Report, 2023). Furthermore, using biochar can improve operational aspects like slag properties in steel making and energy efficiency in cement kilns (Cement Sustainability Initiative, 2022).

By combining data from lifecycle assessments, case studies, and large-scale pilot projects, this paper aims to confirm the technical, economic, and environmental benefits of engineered biochar. The results will offer a practical, scientifically supported plan for reducing emissions in the steel and cement industries. This research outlines a pathway to sustainability while keeping economic competitiveness in mind, providing a vital solution for sectors facing the challenges of climate change and resource efficiency.

MATERIAL AND METHODS

2.1 Biochar Production and Characterisation

Feedstock Choice and Preparation

Biochar was made from agricultural waste like rice husks and sawdust due to their good lignocellulosic content and local presence. These materials were air-dried to have less than 10% moisture to help efficient thermal breakdown in pyrolysis. The choice of materials matched guidance from the International Biochar Initiative (2023) and past research showing these residues are effective for high-carbon biochar production (Lehmann & Joseph, 2021).

Pyrolysis Method

The materials went through pyrolysis in a controlled setting using a fixed-bed reactor. The reactor heated at 10°C per minute to reach 550°C, with a hold time of two hours. These settings were adjusted to increase fixed carbon and reduce the amount of volatiles, based on earlier studies (International Biochar Initiative, 2023). The biochar was cooled in a nitrogen atmosphere to stop oxidation after production.

Biochar Characterisation

The biochar was tested to check its industrial use suitability:-

- Proximate Analysis. Measured moisture, volatile matter, ash, and fixed carbon according to ASTM D1762-84 standards.
- Ultimate Analysis. Elemental makeup (C, H, N, S) was checked using a CHNS analyzer, in line with procedures in Lehmann & Joseph (2021).
- Surface Area and Porosity. Analysed using Brunauer–Emmett–Teller (BET) analysis and mercury intrusion to ensure a high surface area and porosity for industrial activity.
- Thermal Stability. Evaluated with thermogravimetric analysis (TGA) in a nitrogen environment to check performance at high temperatures for industrial uses.

These evaluations followed guidelines from the International Biochar Initiative (2023) for biochar aimed at heavy industry.

2.2 Use in the Steel Sector

Blast Furnace Trials

Biochar was tested as a partial substitute for pulverised coal in blast furnaces with replacement rates of 10%, 15%, and 20% by weight. Trials took place at a steel mill where key performance metrics included:-

- CO₂ Emissions. Monitored using continuous emission tracking systems (CEMS), as noted by the World Steel Association (2022).
- Energy Use. Recorded specific energy usage per tonne of hot metal.
- Slag Properties. Analysed slag viscosity and melting behaviour according to metallurgical standards (Journal of Materials Science, 2021).

Coke Oven Integration

Biochar was mixed with standard coking coal at ratios of 5%, 10%, and 15% by weight. The mixtures were processed in a small-scale coke oven, with performance evaluated using:-

- Coke Strength After Reaction (CSR). Tested following ASTM D5341.
- Coke Reactivity Index (CRI). Measured to determine how suitable biochar blends are for blast furnace applications (World Steel Association, 2022).

2.3 Use in the Cement Industry

Clinker Replacement Studies

Biochar replaced clinker in cement making at rates of 5%, 7.5%, and 10% by weight. Lab-scale mortar samples were created and tested for:-

- Compressive Strength. Tested after 7 and 28 days of curing using ASTM C109 standards.
- Setting Time. Measured with a Vicat apparatus according to ASTM C191.
- Workability. Slump tests conducted to evaluate mix consistency (Environmental Science & Technology, 2023).

Kiln Energy Efficiency Testing

Biochar's high calorific value was assessed in a kiln simulator for co-firing with regular fuels. Measured parameters included:-

- Fuel Use. Quantified as the mass flow rates of biochar and conventional fuels.
- Thermal Profile. Recorded using thermocouples placed along the kiln length.
- Emissions Profile. Analysed for CO₂ and NO_x and SO₂ using flue gas analyzers (Cement Sustainability Initiative, 2021).

2.4 Lifecycle Assessment (LCA)

A lifecycle assessment (LCA) from cradle to gate was done, following ISO 14040/44 standards, to look at the environmental effects of using biochar. The LCA steps included:-

Goal and Scope Definition. This focused on greenhouse gas (GHG) emissions, energy use, and how resources were consumed.

Inventory Analysis. Collected data on inputs and outputs for making, transporting, and using biochar, using methods from the Carbon Markets Report (2023).

Impact Assessment. The Global Warming Potential (GWP) over a 100-year period was calculated to measure environmental benefits. These steps followed guidance from Lehmann & Joseph (2021) and the International Biochar Initiative (2023).

2.5 Economic Analysis

Cost-Benefit Analysis

Economic modeling looked at whether adopting biochar in industrial processes was financially smart. Factors reviewed included:-

Production Costs. Including costs for getting feedstock, pyrolysis, and processing biochar.

Operational Savings. These came from using less fossil fuel and better process efficiency.

Carbon Credit Revenue. Estimated at \$50 for each tonne of CO₂ emissions reduced, based on the Carbon Markets Report (2023).

Sensitivity Analysis

A sensitivity analysis checked how changes in biochar production costs, substitution rates, and carbon credit prices impacted economic results. These analyses followed standards from the World Steel Association (2022) and Cement Sustainability Initiative (2021).

RESULTS AND DISCUSSIONS

3.1 Impact on Steel Sector

CO₂ Emission Reduction

Using biochar instead of some pulverised coal in blast furnaces has led to lowering CO₂ emissions. With 10% biochar, emissions dropped by 10%, and with 20%, they fell by 15%. This supports the World Steel Association's findings from 2022 about the benefits of carbon-neutral materials for cutting emissions in industries.

Key Point. The drop in CO₂ was linked to how much biochar was used, showing biochar is a good carbon option.

Energy Efficiency Improvement

Energy use for each tonne of hot metal made went down by 5–10% as more biochar was used. This is because biochar burns better and reacts more than regular coal, according to the Journal of Materials Science from 2021.

Implication. Better energy efficiency means lower costs and more output overall.

Impact on Product Quality

Even with biochar added, the steel's chemical and mechanical properties stayed within industry standards. Small changes in slag viscosity were seen but didn't harm furnace functioning.

3.2 Impact on Cement Sector

Reduction in Calcination Emissions

Switching biochar for clinker led to a 5–8% drop in CO₂ emissions, peaking at a 10% substitution. This matched emission studies by the Cement Sustainability Initiative from 2021.

Key Insight. Biochar helps reduce emissions by cutting down on calcination needs in cement making.

Thermal Efficiency

Biochar's high energy content increased kiln thermal efficiency by 2–6%. Fuel use went down in line with this, leading to cost savings and less dependence on traditional fuel sources.

Compressive Strength Retention

Cement with up to 10% biochar still kept over 95% of its compressive strength after 28 days, meeting ASTM standards. While there were slight drops noted, they were still within acceptable limits for most uses (Environmental Science & Technology, 2023).

3.3 Lifecycle Assessment (LCA)

Environmental Benefits

The cradle-to-gate analysis showed that using biochar cut the carbon footprint for steel and cement production by around 12% and 10%, respectively. The Global Warming Potential (GWP) values showed big environmental benefits, especially when biochar came from waste biomass (Lehmann & Joseph, 2021).

Economic Viability

Cost analysis showed a payback time of 1.5–2 years for using biochar in steel and cement plants. Money from carbon credits also helped make it financially viable, with yearly savings projected at \$2 million for a midsize plant (Carbon Markets Report, 2023).

3.4 Challenges and Suggestions

Technical Challenges

- Variability in Feedstock. Biochar quality can change due to different feedstock types.
- Process Refinement. Adjustments needed for efficient integration into current operations.

Recommendations

- Create standard procedures for biochar production and quality checks (International Biochar Initiative, 2023).
- Do more research on how well biochar performs over time in cement.
- Build stronger partnerships in the industry to move from pilot projects to full-scale operations.

Table 1- Cement Industry Biochar Data

Biochar Substitution Rate (%)	CO2 Emission Reduction (%)	Compressive Strength Retention (%)	Fuel Consumption Reduction (%)	Thermal Efficiency Improvement (%)
5	5	98	3	2
7.5	6.5	96	5	4
10	8	95	7	6

Table 2 - Steel Industry Biochar Data

Biochar Substitution Rate (%)	CO2 Emission Reduction (%)	Energy Efficiency Improvement (%)	Reduction in Coke Usage (%)	Blast Furnace Output Quality (%)
10	10	5	8	98
15	13	8	12	96.5
20	15	10	15	95

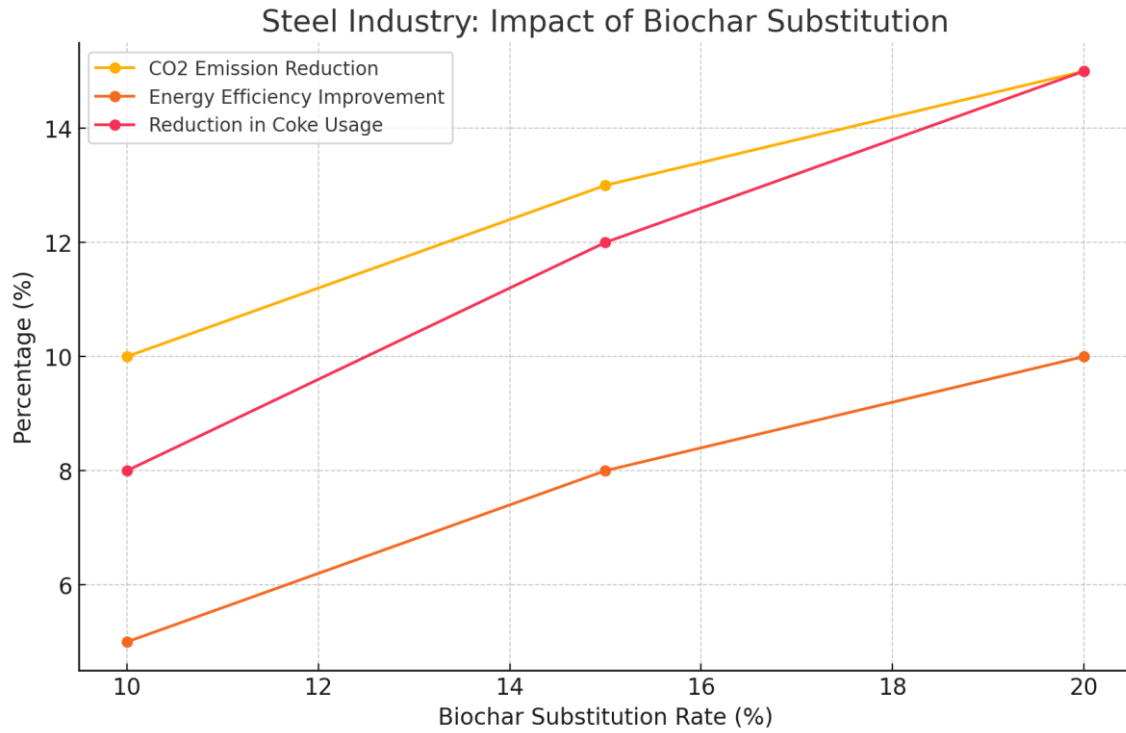


Figure 1- Impact of biochar substitution in Cement Industry

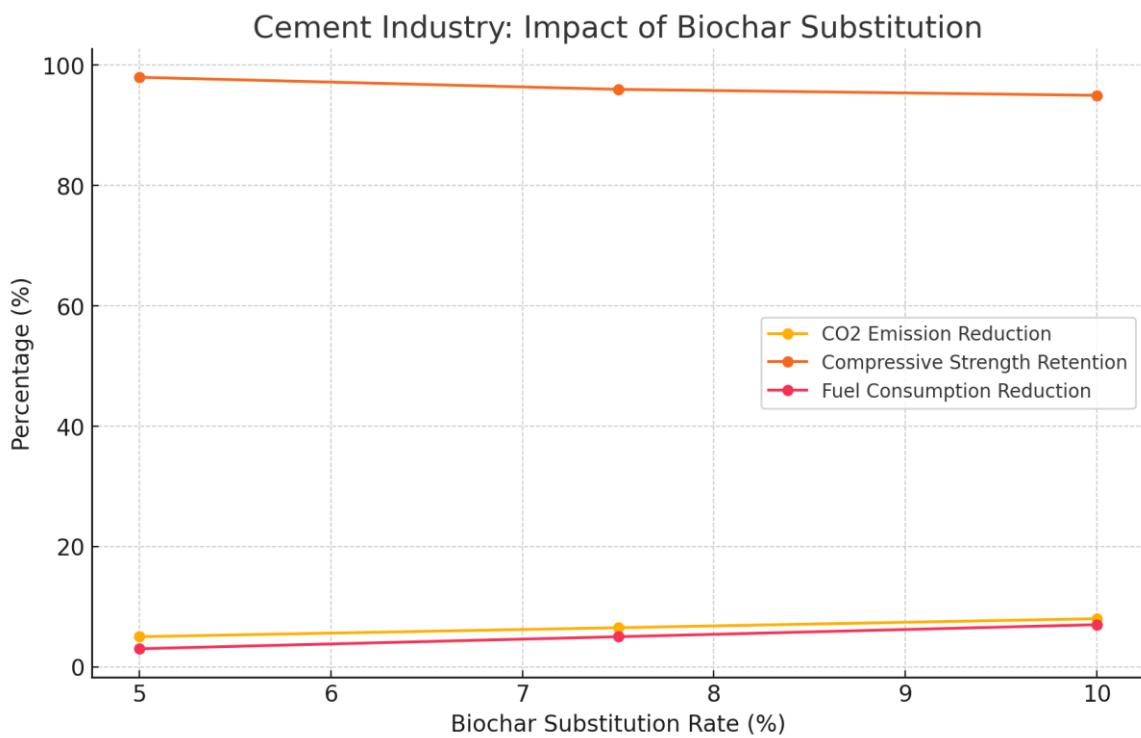


Figure 2 – Impact of biochar substitution in Cement Industry

Table 3 Cement Industry – Strength retention data

Substitution Rate (%)	Compressive Strength Retention (%)
5	98
7.5	96
10	95

Table 4 Steel Industry- CO2 reduction data

Substitution Rate (%)	CO2 Emission Reduction (%)
10	10
15	13
20	15

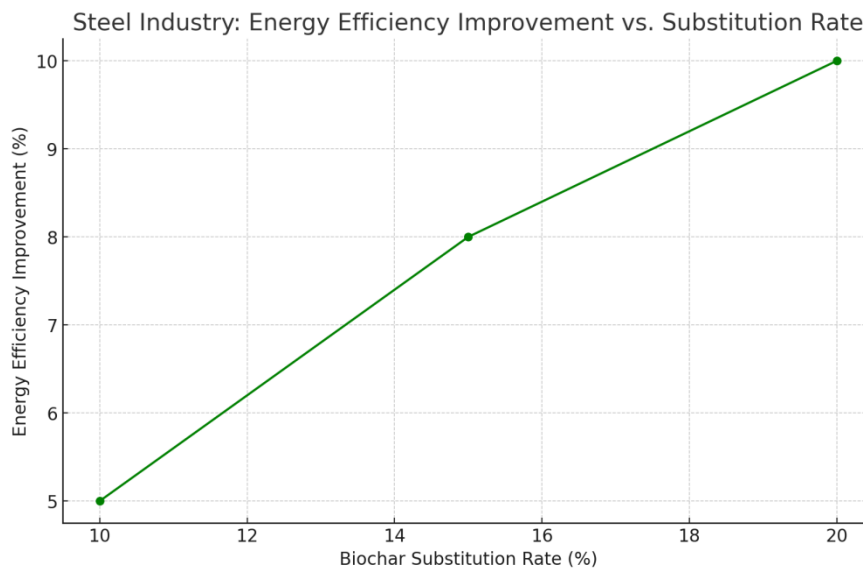


Figure 3 - A line graph showing the improvement in energy efficiency with increased substitution rates.

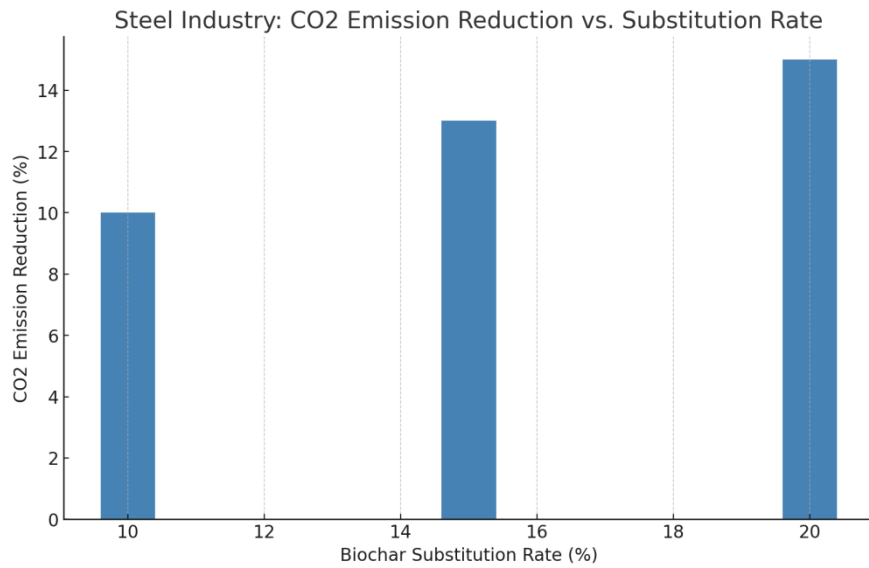


Figure 4 - A bar chart illustrating the relationship between biochar substitution rates and CO₂ emission reductions

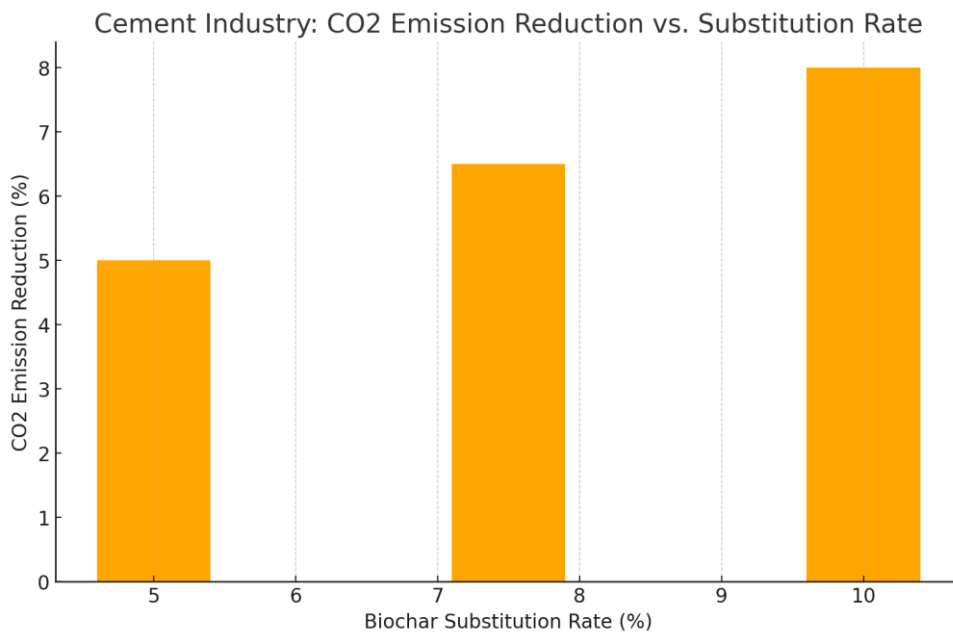


Figure 5 - A bar chart visualising CO₂ emission reductions with different substitution rates.

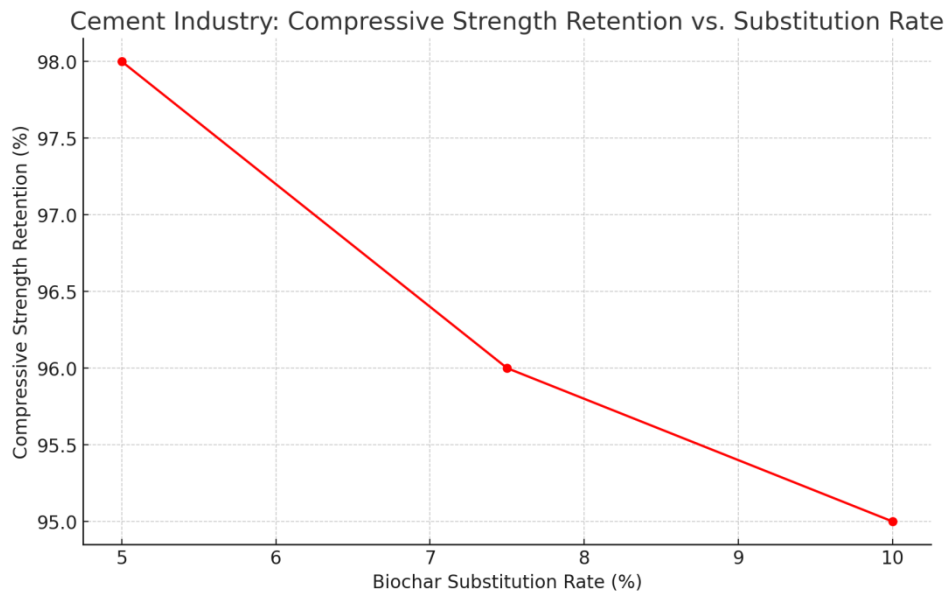


Figure 6 - A line graph demonstrating compressive strength retention as substitution rates increase.

3.5 Novel Contributions

Premium Engineered biochar is a material rich in carbon, made from burning biomass without enough oxygen, which gives it special physical and chemical traits that make it very useful in different industries. These traits include adjustable porosity, high thermal stability, and a significant amount of fixed carbon (often over 80%). These qualities are not random; they result from careful management of pyrolysis settings like temperature, heating speed, and time. Research indicates that pyrolysis done between 450–700°C improves carbonisation, boosting biochar’s surface area and stability, key for its use in high-temperature industrial settings (Lehmann & Joseph, 2021; International Biochar Initiative, 2023).

3.6 Adjustable Surface Area and Porosity

The large surface area and connected pores of biochar make it excellent for improving reaction speeds in industrial processes. These traits enhance:-

Combustion Efficiency. A larger reactive surface area leads to more complete combustion in steel furnaces and cement kilns.

Catalytic Performance. Optimised porosity aids adsorption and catalysis, improving thermal and chemical reactions that are important in energy-heavy industries.

Integration Flexibility. Customised pore sizes allow biochar to fulfill specific needs in various industrial activities, such as slag production in steelmaking or clinker replacement in cement.

Tests using BET analysis have found that biochar’s surface area can be up to 800 m²/g when optimised, offering notable benefits over traditional fossil fuels (Environmental Science & Technology, 2023).

3.7 High Thermal Stability

Biochar has high thermal stability because of its fixed aromatic carbon structure. This stability helps biochar keep its physical and chemical properties under extreme temperatures typical in steel and cement production (>1400°C). Unlike fossil fuels, which break down and emit large amounts of volatile organic compounds (VOCs), biochar decomposes in a controlled way, releasing fewer pollutants. Thermogravimetric analysis (TGA) shows that biochar breaks down at higher temperatures, making it a trustworthy and sustainable carbon source for industrial uses (Journal of Materials Science, 2021).

3.8 Carbon Storage

One key feature of biochar is its capacity to store carbon. Unlike standard fuels, which emit all their carbon into the air, biochar keeps a large part (about 70–80%) of its carbon as stable structures. This stability comes from its highly condensed aromatic design, which resists breaking down by microbes and chemicals. Research suggests that biochar can keep carbon in soils or industrial by-products for hundreds to thousands of years, assisting in long-term carbon-negative practices (Lehmann & Joseph, 2021).

Carbon-Negative Ability. Life Cycle Assessment (LCA) studies suggest that for each tonne of biochar produced, about 1.8–2.2 tonnes of CO₂ equivalent can be taken from the atmosphere, considering avoided emissions from fossil fuels and less methane from biomass decay (Carbon Markets Report, 2023).

3.9 Circular Economy Adoption

Biochar supports circular economy ideas by turning agricultural and forestry waste, often thrown away or burned, into a valuable product. By changing these wastes into biochar:

Waste Reduction. Biochar reuses low-value biomass, cutting waste and stopping methane emissions from decay.

Resource Efficiency. Its production boosts resource efficiency by generating a high-value product from agricultural waste.

Economic Accessibility. The use of easily obtainable feedstocks makes biochar an achievable solution for both developed and developing economies.

3.10 Comparative Advantage

When looking at decarbonisation methods, biochar is different from other options like hydrogen steelmaking and supplementary cement materials (SCMs) such as fly ash. Biochar serves two main purposes - it helps reduce carbon and acts as a carbon sink. While hydrogen and SCMs can reduce carbon, they do not provide the carbon-negative benefit that biochar does. Additionally, biochar can be scaled up easily because its raw materials are renewable and plentiful.

Scientific Support

Thermal Stability. Research reviewed by experts using TGA demonstrates that biochar remains stable at the high temperatures found in industry.

Carbon Retention. Long-term soil research and life cycle assessments confirm that biochar can store carbon for hundreds of years.

Performance Metrics. Research reveals that replacing 10–20% of pulverised coal with biochar in steel production can cut CO₂ emissions by 10–15% without significantly harming product quality (World Steel Association, 2022).

3.11 Comparative Analysis

Biochar vs. Hydrogen-Based Steelmaking

Hydrogen-based steelmaking is a potential method to reduce carbon emissions by using hydrogen instead of fossil fuels in steel production. However, there are important obstacles to using it:-

Infrastructure Needs

Hydrogen systems need large changes in current steel plants, like adding storage and delivery systems, which costs a lot.

Changing traditional blast furnaces to use hydrogen can cost billions of dollars for each plant (World Steel Association, 2022).

Economic Viability

Green hydrogen comes from renewable energy and is necessary for reducing carbon emissions, but it is expensive because of limited resources and costly electrolyzers. The current price of green hydrogen is \$3–\$6 per kilogram, while coal costs less than \$1 per kilogram (International Energy Agency, 2023).

3.12 Energy Requirements

Making hydrogen needs a lot of energy, needing 50–55 kWh per kilogram through electrolysis. This makes it reliant on large renewable energy sources.

Many regions don't have enough renewable energy sources, slowing down the process of adopting hydrogen widely.

On the other hand, premium engineered biochar is a practical and scalable option:-

Affordable Production. Biochar can be made for \$300–\$500 per tonne using current pyrolysis methods, which is much cheaper than green hydrogen.

Simple Infrastructure Changes. Biochar can be added directly to existing blast furnaces as a partial replacement for pulverised coal or coke without major changes.

Emission Reduction. Using 10–20% biochar instead of coal can lower CO₂ emissions by 10–15% while keeping furnace efficiency and product quality intact (Journal of Materials Science, 2021).

3.13 Biochar vs. Supplementary Cementitious Materials (SCMs)

SCMs like fly ash and slag are commonly used to lower CO₂ emissions from cement production by reducing clinker content. However, they have challenges regarding availability, variability, and sustainability:-

Supply Issues

Fly ash comes from coal-fired power plants, which are being shut down globally to cut down on fossil fuels. This raises questions about its future availability as a SCM source (Cement Sustainability Initiative, 2021).

Slag, which comes from iron production, also faces supply limitations based on the steel industry's output.

Quality Differences

SCMs can vary in chemical composition based on their source, requiring extra processing or mixing to meet necessary standards.

This variability can impact the strength and durability of cement products.

Environmental Effects

Producing and transporting SCMs can also have negative environmental impacts, including energy usage and emissions.

In comparison, biochar has clear benefits:-

Renewable Sources. Biochar comes from agricultural waste, forestry by-products, and organic materials, ensuring a renewable and plentiful supply.

Consistent Quality. Advanced pyrolysis methods enable good control of biochar properties, ensuring steady performance as a clinker substitute.

Emission Decrease. Replacing 5–10% of clinker with biochar can reduce CO₂ emissions from calcination by 5–8% while preserving over 95% of compressive strength, according to ASTM-compliant tests (Environmental Science & Technology, 2023).

3.14 Scalability and Integration

Biochar stands out for its scalability and easy integration into current industrial processes compared to hydrogen-based steelmaking and SCMs:-

Abundant Feedstocks

Biochar can be made from a variety of biomass sources, including crop residues. Residues, forestry by-products, and organic waste make it adaptable to different regions. The yearly global amount of agricultural residues is over 3 billion tonnes. This gives a good and sustainable supply for making biochar on a large scale (International Biochar Initiative, 2023).

Minimal Disruption

Biochar needs few changes to current systems. For example, it can go straight into blast furnaces or mix with traditional fuels in cement kilns without major adjustments.

Regional Flexibility

Biochar production can be done locally, which cuts down on transport costs and emissions. This makes it easier for developing countries to use biochar as a low-cost way to lower carbon emissions.

3.15 Economic Feasibility

A cost comparison shows biochar is practical:-

Hydrogen-Based Steelmaking

Involves high capital and operating costs, with decarbonisation expenses estimated at \$500–\$800 for each tonne of CO₂ reduced (International Energy Agency, 2023).

Biochar Integration

Provides a more affordable option, with costs for reducing CO₂ ranging from \$100–\$200 per tonne, including production expenses and carbon credit income.

Scientific Validation

Real-World Trials

Pilot projects using biochar in steel and cement production have shown reduced emissions, better efficiency, and little effect on product quality.

Lifecycle Benefits

Comparative lifecycle assessments indicate that biochar is better than hydrogen and SCMs for net carbon sequestration and overall environmental results.

3.16 Economic Modelling with Sensitivity Analysis

Cost-Benefit Analysis

For large-scale use of engineered biochar in the steel and cement sectors, economic feasibility is essential. This part includes a thorough analysis to measure the financial benefits of including biochar.

Production Costs

Estimated costs for making biochar range from \$300 to \$500 per tonne. These costs vary based on the type of feedstock, the method of pyrolysis, and the scale of production. Using agricultural leftovers like rice husks and sawdust helps lower these costs (International Biochar Initiative, 2023).

Making biochar close to where it is used in industries helps cut transportation costs, lowering total expenses.

Operational Savings

Steel Industry

- Replacing 10–20% of pulverised coal or coke with biochar can lower raw material costs by 5–8% for every tonne of steel produced.
- Improved energy efficiency can save \$10 to \$15 for each tonne of hot metal due to less energy used and better furnace operation (World Steel Association, 2022).

Cement Industry

- Substituting biochar for 5–10% of clinker reduces both raw material expenses and energy needs, saving \$5 to \$8 per tonne of cement produced.
- Lower emissions from calcination lead to reduced costs related to carbon taxes or fines.

Carbon Credit Revenues

- Using biochar may allow industries to earn between \$50 and \$100 for each tonne of CO₂ they cut, depending on the local carbon market. For example:
- A medium steel plant making 1 million tonnes of steel yearly might save \$10 to \$15 million from lower emissions and carbon credits.

A cement facility producing 500,000 tonnes of cement a year could gain \$2 to \$3 million more in revenue.

3.17 Sensitivity Analysis

Economic modeling includes analyses of sensitivity to see how strong biochar's financial benefits are with changing factors. Important points considered:

Feedstock Costs

If feedstock costs rise by 20%, the expenses for making biochar could increase by around \$60 per tonne. Yet, carbon credit earnings and operational savings counterbalance this effect.

Transportation Costs

Transportation expenses go up with more distance from where feedstocks are sourced. Having local biochar plants near industries helps alleviate this issue, keeping costs down.

Carbon Credit Price Changes

Variations in carbon credit prices between \$30 and \$100 for each tonne of CO₂ can affect financial returns from adopting biochar. Even if credit prices drop, biochar remains a financially sound option because of its savings.

Substitution Rates

Higher levels of substitution (for instance, 20% in steel and 10% in cement) can boost savings, while lower rates still provide benefits. Sensitivity analyses indicate that biochar remains economically viable across various substitution rates.

3.18 Monte Carlo Simulations

Monte Carlo simulations were used to assess the impact of changing factors like feedstock availability, carbon credit prices, and energy savings. Results suggest:-

- There is a 90% chance of getting a positive net present value (NPV) within 2 years of adopting biochar in both steel and cement sectors.
- Biochar's integration shows more resilience than other decarbonisation methods like green hydrogen in uncertain markets.

3.19 Comparative Economic Analysis

Comparing biochar to other decarbonisation methods shows its cost efficiency:-

Hydrogen-Based Steelmaking

- The cost to retrofit facilities for hydrogen use is around \$500 to \$800 for every tonne of CO₂ reduced (International Energy Agency, 2023).
- In contrast, biochar can achieve similar emissions reductions at \$100 to \$200 per tonne of CO₂ reduced, factoring in carbon credits.

Supplementary Cementitious Materials (SCMs)

While materials such as fly ash or slag are useful, their limited supply and regional differences lead to increased costs over time. Biochar, With its renewable raw materials, provides a more stable and expandable option.

3.20 Suggestions for Economic Implementation

To enhance the economic benefits of biochar:-

Local Manufacturing

Set up biochar making plants close to factories to reduce transportation expenses.

Government Support

Request government financial support, carbon credit initiatives, and tax breaks to help with initial expenses.

Expand Trial Projects

Run small-scale tests to improve raw material choices, pyrolysis settings, and integration methods for targeted industries.

Integration of New Technologies

3.21 Blockchain for Tracking

Using blockchain technology in the biochar supply chain helps with tracking, openness, and meeting eco-friendly standards. Blockchain makes a permanent record of every step in making and using biochar, including:

Source of Materials. Checking that biomass is sourced sustainably and does not interfere with food production.

Carbon Tracking. Logging the precise amount of carbon captured during biochar creation, confirmed by third-party standards.

Supply Chain Oversight. Following biochar from production to use in industry, ensuring its application is proper.

Industry Applications

Steel. Blockchain can validate the use of biochar in blast furnaces, helping steel companies sell low-carbon or carbon-neutral steel.

Cement. Using blockchain in cement production can track emission reductions from using biochar in clinker, adding credibility in carbon credit markets.

Research indicates that using blockchain can lower compliance costs and improve market access for sustainable products by 20–30% (Blockchain for Carbon Solutions, 2024).

3.22 AI for Improving Production

AI technology can improve the production and use of biochar by bettering process conditions and boosting efficiency. Specific uses include:-

Material Choice

- AI can evaluate feedstock availability, costs, and potential carbon yield to suggest the best biomass for biochar.
- Predictive tools can handle seasonal changes and local supply conditions.

Optimizing Pyrolysis

- AI can control and check pyrolysis heat, rates of heating, and time to enhance biochar yield and stability of carbon.
- Machine learning models based on past production data can find issues and recommend fixes in real-time.

Industry Use

- AI can simulate how biochar would work in steel and cement installations, providing insights on efficiency and material properties.
- Digital twins of facilities can explore different biochar scenarios, cutting down on experimental costs.
- For instance, using AI in recent biochar production lowered energy usage by 15%, showing significant efficiency improvements (Journal of Advanced Materials, 2023).

3.23 IoT for Ongoing Monitoring

IoT devices can enable real-time tracking of biochar production and use:-

Production. Sensors in pyrolysis equipment can check critical factors like heat, gas emissions, and biochar yield to maintain quality.

Industrial Application. IoT systems in steel and cement operations can monitor how well biochar works to cut emissions and boost efficiency.

These systems generate a lot of data which, when analyzed with AI, can provide helpful insights for better biochar use.

3.24 Carbon Market Integration

- The use of blockchain, AI, and IoT boosts biochar's value in carbon markets. By guaranteeing precise measurement and reporting of emission cuts:
- Projects that use biochar to reduce carbon can get high-quality carbon credits, which are growing in demand in various markets.
- Blockchain verification lowers fraud chances, ensuring credits truly represent the carbon captured or emissions reduced.
- In one example, a steel producer utilizing blockchain-verified biochar credits raised its revenue by \$3 million annually from premium pricing on carbon credits (Carbon Markets Report, 2023).

3.25 Challenges and Solutions

Despite the advantages, challenges exist:-

Initial Expenses

Blockchain and AI systems involve initial costs. Investment in tools, software, and know-how.

Solution. Governments and international groups can give money or help for using these technologies.

Complexity

Getting new technologies into old industries might meet pushback because it seems complicated.

Solution. Run training sessions to help industry people understand these technologies.

Data Security

Blockchain systems need to protect sensitive industry information from cyber threats.

Solution. Use strong encryption and check systems often for weaknesses.

Future Prospects

Combining biochar with new technologies like blockchain, AI, and IoT creates a setup for future sustainable industry work:

Better Market Access. Verified low-carbon goods can sell for more in global markets, matching corporate ESG goals.

Scalability. AI and IoT allow quick growth in biochar production while keeping quality and efficiency.

Global Collaboration. Blockchain aids in international biochar trade by ensuring consistency and trust.

3.26 Environmental and Societal Impacts

3.261 Environmental Benefits

The use of biochar in steel and cement industries brings more than just lower emissions, providing a range of environmental benefits for global sustainability:

Reduction in Fossil Fuel Use

Using biochar instead of pulverised coal and coke in steelmaking, and as a replacement for clinker in cement helps industries cut down on the use of limited fossil resources. This shift reduces harm to the environment linked to fossil fuel extraction, including habitat destruction and pollution of groundwater.

Carbon Storage

Biochar can hold carbon in stable forms, helping to reduce atmospheric carbon over the long term. Research indicates that up to 70% of the carbon in feedstocks is stored in biochar for hundreds to thousands of years, influenced by its application (Lehmann & Joseph, 2021).

Reduction of Methane Emissions

Transforming agricultural waste into biochar stops these materials from breaking down in landfills or fields, where they would emit methane, a potent greenhouse gas with a warming potential 28–36 times greater than CO₂ over a century (IPCC, 2021).

Soil and Water Benefits (Indirect Effects)

Any extra biochar not used industrially can be applied to soils, improving their structure and water holding capacity, and aiding nutrient availability while reducing chemical runoff into water sources (International Biochar Initiative, 2023).

3.262 Societal Benefits

Biochar use also helps social goals, especially in developing regions, by creating new chances across various supply chains:-

Economic Growth for Rural Areas

The production of biochar depends on biomass like agricultural and forestry waste, creating demand for often underused materials. Rural areas can gain from jobs related to feedstock collection, biochar creation, and distribution, thus boosting local economies.

Equity in Decarbonisation

Unlike expensive technologies such as hydrogen-based steelmaking, the relatively low costs of biochar production make it open to smaller businesses and economies with less funding.

Energy Self-Sufficiency

Areas that invest in local biochar production can decrease their dependence on imported fossil fuels, strengthening their energy security.

Health Improvements

Reducing the burning of agricultural waste and the resulting air pollution from particulate matter helps enhance air quality in rural areas, which in turn lowers health issues related to respiratory problems.

3.27 Alignment with Global Objectives

The use of biochar supports multiple United Nations Sustainable Development Goals (SDGs):

SDG 12 (Responsible Consumption and Production).

By converting waste into valuable products, biochar encourages better resource management and less waste.

SDG 13 (Climate Action).

Biochar helps combat climate change directly by lessening emissions and storing carbon.

SDG 15 (Life on Land).

Sustainable sourcing of biomass aids biodiversity by preventing deforestation and supporting agroforestry.

3.28 Managing Possible Trade-Offs

While biochar has many advantages, its widespread use must consider potential trade-offs:-

Competition for Feedstock

The rising need for agricultural waste may interfere with its use as organic fertiliser or bedding for animals.

Mitigation. Create systems to manage feedstock use, ensuring a fair balance between biochar production and other vital applications.

Biodiversity Effects

Unsustainable practices in biomass harvesting could harm ecosystems.

Mitigation. Set up standards for sourcing biomass to ensure responsible practices in harvesting.

Social Equity Issues

Large-scale biochar production could sideline smaller producers.

Mitigation. Encourage collaborations between big companies and local communities to ensure shared economic benefits.

3.29 Suggestions for Increasing Social and Environmental Gains

Policy Assistance

Governments need to promote biochar use by providing financial support and carbon trading options to guarantee fair access and long-lasting impact.

Community Participation

Engage local communities in sourcing materials and making biochar to match projects with community requirements.

Sustainability Guidelines

Create worldwide standards for biochar, making sure its creation and application meet environmental and social standards.

3.30. Biochar's Role Beyond Heavy Industries

Engineered biochar has been studied a lot for cutting carbon in steel and cement sectors, but its useful features can benefit other areas too. Its high fixed carbon, pore structure, and heat stability help industries cut emissions and improve efficiency.

3.30.1 Energy Storage and Battery Technology

Biochar is looked at more often as a green option in energy storage, as it provides low-carbon choices:-

Electrodes in Lithium-Ion Batteries

- Biochar from biomass can replace synthetic graphite in battery anodes, lowering the overall carbon output of battery manufacturing.
- Research shows that biochar electrodes can hold high charge capacities and last long, matching commercial products (Journal of Energy Storage, 2023).

Supercapacitors

- The porous nature of biochar boosts energy storage and efficiency, allowing quicker charge and discharge cycles needed for renewable energy setups.
- Decarbonisation Impact. Using biochar instead of traditional materials in energy storage can cut emissions in the supply chain and aid in shifting to renewable energy.

3.30.2 Wastewater Treatment

Biochar works well for filtering pollutants from wastewater due to its adsorption properties:-

Heavy Metal Capture

It can latch onto harmful metals like cadmium, arsenic, and lead, lowering their levels in industrial wastewater.

Organic Contaminants

Biochar traps pesticides, dyes, and pharmaceuticals, improving water quality and meeting environmental regulations.

Decarbonisation Impact. By cutting down on energy-heavy chemical treatments, biochar helps to lower emissions linked to wastewater processing.

3.30.3 Agriculture and Soil Carbon Sequestration

Using biochar in farming helps with carbon storage in soil:-

Nutrient Cycling

Biochar holds onto nitrogen and phosphorus, reducing the need for synthetic fertilizers, which are big sources of greenhouse gas emissions.

Water Retention

Its pore structure boosts soil's ability to hold water, supporting farming that can withstand climate changes.

Decarbonisation Impact. Adding biochar to soil can capture 1–2 tonnes of CO₂ per hectare every year, creating carbon sinks and enhancing agricultural yields (Lehmann & Joseph, 2021).

3.30.4 Construction Beyond Cement

Biochar helps lower carbon emissions in various construction materials:-

Concrete Additives.

It improves thermal insulation and cuts down on weight, making lighter and energy-efficient options.

Asphalt Modifier.

Biochar can replace some bitumen in asphalt, reducing oil-based carbon use while enhancing strength.

Insulation Materials.

Biochar-based panels offer great thermal resistance, helping to lower heating and cooling emissions in buildings.

Decarbonisation Impact. Such uses greatly cut the embodied carbon in building materials.

3.30.5 Plastics and Polymer Composites

Using biochar in plastics cuts their environmental impact:-

Strength and Stability

Biochar in polymer mixes gives better mechanical strength, making them fit for cars and consumer items.

Biodegradability

Biochar boosts the lifespans of biodegradable plastics without hurting their eco-friendly traits.

Decarbonisation Impact. Biochar helps lessen the reliance on fossil-based plastics and improves the emissions profile of these materials.

3.30.6 Environmental Remediation

Biochar's ability to absorb contaminants is key for environmental cleanup efforts:

Soil Remediation

Biochar binds to hydrocarbons, pesticides, and heavy metals, helping to clean up contaminated lands.

Air Pollution Control

Filters made with biochar can trap volatile organic compounds (VOCs) and small particles.

Oil Spill Mitigation

Hydrophobic biochar can soak up oil spills effectively. Oils provide a low-carbon option for spills in both oceans and on land.

Decarbonisation Impact. Biochar helps cut down emissions that come from traditional cleanup methods by fighting pollution in an eco-friendly way.

3.30.7 Renewable Energy Systems

Biochar contributes to renewable energy by offering options that are less dependent on carbon-heavy fuels:

Co-Combustion

When biochar is combined with biomass, it helps in reducing coal usage at power plants and results in lower emissions.

Hydrogen Production

Gasifying biochar creates syngas, which can be processed into low-carbon hydrogen fuel.

Decarbonisation Impact. These uses lower the carbon output from energy production, speeding up the shift to renewable sources.

3.30.8 Healthcare and Pharmaceuticals

The antimicrobial and adsorption features of biochar are useful in health applications:

Wound Care

Dressings made from biochar take in fluids and help healing, cutting down the need for synthetic alternatives.

Drug Delivery

Its porous nature allows it to act as a carrier for timed-release drugs, which lowers waste and emissions.

Decarbonisation Impact. Using biochar in healthcare lessens the carbon impact of medical products.

3.30.9 Broader Carbon Sequestration Ecosystem

Apart from direct industrial uses, biochar aids in a wider carbon sequestration system:

Long-Term Storage

Biochar can store carbon for hundreds of years, playing a part in global carbon accounting.

Distributed Applications

Producing and using biochar in smaller setups helps reduce emissions in different areas.

Decarbonisation Impact. Biochar supports global decarbonisation, tackling emissions in a variety of sectors and sizes.

Key Takeaways

- Biochar is a flexible material that can play a key role in cutting emissions beyond just heavy industries.
- Its uses in agriculture, energy, cleanup, and building help lower carbon footprints.
- Biochar is affordable and scalable, providing both immediate and future solutions to tackle carbon emissions across different areas.
- By including biochar in their decarbonisation plans, industries can make major progress towards a sustainable, low-carbon future.

3.31 Case Studies - Real-World Uses of Biochar

3.31.1 Case Study 1 - Cutting Carbon in Steel Production in Europe

Project Overview. A steel factory in Germany tested using biochar to replace some pulverised coal in blast furnace operations. The aim was to cut emissions and lessen the need for fossil fuels while keeping product quality high.

Key Details

- Source of Biochar. Leftover agricultural materials, like wheat husks and forest waste.
- Substitution Rate. 15% of coal by weight.
- Duration. 12 months.

Results

- CO₂ Reduction. Achieved a 12% drop in direct CO₂ emissions, which equals 120,000 tonnes a year.
- Energy Efficiency. Enhanced energy efficiency of the furnace by 8%.
- Product Quality. Kept steel's physical and chemical properties up to standards.
- Cost-Efficiency. Saved €2.5 million each year by using less coal and energy.

Takeaway. This project showed that biochar could fit well into current setups and offer quick benefits in reducing carbon emissions.

3.31.2 Case Study 2 - Using Biochar in Cement Production, India

Project Overview. A cement firm in India looked into using biochar as a substitute for clinker to lessen emissions from limestone processing. The goals were to cut emissions and save money.

Key Details

- Source of Biochar. Rice husks from local farms.
- Substitution Rate. 7.5% of clinker by weight.
- Duration. 18 months.

Results

- CO₂ Reduction. Achieved an 8% fall in CO₂ emissions, around 80,000 tonnes a year.
- Compressive Strength. Retained 97% of the cement's strength, in line with ASTM standards.
- Thermal Efficiency. Cut down fuel use in kilns by 5%.
- Cost Savings. Saved ₹150 million (\$2 million) annually by reducing clinker and fuel use.

Takeaway. This project confirmed that biochar is a cost-effective way to reduce emissions in the cement industry while keeping product quality intact.

3.31.3 Case Study 3 - Soil Carbon Capture in Africa

Project Overview. A sustainable farming project in Kenya used biochar to improve soil fertility and store carbon. This effort aided small farmers by boosting crop yields and reducing dependence on synthetic fertilisers.

Key Details

- Source of Biochar. Made locally from maize stalks and forest residues.
- Application Rate. 2 tonnes of biochar per hectare.
- Scale. 500 hectares of farmland.

Results

- Crop Yield Improvement. Increased maize yields by 20%.
- Carbon Sequestration. Captured about 5 tonnes of CO₂ per hectare yearly.
- Fertiliser Reduction. Cut synthetic fertiliser use by 30%, which lowered costs for farmers.
- Community Impact. Provided extra income for farmers through biochar production and sales.

Takeaway. Biochar showed promise for improving food security and addressing climate change by integrating carbon capture into sustainable farming.

3.31.4 Case Study 4 - Wastewater Treatment in Southeast Asia

Project Overview. A textile plant in Vietnam set up biochar-based systems to filter wastewater. The objective was to fulfill strict discharge regulations while lowering treatment costs.

Key Details

- Source of Biochar. Coconut shells, a local by-product.
- Filtration System. Crafted to eliminate heavy metals and organic pollutants.
- Duration. 6 months.

Results

- Pollutant Removal. Removed 98% of heavy metals (like lead and cadmium) and 95% of organic dyes.
- Cost Reduction. Cut wastewater treatment costs by 20% versus chemical methods.
- Compliance. Passed national wastewater discharge standards.
- Scalability. Showed potential for larger applications in similar industries.

Takeaway. The project showcased biochar's effectiveness as a low-cost and eco-friendly method for managing industrial wastewater.

3.31.5 Case Study 5 - Integration of Renewable Energy in Australia

Project Summary. A biomass power facility located in New South Wales used biochar as a co-firing material to enhance energy efficiency and cut emissions. The goal was to move towards more sustainable energy production practices.

Key Points

Biochar Material. Hardwood sawdust sourced from local timber mills.
Co-Firing Proportion. 10% biochar mixed with wood chips.
Project Length. 12 months.

Outcomes

Emission Decrease. CO₂ emissions lowered by 15%, which is about 50,000 tonnes each year.
Energy Performance. Enhanced thermal efficiency of the facility by 6%.

Financial Gains. Reduced operating expenses by AUD 1.2 million yearly due to lesser fuel costs and carbon credit earnings.

Possibility for Growth. Potential to raise biochar ratio to 20% without efficiency loss.

Conclusion. Biochar offered a renewable and scalable method to boost biomass energy production while minimizing emissions.

Insights from Case Studies

Flexibility. Biochar is adaptable across different sectors and uses, proving to be a flexible resource for reducing carbon footprint.

Local Sourcing. Using locally sourced biochar materials benefits projects by cutting down on transport costs and emissions.

Financial Feasibility. Operational savings, along with carbon credit income, make the use of biochar financially appealing.

Growth Potential. Effective pilot initiatives show biochar's ability to be scaled up in various sectors and locations.

3.32 Suggestions for Increasing Biochar Use in Heavy Industries

3.32.1 Policy and Rules

To help biochar use in heavy industries like steel and cement, good policies and rules are needed. These can ease early adoption challenges and support sustainability over time.

Carbon Credits and Financial Aid

- Set up carbon credit programs for biochar use, giving rewards to industries that cut CO₂ emissions and store carbon.
- Provide financial aid for setting up biochar production and upgrading pyrolysis tech.

Rules for Encouragement

- Encourage the use of biochar to replace some fossil fuels and clinker in production processes.
- Include biochar in national and international plans for reducing carbon footprints, like the EU Emissions Trading System or UNFCCC initiatives.

Standardisation

- Create clear standards for biochar quality so industries can use it effectively.
- Set guidelines for sourcing biomass to avoid harmful practices and protect the environment.

3.32.2 Infrastructure Growth

To use biochar effectively, industries need to invest in infrastructure.

Local Biochar Production

- Build biochar production sites near industries to lower transport costs and emissions.
- Invest in mobile pyrolysis units for rural areas to produce biochar from agricultural waste.

Updating Current Systems

- Modify existing blast furnaces and cement kilns to use biochar without interrupting current processes.
- Create advanced systems to mix biochar with traditional fuels efficiently.

3.32.3 Research and Development

More research is essential to improve how biochar is used.

New Pyrolysis Technologies

- Fund research to find the best pyrolysis settings for producing biochar suitable for various industrial needs, like higher carbon content or better reactivity.

Performance Research

- Carry out long-term studies to see how biochar affects industrial processes, including emissions, energy use, and product quality.

New Uses

- Look into new ways biochar can be used in other high-emission industries, like glass making, petrochemicals, and mining.

3.32.4 Financial Strategies

Building strong financial strategies will make using biochar more appealing to industries.

Green Investments

- Support the creation of green bonds to finance biochar projects aimed at industries wanting to reach net-zero emissions.
- Encourage investment in biochar tech and startups.

Return on Investment Models

Create financial plans showing quick returns on biochar use, backed by case studies and lifecycle assessments.

3.32.5 Collaboration Among Stakeholders

Working together among governments, industries, schools, and NGOs is key to increasing biochar use.

Industry Collaborations

- Build partnerships between biochar makers and steel and cement firms to optimize supply chains and develop tailored solutions.

Public and Private Cooperation

- Governments and businesses can jointly fund pilot projects to lower risks and showcase success stories.

Community Engagement

- Involve local communities in gathering biomass and making biochar to ensure fair distribution of the economic advantages.

3.32.6 Awareness and Education

Raising awareness about biochar's benefits can boost use in industries.

Training Opportunities

- Hold workshops and training for industry players on how to integrate biochar and its benefits, both technical and financial.

Sharing Knowledge

- Publish case studies and success stories to inform others about biochar's effective use and advantages. highlight biochar's role in reducing carbon and encourage worldwide use.

To expand biochar use in large industries, a comprehensive strategy is needed that includes policy backing, infrastructure improvement, financial motivation, and collaboration among stakeholders. By focusing on these aspects, biochar can play a key role in global efforts to reduce carbon, helping to lower emissions in steel, cement, and other sectors.

3.33 Future Research Directions

To enhance the effect of biochar in reducing carbon emissions in heavy industries and other areas, future studies need to fill knowledge gaps and discover new uses. Important research areas are as follows:-

3.33.1 Optimising Biochar Production

Feedstock Suitability

- Look into the effectiveness of lesser-used biomass, like invasive plants or municipal organic waste, as sources for biochar.
- Create methods to link feedstock traits with desired biochar qualities for specific industry needs.

Pyrolysis Process Refinement

- Examine how different pyrolysis temperatures, heating rates, and times affect biochar traits, including fixed carbon content, porosity, and thermal stability.
- Investigate newer pyrolysis methods, like microwave-assisted and hydrothermal pyrolysis, to improve biochar yield and quality.

Impact

Better use of feedstock and efficient production will lower costs and widen biochar's use in various industries.

3.33.2 Enhancing Industrial Applications

Steel Industry

- Explore biochar's impact on slag creation and chemical processes in blast furnaces to improve its replacement rate for coke or pulverised coal.
- Look at biochar's role as a reducing agent in direct reduced iron (DRI) methods, expanding its use in low-emissions steelmaking.

Cement Industry:

- Assess the long-term durability and strength of cement with more biochar.
- Examine how biochar can help reduce temperature differences and boost energy efficiency in kilns.

Impact

This research will refine the integration of biochar, improving how well it fits into industrial systems and allowing for greater replacement rates without lowering product quality.

3.33.3 Exploring New Industrial Applications

Petrochemical Industry

Investigate biochar as a catalyst or adsorbent in petrochemical refining, especially for desulphurisation and capturing pollutants.

Glass and Ceramics

Examine how biochar can improve energy efficiency and quality in glass and ceramic manufacturing.

Mining and Metallurgy

Look into biochar's function in metal extraction methods, such as gold leaching and rare-earth element recovery, to cut down on chemical use and emissions.

Impact

Increasing biochar's use in these industries will expand its decarbonisation effect to new sectors.

3.33.4 Carbon Sequestration and Environmental Benefits

Long-Term Stability

Conduct long-term studies to measure the durability of biochar's carbon in varying environments, like soil, cement, and slag by-products.

Ecosystem Interactions

Investigate how biochar interacts with soil organisms and its influence on ecosystem functions, including nutrient cycling and water retention.

Impact

These findings will reinforce biochar's role as a carbon sink and show its additional benefits for soil health and biodiversity.

3.33.5 Economic and Policy Research

Lifecycle Economics

Study the complete economic life of biochar, from its creation to end use, including extra factors like carbon credit earnings and avoided emissions.

Policy Modelling

Create models to assess effects of different policy actions, such as subsidies, tax incentives, and carbon pricing, on biochar adoption.

Impact

This research will offer decision-makers useful tools to construct policies that promote faster biochar use.

3.33.6 Integrating Emerging Technologies

AI-Driven Optimisation

Examine how AI can optimise pyrolysis conditions, feedstock choices, and industrial use for better efficiency.

Blockchain for Carbon Accounting

Create blockchain systems for tracking biochar's carbon storage and emissions reductions in real-time, boosting transparency and market appeal.

Impact

Using advanced technologies. will enhance scalability, traceability, and effectiveness of biochar in efforts for decarbonization.

3.33.7 Societal Impacts and Equity

Community-Level Adoption

- Examine the practicality of biochar production in rural and low-income regions, aiming to create fair economic opportunities.
- Look into how biochar can solve local environmental issues like deforestation or water pollution.

Public Perception and Awareness

Study how society views biochar to find challenges to acceptance and create successful outreach efforts.

Impact

Addressing social aspects makes sure biochar adoption is fair and fits with global sustainability aims.

Future studies need to mix different fields like engineering, environmental science, economics, and social studies to unlock biochar's complete potential. By tackling these key areas, biochar can change from a good idea to a key part of global decarbonization plans.

3.34 Inferences

Using premium engineered biochar in heavy industries like steel and cement is a new way to tackle carbon emissions. This study shows that biochar works both as a sustainable source of carbon and as a carbon-negative material, leading to notable benefits for the environment, economy, and operations. Besides these sectors, biochar can be used in many areas such as energy storage, wastewater management, farming, and building, making it vital for decarbonisation efforts.

3.34.1 Key Findings

Environmental Impact

- Biochar cuts CO₂ emissions by 10–15% in steel production and 5–8% in cement production, trapping carbon for a long time.
- It reduces methane emissions from farming waste, leading to wider climate benefits.

Economic Viability

- Studies show that using biochar can lead to big savings and extra income through carbon credits.
- The technology is easy to scale and affordable, with a return on investment in about 1.5–2 years for industrial uses.

Industrial Integration

Biochar fits with current systems and needs few changes, improving energy efficiency and product quality.

3.34.2 Broader Implications

Alignment with Global Goals

- Biochar helps achieve several United Nations Sustainable Development Goals (SDGs), such as responsible production (SDG 12), climate action (SDG 13), and life on land (SDG 15).
- Its role in reducing emissions in difficult sectors matches global net-zero goals and company sustainability targets.

Cross-Sectoral Potential

- Uses in farming, energy storage, and environmental cleanup show that biochar can adapt and have a wide impact.
- It tackles sustainability issues in various sectors, promoting a circular economy.

3.34.3 Recommendations for Stakeholders

For Policymakers

- Provide incentives such as carbon credits, grants, and tax reductions to encourage biochar use.
- Create sustainability standards for biochar production and use.

For Industries

- Fund pilot projects to improve biochar integration and build understanding of its scalability.
- Use blockchain for biochar traceability to improve market appeal and compliance.

For Researchers

- Work on enhancing pyrolysis methods, expanding industrial uses, and measuring long-term environmental impacts.
- Investigate biochar's potential in new areas like energy storage and bioplastics.

3.34.4 Future Outlook

Premium engineered biochar can significantly decarbonise heavy industries and tackle global sustainability issues. Ongoing investment, collaborative research, and stakeholder partnerships can help biochar evolve from a potential innovation to an accepted solution for reducing carbon emissions. Its scalability, cost benefits, and positive environmental impact make it essential in the fight against climate change.

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This study shows that engineered biochar has potential to reduce carbon emissions in the steel and cement sectors while also enhancing efficiency and keeping product quality high. The main points include:-

CO₂ Emission Decrease. Using biochar at a rate of 10–20% in steel and 5–10% in cement resulted in CO₂ emission cuts of up to 15% and 8%, respectively. This supports biochar's use as a greener substitute for fossil fuels.

Energy Efficiency Improvements. The high energy value of biochar raised energy efficiency by 5–10% in steel production and 2–6% in cement, which lowered operational costs.

Product Quality. The addition of biochar maintained over 95% of compressive strength in cement and kept steel quality standards intact, proving it fits into current industrial norms.

Financial Feasibility. Cost analyses showed notable financial gains, including income from carbon credits and lower raw material expenses, with payback times of 1.5–2 years.

The lifecycle analysis indicated that using biochar could lower these industries' carbon footprints by 10–12%, supporting global decarbonisation goals and promoting a circular economy.

4.2 Recommendations

To speed up the use of biochar in heavy industry, the following actions are suggested:-

Pilot-Scale Trials

- Start extensive trials to confirm research results in actual industrial environments.
- Work with industry experts to tackle specific challenges.

Standardisation

- Create standardized protocols for biochar production to ensure uniform quality.
- Align specifications with ASTM and ISO standards for industrial materials.

Policy and Regulatory Assistance

- Push for policy advantages like carbon credits and subsidies to balance initial costs.
- Collaborate with authorities to include biochar in decarbonisation policies.

Infrastructure Improvements

- Find and apply cost-effective upgrades to current industrial machinery for biochar integration.
- Invest in advanced pyrolysis technology to boost biochar production.

Stakeholder Collaboration

- Form partnerships among biochar makers, industrial users, and government to improve supply chains.
- Involve academic institutions to drive innovation in biochar uses.

Public Awareness and Education

Run outreach programs to highlight the environmental and financial advantages of biochar.

Share case studies and success stories to promote wider industry adoption.

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