International Journal of
Environmental Sciences & Natural Resources
ISSN: 2572-1119

Review Article
Volume 34 Issue 1 - September 2024
DOI: 10.19080/IJESNR.2024.34.556382

Int J Environ Sci Nat Res

Review: Green Energy Alchemy: Converting Industrial Flue Gas into Eco-Friendly Charcoal

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Submission: August 16, 2024; **Published:** September 12, 2024

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Abstract

This research presents an innovative approach to charcoal production by utilizing industrial flue gas as an energy source, addressing significant environmental concerns. Over the past five years, data shows increasing levels of pollutants such as SO_2, NO_x, PM, CO, and VOCs, which have contributed to worsening air quality (AQI) and environmental degradation. The process involves the collection, purification, and transportation of flue gas to a pyrolysis reactor, where it facilitates the carbonization and heating of biomass. The resulting charcoal serves various applications and represents a sustainable, renewable fuel alternative. Implementing this method can reverse the adverse trends shown in the environmental impact graph, potentially lowering AQI and the environmental degradation index. Furthermore, it can reduce the incidence of respiratory diseases and mortality rates linked to air pollution. The method significantly reduces greenhouse gas emissions and mitigates flue gas release into the atmosphere, contributing to environmental protection and the fight against climate change. By converting a harmful pollutant into a valuable energy resource, this approach enhances energy efficiency and sustainability. Despite challenges such as the efficiency of flue gas purification and economic costs, the method's benefits highlight its potential for addressing energy conservation, environmental pollution, and climate change.

Keywords: Industrial flue gas; Chemical compositions flue gas; Environmental impact; Health impact; Analysis of energy source

Introduction

Industrial operations such as steel manufacturing [1], cement production, and electricity generation generate substantial volumes of flue gas as a byproduct. Traditionally, this flue gas is released into the atmosphere, contributing to environmental pollution. However, recent research has explored the potential of utilizing this flue gas as a valuable energy source for producing charcoal a renewable fuel with diverse applications in cooking, heating, and power generation [2].

Flue gas composition is complex, typically comprising carbon dioxide (CO_2), carbon monoxide (CO), nitrogen (N_2), water vapor (H_2O), and varying levels of pollutants such as sulfur oxides and particulate matter. Innovations in capture technologies, including adsorption processes and chemical reactions, enable the extraction and isolation of these components from flue gas for subsequent utilization [3].

The integration of captured flue gas into the charcoal production process serves multiple purposes. It acts as a primary energy source for driving the carbonization reactions essential for converting biomass into charcoal. This integration eliminates the need for additional external energy inputs, such as electricity or conventional fuels, thereby enhancing the economic viability and sustainability of the process. An intriguing aspect is the role of carbon dioxide within flue gas. While traditionally considered a greenhouse gas, in this context, it serves as a reactant that enhances the efficiency and quality of the charcoal production process. This dual benefit not only mitigates greenhouse gas emissions by utilizing CO_2 but also improves the overall environmental footprint of charcoal production. From an environmental perspective, redirecting flue gas from industrial operations into charcoal production offers substantial advantages. It significantly reduces the emission of flue gases into the atmosphere, thereby mitigating their impact on climate change and improving air quality. This approach aligns with global efforts towards sustainable development by promoting cleaner energy alternatives and efficient resource utilization [4].

Economically, leveraging flue gas as an energy source for charcoal production presents compelling advantages for industries. It reduces operational costs by utilizing a waste product as a primary energy input, thereby enhancing economic efficiency and competitiveness. Furthermore, potential revenue streams from carbon capture and utilization initiatives provide additional financial incentives, supporting broader adoption and implementation across industrial sectors. While the concept shows promise, further advancements in technology and research are necessary to optimize processes and facilitate large-scale deployment. Nonetheless, the utilization of flue gas for charcoal production represents a forward-thinking strategy to transform industrial waste into a valuable energy resource, contributing to sustainable development goals and environmental stewardship on a global scale [5].

A byproduct of several industrial operations, including the manufacture of steel, cement, and electricity, is industrial flue gas. Although this flue gas is normally vented into the environment, it may also be utilized as a source of energy to produce charcoal. For cooking, heating, and power generation, charcoal is a sustainable and renewable fuel [6]. A byproduct of several industrial operations, including the manufacture of steel, cement, and electricity, is industrial flue gas. Although this flue gas is normally vented into the environment, it may also be utilized as a source of energy to produce charcoal. For cooking, heating, and power generation, charcoal is a sustainable and renewable fuel [7].

This study investigates the feasibility and potential of utilizing flue gas as an energy source for charcoal production. It begins by examining the composition of flue gas, which primarily consists of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen (N_2), water vapor (H_2O), and traces of other pollutants. Various techniques, such as adsorption processes and chemical reactions, can be employed to isolate and capture these components for subsequent use [6].

The captured flue gas can be channelled into the charcoal production process to fuel the carbonization reactions. This energy input eliminates the need for additional external energy sources, such as electricity or fossil fuels, making the process more sustainable and cost-effective. Moreover, the carbon dioxide present in flue gas can act as a reactant in the production of high-quality charcoal, further enhancing the efficiency of the process [8]. The integration of flue gas as an energy source for charcoal production offers several environmental benefits. Firstly, it reduces the emission of flue gas into the atmosphere, mitigating its impact on climate change. Additionally, the capture and utilization of flue gas components contribute to the reduction of greenhouse gas emissions and air pollution. This approach aligns with sustainable development goals and international commitments towards reducing carbon footprint and promoting cleaner energy alternatives [9].

Furthermore, the economic advantages of utilizing flue gas for charcoal production are substantial. By employing a waste product as an energy source, industries can reduce their reliance on expensive energy inputs, thus decreasing production costs [10]. Additionally, the potential revenue streams generated from carbon capture and utilization can provide added economic incentives [9].

Overall, utilizing flue gas as a source of energy for charcoal production offers a viable and sustainable pathway towards reducing greenhouse gas emissions, mitigating climate change, and promoting efficient resource utilization. Further research and technological advancements are necessary to establish optimized processes and industrial-scale implementation. However, this approach holds significant promise in transforming a waste product into a valuable energy resource for charcoal production [11].

Flue gas is a byproduct of combustion processes, such as those used in power plants, industrial facilities, and residential heating systems. It is primarily composed of nitrogen and carbon dioxide, but it can also contain other pollutants such as sulfur oxides, nitrogen oxides, and particulate matter. Flue gas emissions are a major contributor to air pollution, which can have a significant impact on human health and the environment. In recent years, there has been growing interest in the potential use of flue gas as a source of energy. One promising application is the use of flue gas to produce charcoal, a renewable and sustainable fuel that can be used for cooking, heating, and other purposes [12].

The use of flue gas as an energy source for charcoal production would reduce the need to deforest trees for charcoal production. The reduced air pollution from the use of flue gas as an energy source for charcoal production would improve air quality, which would in turn improve public health. Reduced greenhouse gas emissions from the use of flue gas as an energy source for charcoal production would help to mitigate climate change [13]. Charcoal briquettes are made by combining a binder (often soil, compost, or paper) with charcoal dust and water. The mixed materials are then compressed into a uniform solid unit (either by hand or in a mechanised press) and used like lump charcoal or firewood [14].

Manufacturing Process of Charcoal Flue Gas Used as Source of Energy

The manufacturing process of charcoal utilizing flue gas as a source of energy involves several key steps to efficiently convert biomass into a renewable fuel detailed overview of how flue gas can be integrated into the charcoal production process [15]:

Flue gas capture and preparation

a) Capture Techniques: Flue gas, generated from industrial operations such as steel manufacturing or power generation, is captured using specialized systems. These systems can employ various technologies including absorption processes (such as amine scrubbing) or adsorption methods (using activated carbon or other sorbents) [16].

b) Pre-treatment: Once captured, the flue gas may undergo pre-treatment steps to remove contaminants or adjust its composition to optimize its use in the charcoal production process. This step ensures that the flue gas is suitable and efficient as an energy source [17].

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Charcoal production process

a) Feedstock Preparation: Biomass feedstock, which can include wood chips, sawdust, agricultural residues, or even municipal solid waste, is prepared for carbonization. This may involve shredding, drying, and sizing the biomass to achieve optimal carbonization results [12].

b) Carbonization: The prepared biomass undergoes carbonization, a process where it is heated in the absence of oxygen (pyrolysis). This step breaks down the organic materials into charcoal (solid carbon), volatile gases, and liquid by-products (pyrolysis oil) [18].

c) Energy Input: Instead of using external energy sources like electricity or fossil fuels, the captured flue gas is introduced into the carbonization chamber. Flue gas serves as the primary energy source to maintain and sustain the carbonization process. It provides the necessary heat for pyrolysis, ensuring efficient conversion of biomass into charcoal [13].

Utilization of flue gas components

a) Carbon Dioxide (CO_2) Utilization: Carbon dioxide present in flue gas can participate in chemical reactions during carbonization, enhancing the quality and yield of charcoal produced. This utilization of CO_2 helps in reducing emissions and improving the overall efficiency of the process [14].

b) Heat and Energy Recovery: The heat energy derived from flue gas not only sustains the carbonization process but can also be utilized for other industrial purposes, such as heating or steam generation, thereby increasing the overall energy efficiency of the operation [19].

Environmental and economic benefits

a) Environmental Impact: By utilizing flue gas as an energy source for charcoal production, the process significantly reduces emissions of greenhouse gases and air pollutants that would otherwise be released into the atmosphere. This contributes to mitigating climate change and improving local air quality [20].

b) Economic Viability: Industries benefit economically by reducing their reliance on costly external energy sources. The integration of flue gas as an energy input lowers production costs, enhances resource efficiency, and potentially creates revenue streams through carbon capture and utilization initiatives [21].

Technological advancements and optimization

a) Research and Development: Ongoing research focuses on optimizing the integration of flue gas into charcoal production processes. This includes improving capture technologies, enhancing carbonization efficiency, and exploring new applications for flue gas components [22].

b) Scale-up and Implementation: While the concept shows promise, scaling up these integrated systems requires further technological advancements and investment. Industrial-scale implementation will benefit from advancements in process control, automation, and cost-effective capture technologies [23].

In conclusion, utilizing flue gas as a source of energy for charcoal production represents a sustainable and innovative approach to transform industrial waste into a valuable resource. It aligns with global efforts towards sustainable development, offering environmental benefits while supporting economic efficiency in industrial operations [24].

According to [11] Manufacturing Process of Charcoal Utilizing Flue Gas as a Source of Energy, Including Temperature Range, Pressure Considerations, Equipment Setup, and Overall Design Requirements [25]

Temperature range

The carbonization process, where biomass is converted into charcoal, typically occurs within a temperature range of 300°C to 600°C (572°F to 1112°F). This temperature range ensures that pyrolysis the decomposition of organic materials in the absence of oxygen efficiently produces charcoal along with volatile gases and liquids [26].

Pressure considerations

The carbonization process is generally conducted under atmospheric pressure. However, specific equipment designs and processes may involve slight variations in pressure depending on the type of biomass and the desired characteristics of the charcoal produced. Generally, the pressure is maintained at atmospheric levels to facilitate efficient heat transfer and volatile gas release [27].

Equipment setup

Carbonization chamber (carbonizer)

a) Design: The carbonization chamber is designed to withstand high temperatures and is insulated to maintain heat efficiently. It can be a vertical or horizontal cylinder made of heat-resistant materials such as steel or refractory bricks [28].

b) Temperature Control: Temperature inside the carbonization chamber is crucial and is controlled using burners or heaters fueled by the captured flue gas. Temperature sensors and controllers ensure precise regulation of the carbonization process [29].

Flue gas capture system

a) Capture Techniques: Flue gas from industrial processes is captured using specialized systems such as absorption towers or adsorption units. Pre-treatment: Flue gas may undergo pre-treatment to remove particulates, sulfur compounds, and adjust its composition to optimize energy content and reduce corrosion potential [16].

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b) Distribution: Captured flue gas is fed into the carbonization chamber through a controlled inlet system. The flow rate and distribution ensure uniform heat distribution inside the chamber for efficient pyrolysis [30].

Heat recovery system

a) Heat Exchangers: Heat recovery systems may be integrated to capture excess heat from flue gas for heating purposes elsewhere in the facility or for preheating incoming biomass [31]. Energy Efficiency: Optimizing heat recovery helps in reducing energy consumption and improving overall process efficiency [32].

Product collection and handling

a) Charcoal Collection: After completion of the carbonization process (typically several hours), the charcoal is cooled and collected from the chamber [33]. By-products Handling: Volatile gases and liquids generated during pyrolysis (pyrolysis oil and gases) may be collected and processed further for additional energy recovery or other industrial applications [34].

Overall Design Requirements

Safety and environmental compliance

a) Design: The design must comply with safety standards to handle high temperatures and potentially hazardous gases. Environmental considerations include minimizing emissions and ensuring compliance with local regulations for air quality and waste management [6].

b) Process Efficiency: Efficient heat transfer and temperature control are critical for maximizing charcoal yield and quality. Integration of flue gas as an energy source should optimize energy use and minimize operational costs [7].

c) Automation and Control Systems: Automated control systems monitor and regulate temperature, flow rates, and other process parameters for consistent and efficient operation. Data logging and analysis may be employed for process optimization and troubleshooting [18].

d) Scalability and Flexibility: Designs should be scalable to accommodate varying capacities of biomass processing. Flexibility in operation allows for adjustments to accommodate different biomass types and variations in flue gas composition [6]. Integrating flue gas as an energy source for charcoal production involves sophisticated engineering and design considerations to ensure safety, efficiency, and environmental compliance [8]. The process leverages captured industrial emissions to produce a valuable renewable fuel while reducing environmental impact. Ongoing research and development aim to further optimize these systems for broader industrial adoption and sustainability [15] (Table 1).

Table 1: Temperature, Pressure and Flue Gas Flow Rate in Different Industry.

Industry	Temperature Range (°C)	Pressure Range (bar)	Flue Gas Flow Rate (m^3/s)
Steel Manufacturing	1200 - 1600	Atmospheric	High (varies by process)
Cement Production	800 - 1000	Atmospheric	High (varies by process)
Electricity Generation (Coal)	400 - 600	Atmospheric	High (varies by plant)
Oil Refineries	300 - 500	Atmospheric	High (varies by refinery)
Biomass Power Plants	400 - 600	Atmospheric	Moderate to High
Natural Gas Processing	200 - 600	Atmospheric	High (varies by process)
Chemical Manufacturing	Ambient to 1000	Atmospheric	High (varies by process)
Glass Manufacturing	1200 - 1600	Atmospheric	High (varies by furnace type)
Aluminium Production	700 - 1000	Atmospheric	High (varies by smelting process)
Petrochemical Refining	200 - 700	Atmospheric	High (varies by process)
Pulp and Paper Mills	200 - 600	Atmospheric	Moderate to High
Food Processing	Ambient to 300	Atmospheric	Moderate to High
Pharmaceutical Manufacturing	Ambient to 200	Atmospheric	Low to Moderate
Automotive Manufacturing	Ambient to 300	Atmospheric	Moderate to High
Textile Manufacturing	Ambient to 200	Atmospheric	Low to Moderate

Source: [36].

Pyrolysis: Without the presence of oxygen, the biomass is heated to a temperature of between 400 and 700°C in a sealed kiln [17].

Steel Manufacturing:

a) Requires very high temperatures for smelting and refining steel.

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b) Operating under atmospheric pressure.

c) Flue gas flow rate varies significantly based on the steelmaking process.

Cement Production:

a) Kilns operate at high temperatures for clinker production.

b) Atmospheric pressure conditions.

c) Flue gas flow rate depends on the type and size of cement kiln.

Electricity Generation (Coal):

a) Boilers operate at high temperatures for steam generation.

b) Typically at atmospheric pressure.

c) Flue gas flow rate varies based on the power plant's capacity and technology.

Oil Refineries:

a) Various processes operate at moderate to high temperatures.

b) Operates under atmospheric pressure in most refinery operations.

c) Flue gas flow rate varies widely depending on refinery capacity and processes.

Biomass Power Plants:

a) Combustion of biomass occurs at moderate temperatures.

b) Operates under atmospheric pressure.

c) Flue gas flow rate varies based on plant size and efficiency.

Natural Gas Processing:

a) Processes involve varying temperatures depending on the specific operation.

b) Typically at atmospheric pressure.

c) Flue gas flow rate varies by the process and plant configuration.

Chemical Manufacturing:

a) Temperatures vary widely depending on the chemical process.

b) Operating under atmospheric pressure.

c) Flue gas flow rate varies by the specific chemical production process.

Glass Manufacturing:

a) Requires very high temperatures for melting and forming glass.

b) Atmospheric pressure conditions.

c) Flue gas flow rate depends on the furnace type and production capacity.

Aluminum Production:

a) Smelting processes operate at high temperatures.

b) Atmospheric pressure conditions.

c) Flue gas flow rate varies by smelting technology and plant size.

Petrochemical Refining:

a) Involves a wide range of temperatures depending on refining processes.

b) Operates under atmospheric pressure.

c) Flue gas flow rate varies by the specific refining process and facility.

Pulp and Paper Mills:

a) Processes involve moderate to high temperatures depending on the production stage.

b) Typically at atmospheric pressure.

c) Flue gas flow rate varies based on the mill's capacity and production methods.

Food Processing:

a) Processes generally operate at lower temperatures compared to heavy industries.

b) Atmospheric pressure conditions.

c) Flue gas flow rate varies based on the size and type of food processing facility.

Pharmaceutical Manufacturing:

a) Operates at relatively low to moderate temperatures for product synthesis and processing.

b) Atmospheric pressure conditions.

c) Flue gas flow rate is generally low to moderate compared to heavy industries.

Automotive Manufacturing:

a) Involves operations at ambient to moderate temperatures for assembly and manufacturing processes.

b) Atmospheric pressure conditions.

c) Flue gas flow rate varies based on the size and production volume of the facility.

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Textile Manufacturing:

a) Operates at ambient to moderate temperatures for weaving, dyeing, and finishing processes.

b) Atmospheric pressure conditions.

c) Flue gas flow rate is typically low to moderate compared to heavy industrial sectors.

The Impact of Flue Gas on Environment and Human Health

The impact of industrial effluent flue gases on the environment and human health over a five-year period can be illustrated through various effects, including air pollution, respiratory diseases, and ecological degradation [8].

Environmental effects

a) Air Quality Degradation: Industrial flue gases often contain pollutants such as nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter. Over five years, the accumulation of these emissions can lead to significant air quality deterioration, contributing to smog formation and acid rain [10].

b) Climate Change: The release of greenhouse gases (GHGs) from industrial processes contributes to global warming. Continuous emissions over five years can exacerbate climate change effects, influencing weather patterns and increasing the frequency of extreme weather events [11].

c) Soil and Water Contamination: Heavy metals and other toxic substances in industrial effluents can leach into the soil and water bodies, leading to long-term ecological damage. This contamination affects biodiversity and can disrupt local ecosystems [2].

Human health effects

a) Respiratory Diseases: Prolonged exposure to polluted air from industrial emissions is linked to respiratory issues such as asthma, chronic bronchitis, and lung cancer. Over five years, populations living near industrial areas may experience increased rates of these health problems.

b) Cardiovascular Issues: Air pollution from industrial flue gases can also lead to cardiovascular diseases. Studies indicate that fine particulate matter can penetrate deep into the lungs and enter the bloodstream, increasing the risk of heart attacks and strokes.

c) Neurological Effects: Emerging research suggests that exposure to certain industrial pollutants may be linked to neurological disorders, including cognitive decline and developmental issues in children.

In summary, the cumulative effects of industrial effluent flue gases over five years can lead to serious environmental degradation and significant health risks for nearby populations. Addressing these issues requires stringent regulations and effective pollution control technologies to mitigate the adverse impacts of industrial emissions [16] (Table 2) (Figure 1-3).

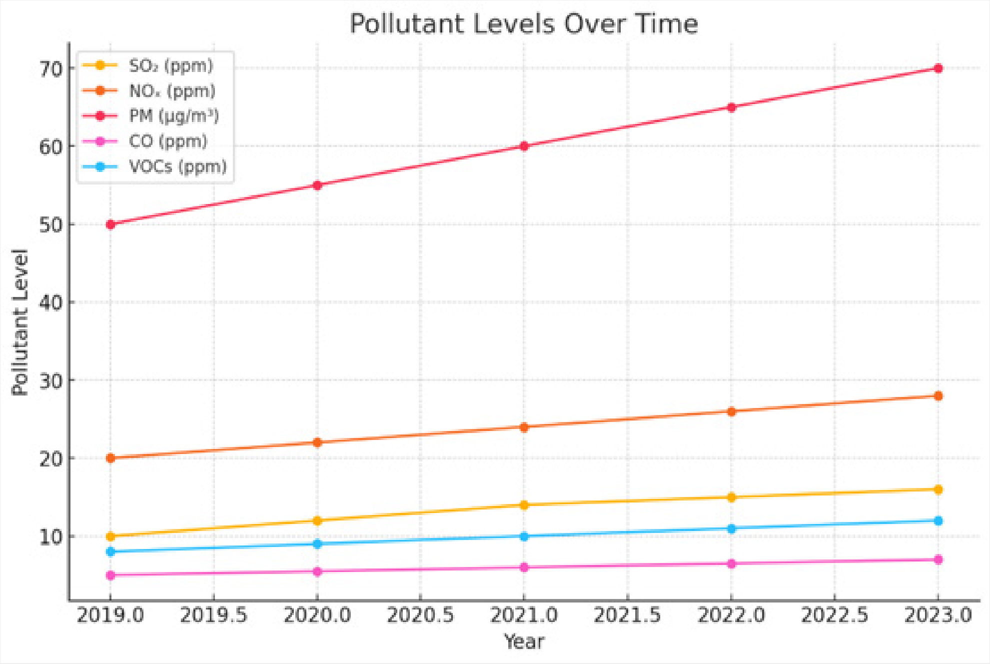

Figure 1: Pollutant level over time.

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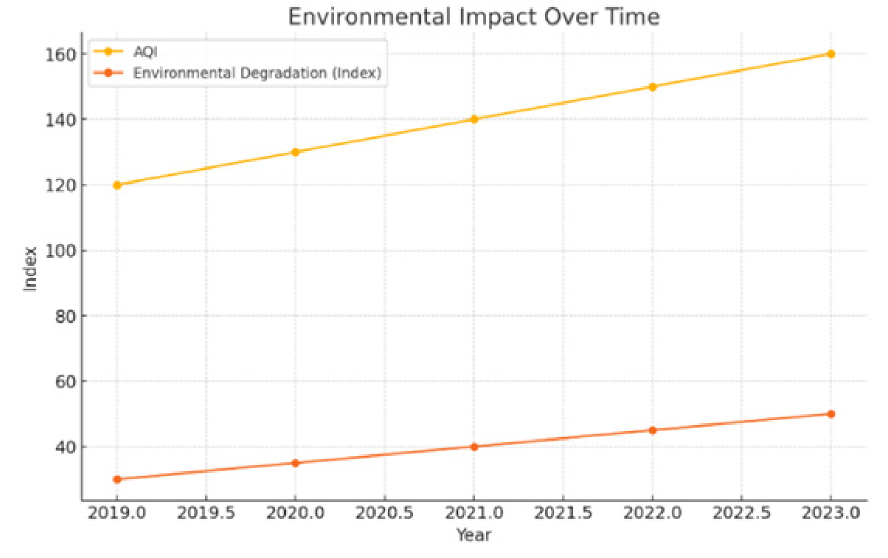

Figure 2: Environmental impact over time.

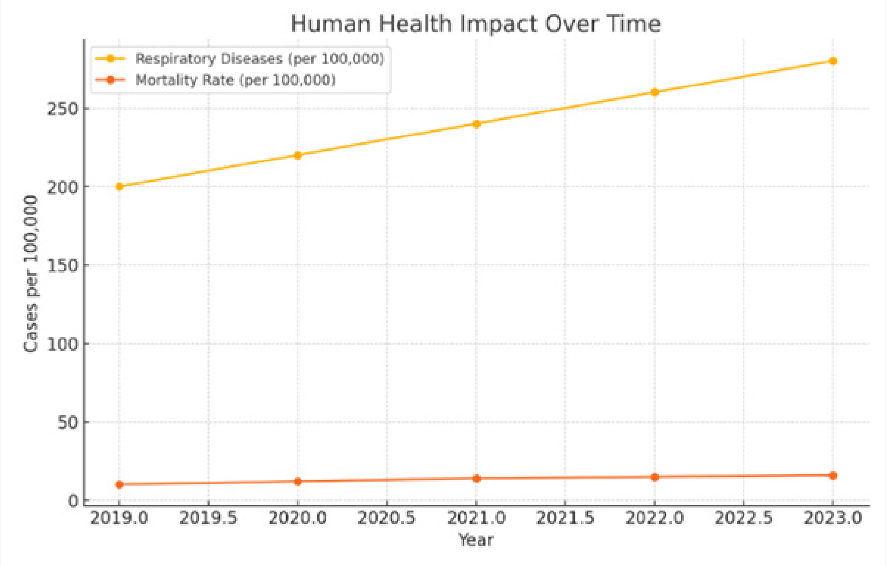

Figure 3: Human health impact over time.

Table 2: Chemical Composition of Effluent Flue Gas and their Effect.

Year	SO_2 (ppm)	NO_x (ppm)	PM ($\mu g/m^3$)	CO (ppm)	VOCs (ppm)	AQI	Environmental Degradation Index)	Respiratory Diseases (per 100,000)	Mortality Rate (per 100,000)
2019	10	20	50	5	8	120	30	200	10
2020	12	22	55	5.5	9	130	35	220	12
2021	14	24	60	6	10	140	40	240	14
2022	15	26	65	6.5	11	150	45	260	15
2023	16	28	70	7	12	160	50	280	16

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Pollutant Levels Over Time: This graph shows the levels of various pollutants (SO_2, NO_x, PM, CO, VOCs) over the five-year period from 2019 to 2023. Environmental Impact Over Time: This graph illustrates the changes in the Air Quality Index (AQI) and Environmental Degradation Index over the same period. Human Health Impact Over Time: This graph depicts the incidence of respiratory diseases and mortality rates related to air pollution over the five years [35].

Conclusion

The research paper presents an innovative method for producing charcoal from wood by utilizing industrial flue gas as a sustainable energy source. This method involves the collection, purification, and transfer of flue gas to a pyrolysis reactor, where it generates the necessary heat for the carbonization process. The resulting charcoal serves as a renewable and eco-friendly fuel, applicable for various uses. The paper emphasizes the technical and economic feasibility of this approach, highlighting its potential to reduce greenhouse gas emissions and mitigate environmental pollution. By integrating flue gas treatment, the method not only enhances energy efficiency but also addresses significant issues related to climate change.

Additionally, the paper discusses the environmental and social benefits associated with this charcoal production technique, while also acknowledging the challenges and limitations that may arise. It suggests areas for further research and development to optimize the process. Ultimately, the findings conclude that utilizing flue gas for charcoal production is a viable and promising solution that contributes to energy conservation and environmental sustainability, making it a noteworthy advancement in the field of renewable energy source.

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DOI: 10.19080/IJESNR.2024.34.556382

How to cite this article: Tsiye T. Review: Green Energy Alchemy: Converting Industrial Flue Gas into Eco-Friendly Charcoal. Int J Environ Sci Nat Res. 2024; 34(1): 556382. DOI: 10.19080/IJESNR.2024.34.556382