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A SUSTAINABLE AGRO-INDUSTRIAL WASTE DERIVED ALTERNATIVE FUEL FOR CEMENT CLINKER PRODUCTION WITH ENHANCED CLINKER MINERALOGY AND REDUCED CARBON EMISSIONS

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ABSTRACT The cement industry is among the largest industrial contributors to global carbon dioxide emissions and fossil fuel consumption. Simultaneously, India generates enormous quantities of agricultural residues, a substantial portion of which is disposed of through open-field burning, causing severe environmental pollution and loss of biomass resources. The present study investigates the development and utilization of AFR-09, a novel briquetted alternative fuel prepared from rice husk, bagasse, coir pith, groundnut shell, casuarina leaves, coal dust, and plastic waste wax for partial substitution of coal in cement clinker production. AFR-09 briquettes were fabricated using a hydraulic briquetting process and evaluated for calorific value, combustion characteristics, emission behavior, and influence on clinker phase formation. The briquettes exhibited a gross calorific value of 3093 kcal/kg and a net calorific value of 2784 kcal/kg, indicating suitability for cement kiln co-processing. Experimental clinkerization studies were conducted with 0%, 10%, 20%, and 30% coal replacement levels at temperatures between 1350–1450 °C. The results demonstrated substantial reductions in gaseous emissions, including approximately 81% reduction in SO_2 emissions and nearly 23% reduction in CO_2 emissions at 30% AFR substitution. Mineralogical analysis revealed progressive enhancement in clinker quality, with C_3S increasing from 45.67% to 49.67%, while C_2S and C_3A decreased systematically, indicating improved hydraulic activity and sulfate resistance. Clinker formation efficiency increased from 63.1% to 68.4%, confirming the mineralizing effect of AFR-09 without destabilizing kiln chemistry. The findings establish AFR-09 as a technically feasible, environmentally sustainable, and economically promising alternative fuel that supports circular economy principles and industrial decarbonization in the Indian cement sector.

KEYWORDS : Alternative Fuel, Agricultural Residue, Cement Clinker, Mineralizer, Circular Economy, CO_2 Reduction, India.

1. INTRODUCTION

The cement industry is one of the major contributors to global greenhouse gas emissions and industrial energy consumption due to its dependence on fossil fuels and energy-intensive clinker production processes. Cement manufacturing contributes significantly to anthropogenic CO_2 emissions because of limestone calcination and coal combustion during kiln operations [1-5]]. In addition to carbon dioxide, cement plants emit considerable quantities of sulfur oxides, nitrogen oxides, and particulate matter, which negatively affect environmental quality and human health [4-10]. Increasing environmental concerns and stringent emission regulations have therefore encouraged the search for sustainable and low-carbon fuel alternatives for cement manufacturing.

India, being one of the world's largest agro-based economies, generates nearly 686 million tonnes of agricultural residues annually. However, a substantial fraction of these residues is disposed of through open-field burning, especially in northern agricultural regions, leading to severe air pollution, greenhouse gas emissions, and nutrient depletion in soils. Agricultural residues such as rice husk, bagasse, coir pith, and groundnut shell possess significant calorific value and are therefore considered promising renewable resources for waste-to-energy applications. The improper management of biomass waste not only creates environmental problems but also represents a major loss of potential energy resources [11].

The utilization of alternative fuels and raw materials (AFR) in cement kilns has emerged as an effective strategy for reducing fossil fuel consumption and lowering industrial carbon footprints. Cement kilns are particularly suitable for co-processing waste-derived fuels because of their high operating temperatures, long residence times, and ability to incorporate ash into clinker mineral phases without generating secondary waste [12]. Previous investigations have demonstrated that partial substitution of coal with biomass-derived fuels can significantly reduce CO_2 emissions while maintaining clinker quality and kiln efficiency [3,11,12]. Furthermore, co-processing technologies provide a practical pathway for simultaneous waste management and sustainable energy recovery.

Among various biomass resources, sugarcane bagasse is one of the most abundantly available agro-industrial residues in India, with annual production exceeding 90 million tonnes. Similarly, rice husk generated during rice milling and coir pith from coconut processing industries are available in large quantities and possess suitable combustion characteristics for thermal applications. The mineral composition of these biomass materials can also influence clinker chemistry by participating in silicate and aluminate phase formation during clinkerization. In recent years, biomass briquetting technology has gained considerable attention because densified briquettes offer improved handling, transportation, combustion efficiency, and energy density compared to loose agricultural residues [2,11].

In addition to biomass utilization, plastic waste management has become another major environmental challenge worldwide. Waste plastic-derived waxes and pyrolysis products have shown considerable potential as supplementary fuel components in industrial combustion systems. The integration of plastic waste into biomass briquettes not only improves binding properties and calorific value but also contributes to circular economy practices through waste valorization. Such integrated waste-to-energy approaches align with India's National Bioenergy Programme and carbon reduction initiatives under the Carbon Credit Trading Scheme, 2023.

Recent advances in sustainable and green technologies have further emphasized the importance of renewable feedstocks and environmentally benign industrial processes [6, 9]. Green chemistry approaches encourage the transformation of agricultural and industrial wastes into value-added products with reduced environmental impact. Consequently, the development of multifunctional alternative fuels capable of simultaneously reducing emissions and improving clinker quality represents an important research direction for sustainable cement manufacturing.

In the present study, a novel briquetted alternative fuel designated as AFR-09 was developed using rice husk, bagasse, coir pith, groundnut shell, casuarina leaves, coal dust, and plastic waste wax. The objective of this work was to evaluate the feasibility of AFR-09 as a partial coal substitute in cement clinker production. The influence of AFR-09 on calorific value, gaseous emissions, clinker phase evolution, and clinker formation efficiency was systematically investigated at different coal replacement levels (0–30%). Particular attention was given to the formation of major clinker phases including tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF), which govern the hydraulic performance of cement. The study aims to establish AFR-09 as a sustainable and technically viable alternative fuel that supports circular economy principles, waste valorization, and decarbonization of the Indian cement industry.

2. MATERIALS AND METHODS:

2.1 Materials

The preparation of AFR-09 briquettes involved the utilization of several agro-industrial residues and biomass resources including sugarcane bagasse, rice husk, coir pith, casuarina leaves, groundnut shell, coal dust, and waste plastic wax. These materials were selected based on their availability, calorific potential, combustion behavior, and suitability for cement kiln co-processing.

Sugarcane bagasse was selected as one of the primary biomass constituents due to its abundant availability in India and favorable fuel characteristics. India produces approximately 91–120 million tonnes of bagasse annually, making it one of the most consistent and reliable agro-residues for large-scale energy applications. The widespread cultivation of sugarcane in states such as Uttar Pradesh, Maharashtra, and Karnataka ensures a continuous supply of bagasse throughout the year. In addition to its renewable nature, bagasse possesses good combustion efficiency and moderate ash content, which makes it suitable for briquette production and thermal utilization in cement industries.

Rice husk was incorporated into the briquette formulation because of its high silica content and extensive availability from rice milling operations. India generates nearly 25 million tonnes of rice husk annually, while the combined production of rice straw and husk exceeds 120 million tonnes per year. The enormous quantity of rice residues generated in agricultural regions has become a major environmental challenge because a significant fraction is disposed of through open burning practices. The utilization of rice husk in alternative fuel preparation therefore provides a sustainable pathway for biomass waste management while simultaneously reducing dependence on fossil fuels.

Coir pith, obtained as a by-product from coconut processing industries, was also used as a biomass component in AFR-09. Approximately 7.5 million tonnes of coir waste are generated annually in India, with major production concentrated in southern states such as Tamil Nadu and Kerala. Coir pith possesses fibrous organic matter and moderate calorific value, which contributes to stable briquette formation and combustion performance. The incorporation of coir waste into fuel briquettes additionally supports value addition of industrial biomass residues that are otherwise underutilized.

Casuarina leaves were included as a supplementary biomass resource due to their relatively high energy density and combustion stability. Unlike conventional agricultural residues, Casuarina equisetifolia is cultivated specifically for biomass and energy applications rather than as a by-product of food crops. Therefore, national residue generation estimates are generally unavailable for this material. Nevertheless, its rapid growth rate and suitability for plantation-based biomass production make it an attractive renewable energy feedstock for alternative fuel development. The inclusion of casuarina biomass in AFR-09 was primarily intended to enhance calorific value and combustion efficiency rather than solely address agricultural waste disposal.

2.2 Preparation of AFR Briquettes

These mill AFR briquettes, produced by hydraulic briquetting press machine (Fig. 1). Materials used in briquettes wax, coal dust, paddy straw, bagasse, casuarina leaves, coir pith and ground nut shell. All solids were dried at 105 °C until moisture content wa 184 s less than 10%. The plastic waste wax was melted to softening at 60–80 °C. The dry components () were weighed material-wise and mixed well in a mechanical mixer. Melted wax was slowly mixed in until a homogenous mass formed. The resulting mixture was briquetted in a briquetting press to give briquettes. The briquettes were dried in air and then oven cured to develop adequate mechanical strength.

Table: 1 Composition of AFR 9

Name	AFR-9
Coal Dust	30.75
Rice husk	18.95
Bagasse	14.50
Casuarina leaves	10.40
Coir pith	12.40
Groundnut shell	13.00
Total Ratio	100.0

Fig. 1 Preparation of AFR Briquettes by Hydraulic Briquetting Press Machine

2.3 Determination of Calorific Value of Briquettes

A weighed fuel sample is placed in a bomb calorimeter and combusted in excess oxygen. The temperature rise of the surrounding water bath is measured, and the Gross Calorific Value (GCV) is calculated using the calorimeter constant. The Net Calorific Value (NCV) is then determined by correcting GCV for the latent heat of vaporization of water formed from hydrogen in the fuel and inherent moisture:

$NCV = GCV - [(9 \times H) + M] \times 587$, Moisture $= 5\,\%$, $H = 5.3\,\%$

Where H and M are fuel hydrogen and moisture fractions. NCV represents the usable energy in practical combustion.

AFR	GCV (kcal/kg)	NCV (kcal/kg)
AFR-9	3093	2784

2.4 Combustion and Emission Measurement System

Combustion experiments were conducted using a modified laboratory muffle furnace capable of operating up to 1000 °C. The furnace was equipped with Quartz combustion chamber, Gas outlet port, Heated transfer line (>120 °C) Gas absorption system and gas analyzer. The furnace was preheated to 850 ± 20 °C. Test samples (0.5–2.0 g) were placed in quartz combustion boats and introduced into the furnace under controlled airflow to ensure complete combustion. Flue gases were continuously extracted and directed to gas analysis systems.

2.4.1 Determination of SO_2, NO_2, and CO_2 Emissions

Major gases which were evolved were evaluated by using absorption and analyzing systems. SO_2 was absorbed in hydrogen peroxide or sodium hydroxide solution and quantified using ion turbidimetric analysis. NO_2 was measured by absorption in alkaline potassium permanganate solution followed by spectrophotometric analysis. CO_2 concentration was measured using gas analyzer All emissions were normalized to fuel mass (kg/kg fuel).

Table 2: Results of SO_2, NO_2, and CO_2 Emissions

Fuel Type	Coal Replacement (%)	So_2 (kg/kg fuel)	No_2 (kg/kg fuel)	Co_2 (kg/kg fuel)
Coal (Baseline)	0%	0.012	0.008	2.4
AFR-09	10%	0.0021	0.0072	1.765
AFR-09	20%	0.0022	0.0075	1.805
AFR-09	30%	0.0023	0.0078	1.845

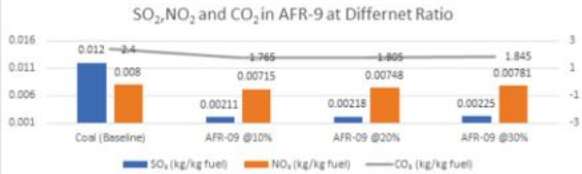


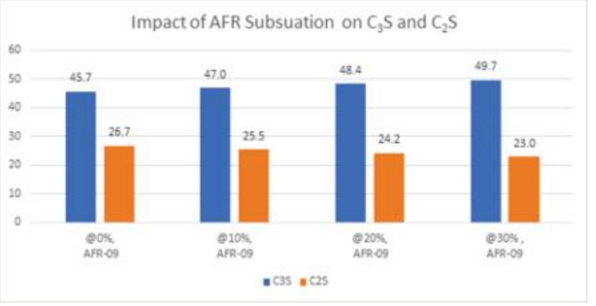
Fig. 2 SO_2, NO_2 & CO_2 Emission

2.5 Clinker Preparation

Clinker was prepared under laboratory conditions using the standard nodulization and firing method Figure 2. The raw mix was blended with AFR briquettes at different substitution levels of coal (0%, 10%, 20%, and 30%). The mixture was granulized into nodules of approximately 10 mm size. These nodules were dried and then fired in a laboratory furnace at temperatures of 1350°C, 1400°C, and 1450°C. A period of 20 minutes was maintained at the target temperature. After firing, the clinker samples were cooled under ambient conditions. The degree of clinkerization was evaluated based on free lime content.

Table 3 Coal Replacement with 10%, 20%, 30%.

Parameter	@0%, AFR-09	@10%, AFR-09	@20%, AFR-09	@30% AFR-09
C3S	45.67	47.02	48.35	49.67
C2S	26.74	25.48	24.23	22.99
C3A	8.49	8.30	8.12	7.93
C4AF	12.14	12.07	12.01	11.94



3 RESULTS AND DISCUSSION

The incremental replacement of conventional kiln feed with 10–30% AFR-09 produced a systematic, chemically coherent shift in the four major clinker phases (C_3S, C_2S, C_3A, C_4AF). These changes are statistically and industrially significant, indicating that AFR-09 actively participates in melt-phase chemistry during clinkerization.

C_3S increases monotonically (45.67 → 49.67 wt%)

C_2S decreases correspondingly (26.74 → 22.99 wt%)

C_3A and C_4AF show smaller but consistent reductions.

This pattern is characteristic of a mineralizing agent or a flux with moderate iron content, rather than an inert diluent. An empirical clinker formation efficiency can be defined as: η=C3S C3S+C2S×100η=C3S+C2SC3S×100

Table 4: Clinker Formation Efficiency

AFR-09	η (%)	Improvement
0%	63.1	Reference
10%	64.9	+1.8
20%	66.6	+3.5
30%	68.4	+5.3

AFR-09 progressively improves clinker formation efficiency by shifting the silicate phase balance toward alite. The addition of 10–30% AFR-09 to the cement raw mix systematically modifies clinker phase formation. C_3S increases by up to 4.0 wt% while C_2S decreases by 3.75 wt%, indicating effective mineralization without destabilizing the liquid phase. C_3A shows a modest but beneficial reduction (~0.56 wt%), and C_4AF remains nearly constant, confirming that AFR-09 does not disrupt the ferrite–aluminate equilibrium. These results are consistent with a weak-to-moderate multicomponent mineralizer. The optimum clinker mineralogy for hydraulic activity is achieved at 30% AFR-09, where C_3S approaches 50 wt% and C_3A falls below 8 wt%.

4. Conclusion and Future Prospectus

The study demonstrates that AFR-09 is an effective and sustainable alternative fuel for the Indian cement industry by utilizing large quantities of agricultural residues such as rice husk, bagasse, and coir pith, thereby addressing biomass waste disposal and reducing open-field burning. The calorific value of AFR-09 was found to be comparable to low-grade coal, confirming its suitability for cement kiln co-processing. A substantial reduction in gaseous emissions was achieved, with SO_2 emissions decreasing by nearly 81% and CO_2 emissions by about 23%, indicating significant environmental benefits and improved compliance with emission standards.

The clinker mineralogical analysis revealed favorable phase evolution with an increase in C_3S content from 45.67% to 49.67%, which is expected to enhance cement strength development. Simultaneously, the reduction in C_2S and C_3A contents contributes to lower heat of hydration and improved sulfate resistance, while the stability of C_4AF indicates smooth kiln operation. The clinker formation efficiency increased from 63.1% to 68.4% at 30% AFR replacement, confirming that AFR-09 acts as a weak-to-moderate mineralizer that promotes alite formation without destabilizing the liquid phase. Overall, the findings establish that 30% coal replacement with AFR-09 provides optimal clinker quality and significant emission reductions, making it a technically viable and environmentally beneficial fuel alternative. The approach strongly supports circular economy principles and aligns with national initiatives such as India's National Bioenergy Programme, the Swachh Bharat Mission, and carbon reduction targets under the Carbon Credit Trading Scheme. The future prospects of the study suggest the possibility of increasing AFR substitution levels up to 50–70% to achieve near-fossil-free cement production. The development of a national GIS-based AFR database could improve feedstock management and supply-chain optimization for cement plants across India. Integration of AFR adoption with policy instruments such as the Perform, Achieve, and Trade (PAT) scheme and carbon credit trading mechanisms may accelerate industrial decarbonization and reduce cement-sector carbon intensity by 2030. Furthermore, the AFR-09 model has potential for adaptation in other agro-based economies, enabling global replication of India's circular economy strategy.

In conclusion, AFR-09 emerges as a scalable and indigenous solution for simultaneously addressing agricultural residue management and cement industry decarbonization. By converting waste biomass into a value-added fuel that also improves clinker quality, the study provides a practical pathway toward a low-carbon and sustainable cement sector while contributing to India's long-term net-zero ambitions and environmental improvement.

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