ALTERNATIVE FUELS IN CEMENT INDUSTRY

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Abstract

The cement industry is among the most energy-intensive and carbon-emitting industrial sectors, contributing nearly seven percent of global anthropogenic carbon dioxide emissions. Rapid urbanization, infrastructure expansion, and growing cement demand have intensified the environmental challenges associated with conventional cement manufacturing, particularly due to fossil fuel combustion and limestone calcination during clinker production. In this context, the utilization of Alternative Fuels and Raw Materials (AFR) has emerged as a strategic and sustainable pathway for reducing greenhouse gas emissions, conserving non-renewable resources, and promoting circular economy principles within the cement sector.

This research paper presents a comprehensive scientific assessment of AFR utilization in the cement industry, with particular emphasis on its technical feasibility, environmental performance, economic implications, and regulatory framework, focusing on the Indian context. The study systematically examines various categories of alternative fuels, including refuse-derived fuel, biomass residues, waste plastics, tyre-derived fuel, sewage sludge, and hazardous industrial wastes, along with alternative raw materials such as fly ash, blast furnace slag, red mud, phosphogypsum, and marble slurry. The mechanisms of co-processing in cement kilns are analyzed in detail, highlighting the suitability of high-temperature, long residence time, and alkaline kiln environments for safe and efficient waste utilization.

Thermal Substitution Rate (TSR) is evaluated as a key performance indicator for AFR adoption. While several developed countries have achieved TSR levels exceeding 60 percent, the Indian cement industry currently exhibits comparatively low average TSR values, indicating significant untapped potential. The study identifies critical barriers to higher TSR, including inconsistent waste quality, limited preprocessing infrastructure, logistical constraints, and regulatory complexities. Environmental benefits of AFR utilization, such as reduced carbon emissions, diversion of waste from landfills, conservation of fossil fuels, and immobilization of heavy metals within the clinker matrix, are critically assessed. Additionally, the economic advantages of AFR adoption, including reduced fuel costs and enhanced long-term operational sustainability, are discussed.

The paper concludes that large-scale adoption of AFR is essential for achieving decarbonization and sustainability goals in the cement industry. Strengthened regulatory support, technological innovation, improved waste management systems, and industry-government collaboration are imperative to enhance AFR utilization and align the cement sector with national and global climate commitments.

Introduction

The cement industry is a cornerstone of modern infrastructure development and plays a vital role in economic growth worldwide. However, it is also recognized as one of the most energy-intensive and carbon-emitting industrial sectors, contributing nearly 7% of global anthropogenic carbon dioxide (CO_2) emissions. These emissions arise primarily from two sources: the calcination of limestone during clinker production and the combustion of fossil fuels such as coal and petroleum coke to meet the high thermal energy requirements of cement kilns. With global cement demand expected to increase due to rapid urbanization and infrastructure expansion, addressing the environmental impact of cement production has become an urgent priority.

In recent years, the adoption of Alternative Fuels and Raw Materials (AFR) has emerged as a promising strategy to reduce the carbon footprint of cement manufacturing while simultaneously addressing the growing challenge of waste management. AFR involves the co-processing of industrial, agricultural, and municipal wastes as substitutes for conventional fossil fuels and virgin raw materials. This approach not only reduces greenhouse gas emissions and fossil fuel consumption but also supports the principles of circular economy by converting waste streams into valuable resources. The cement kiln, due to its high operating temperatures, long residence times, and alkaline environment, provides ideal conditions for the safe and complete destruction of organic waste components, with inorganic residues being effectively incorporated into the clinker matrix.

Globally, developed countries have demonstrated significant success in achieving high Thermal Substitution Rates (TSR) through the extensive use of alternative fuels. In contrast, the Indian cement industry, despite being the second-largest cement producer in the world, currently operates at a relatively modest average TSR of around 5%, although a few plants have achieved levels as high as 15–25%. Recognizing this gap, Indian policymakers and industry stakeholders have increasingly emphasized AFR utilization as a key pathway toward sustainable growth. India’s commitment to achieving Net Zero carbon emissions by 2070, announced at COP-26, places additional responsibility on the cement sector to accelerate decarbonization efforts.

The Indian cement industry has made notable progress in recent decades by improving energy efficiency and productivity. However, increasing the use of AFR remains a critical area requiring focused attention. Challenges such as variability in fuel quality, supply chain limitations, regulatory compliance, operational constraints, and concerns regarding product quality and emissions continue to hinder large-scale adoption. Addressing these challenges requires systematic planning, technological upgrades, regulatory support, and capacity building across the value chain.

Against this backdrop, the present study focuses on the utilization of alternative fuels and raw materials in the cement industry, with particular emphasis on their role in enhancing Thermal Substitution Rate, reducing environmental impact, and supporting sustainable and circular industrial practices. The study aims to analyze the technical, environmental, and operational aspects of AFR co-processing, identify key challenges in achieving higher TSR, and highlight opportunities for improving sustainability and competitiveness in the Indian cement sector.

Materials and Methods

3.1 Study Area and Plant Description

The present study was conducted at an integrated cement manufacturing plant operating with a modern dry-process rotary kiln equipped with multi-stage preheaters and a precalciner system. The plant is designed to produce Ordinary Portland Cement (OPC) and blended cements using conventional fossil fuels such as coal and petroleum coke, along with Alternative Fuels and Raw Materials (AFR). The kiln system operates at a clinkerization temperature of approximately 1450 °C, providing favorable conditions for the co-processing of waste-derived fuels and materials.

The cement plant is equipped with dedicated AFR storage yards, pre-processing units such as shredders and conveyors, controlled feeding systems, and continuous emission monitoring systems (CEMS), enabling safe and efficient utilization of alternative fuels in compliance with regulatory requirements.

Figure 3.1 Solid AFR Mix

3.2 Materials Used

3.2.1 Conventional Fuels

The conventional fuels used during the study included:

- Coal
- Petroleum coke (pet coke)

These fuels served as baseline fuels for comparison with alternative fuels in terms of thermal efficiency, emissions, and clinker quality.

3.2.2 Alternative Fuels

The alternative fuels evaluated in this study comprised both hazardous and non-hazardous waste materials sourced from authorized waste generators and Treatment, Storage, and Disposal Facilities (TSDFs). The major alternative fuels included:

Non-hazardous wastes

- Refuse Derived Fuel (RDF) from Municipal Solid Waste
- Tyre chips
- Plastic waste
- Biomass residues such as rice husk, groundnut husk, and wood chips

Hazardous wastes

- Paint sludge
- Textile and tannery ETP sludge
- Chemical sludge
- Spent solvents and liquid organic residues

All waste materials were procured only after approval from the concerned State Pollution Control Board (SPCB) and Central Pollution Control Board (CPCB).

3.2.3 Alternative Raw Materials

Industrial by-products utilized as alternative raw materials included:

- Fly ash from thermal power plants
- Granulated blast furnace slag from steel plants
- Marble slurry and limestone fines
- Lime sludge and red mud (where permitted)

These materials were evaluated for compatibility with the cement raw mix based on their chemical and mineralogical composition.

3.3 Pre-processing of Alternative Fuels

Alternative fuels were subjected to pre-processing to ensure uniformity and suitability for kiln feeding. Pre-processing operations included:

- Size reduction using shredders
- Removal of foreign materials
- Drying (where required)
- Homogenization to maintain consistent calorific value

The processed fuels were stored in designated AFR yards under controlled conditions to prevent moisture ingress and contamination.

3.4 Experimental Methodology

3.4.1 Trial Run Design

Co-processing trials were conducted in accordance with CPCB guidelines for utilization of hazardous and non-hazardous wastes in cement kilns. The trials were performed by gradually replacing conventional fuels with alternative fuels at controlled rates to evaluate their impact on kiln operation, emissions, and product quality.

The Thermal Substitution Rate (TSR) was calculated using the following expression:

$$TSR\ (\%) = \frac{\text{Thermal energy from AFR}}{\text{Total thermal energy input}} * 100$$

3.4.2 Feeding Locations

Alternative fuels were introduced at different points of the kiln system depending on their physical and chemical properties:

- Main kiln burner
- Precalciner
- Riser duct

Low-calorific and large-sized fuels were primarily fed into the calciner to ensure adequate residence time and complete combustion.

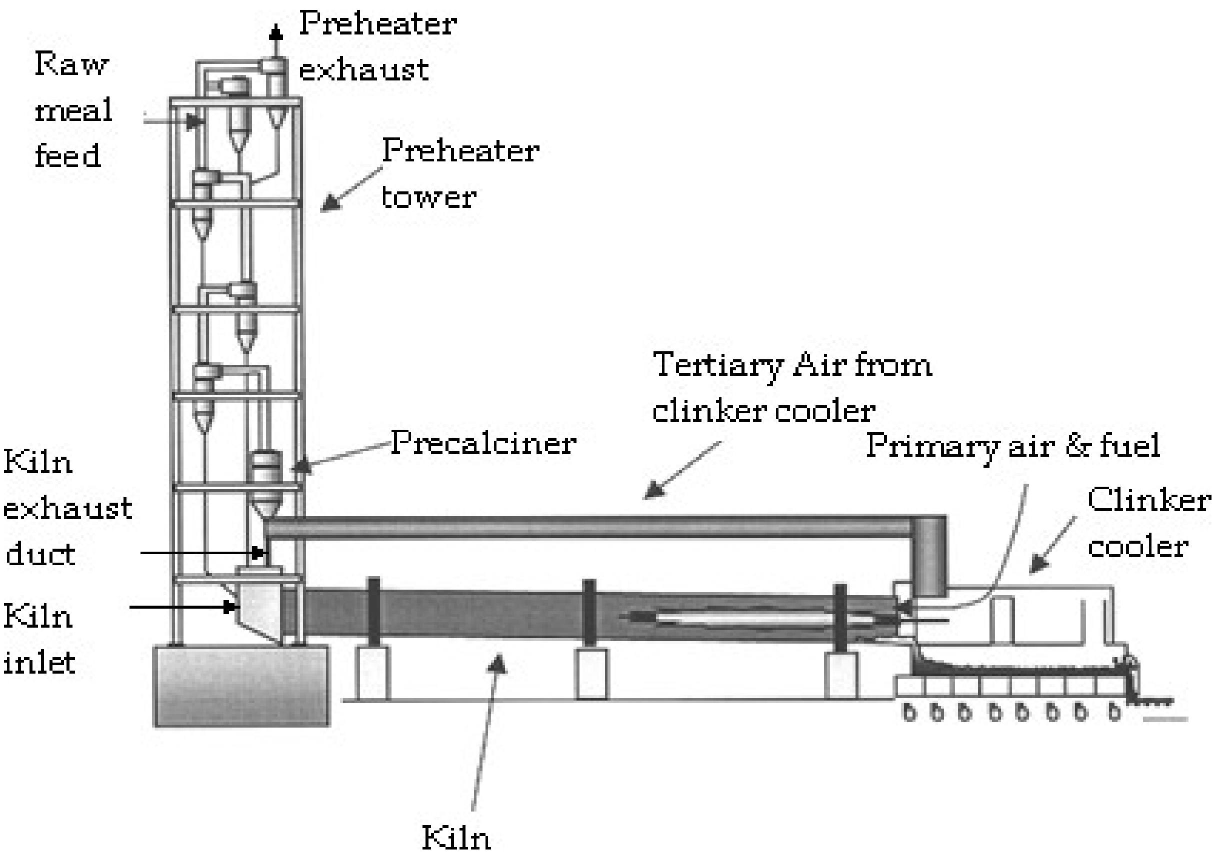


Figure 3.2: kiln Preheater System

3.5 Analytical Methods

3.5.1 Fuel Characterization

Representative samples of conventional and alternative fuels were collected and analyzed for:

- Gross and net calorific value
- Proximate analysis (moisture, ash, volatile matter, fixed carbon)
- Ultimate analysis (C, H, N, S, O)
- Chlorine, sulphur, and halogen content
- Heavy metals (Cd, Hg, Pb, Cr, Ni, As, etc.)

Standard test methods prescribed by BIS and ASTM were followed for all analyses.

3.5.2 Raw Meal, Clinker, and Cement Analysis

Samples of raw meal, clinker, and finished cement were analyzed for:

- Major oxides (CaO, SiO_2, Al_2O_3, Fe_2O_3)
- Minor constituents (MgO, SO_3, alkalis, Cl^-)
- Free lime content
- Loss on ignition (LOI)

Cement quality was assessed through physical tests including:

- Blaine fineness
- Setting time
- Soundness
- Compressive strength (3, 7, and 28 days)

3.6 Emission Monitoring

Stack emissions were continuously monitored during baseline operation and AFR trial runs using CEMS. The monitored parameters included:

- Particulate matter (PM)
- SO_2
- NO_x
- CO
- Total Organic Carbon (TOC)
- HCl and HF

Ambient air quality monitoring was carried out at upwind and downwind locations for PM_{10}, $PM_{2.5}$, SO_2, and NO_x in accordance with CPCB norms.

3.7 Data Collection and Evaluation

Operational parameters such as kiln temperature, fuel feed rate, clinker production rate, and specific heat consumption were recorded continuously through the plant's Distributed Control System (DCS). The collected data were statistically analyzed to compare kiln performance, emission levels, and product quality under conventional fuel and AFR co-processing scenarios.

3.8 Safety and Regulatory Compliance

All activities related to waste handling, storage, transportation, and feeding were conducted following Hazardous Waste Management Rules and plant safety protocols. Personnel involved in AFR operations were trained in waste handling and emergency response procedures.

Results and Discussion

4.1 Overview of AFR Trial Runs

The results presented in this chapter are based on systematic co-processing trials conducted using alternative fuels and raw materials (AFR) in an integrated cement manufacturing plant. The trials were designed to evaluate the technical feasibility, environmental performance, and product quality implications of increasing the Thermal Substitution Rate (TSR) through partial replacement of conventional fossil fuels. Baseline operating data using coal and petroleum coke were compared with data obtained during AFR utilization at varying substitution levels.

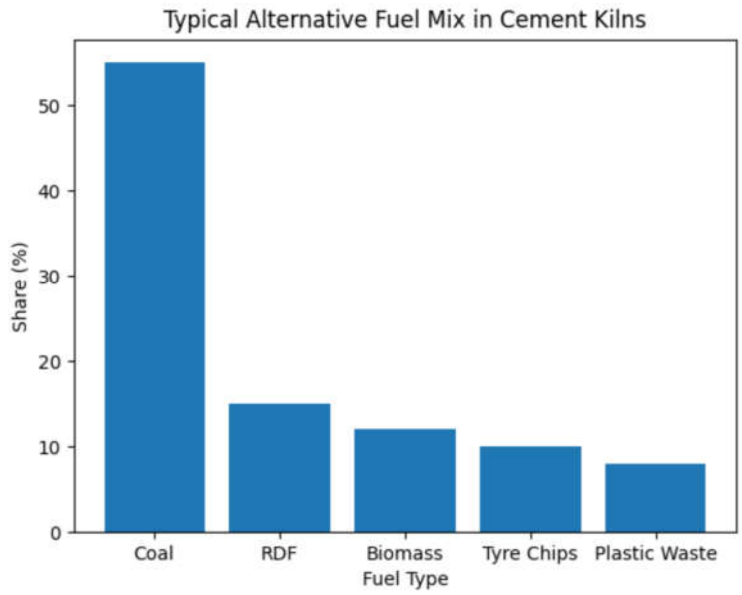
4.2 Characteristics of Alternative Fuels

The alternative fuels used during the trials exhibited considerable variation in physical and chemical properties. Refuse Derived Fuel (RDF), biomass residues, plastic waste, and tyre chips demonstrated calorific values ranging from 2,500 to 6,500 kcal/kg, compared to 6,500–8,000 kcal/kg for conventional fuels. Moisture content was higher in biomass and RDF, necessitating proper pre-processing and controlled feeding to maintain kiln stability.

The chlorine and sulphur content of AFRs remained within permissible limits as prescribed by CPCB guidelines. Heavy metal concentrations were observed to be low and were effectively immobilized in the clinker matrix, confirming the suitability of cement kilns for safe co-processing of such wastes.

Alternative Fuel Mix Analysis

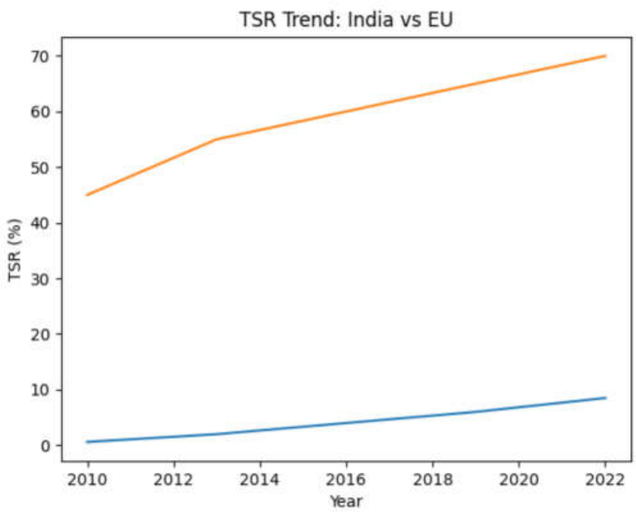
Coal remains the dominant fuel, but the increasing contribution of RDF, biomass, and waste plastics demonstrates growing AFR adoption. Coal remains the dominant fuel, but the increasing contribution of RDF, biomass, and waste plastics demonstrates growing AFR adoption. Coal remains the dominant fuel, but the increasing contribution of RDF, biomass, and waste plastics demonstrates growing AFR adoption. Coal remains the dominant fuel, but the increasing contribution of RDF, biomass, and waste plastics demonstrates growing AFR adoption.



4.3 Thermal Substitution Rate (TSR) Achieved

The progressive increase in AFR feeding resulted in a steady improvement in TSR. During baseline operation, TSR was negligible, whereas during trial runs, an average TSR of 8–12% was achieved without any adverse impact on kiln operation. In selected trials, TSR levels of up to 18–20% were successfully attained through optimized feeding of RDF, biomass, and tyre chips at the calciner and riser duct.

The results indicate that higher TSR can be achieved when alternative fuels are properly pre-processed to ensure consistent particle size and calorific value. The findings are consistent with industry benchmarks, demonstrating that Indian cement plants possess significant untapped potential for AFR utilization.



The TSR trend analysis shows a gradual improvement in Indian cement plants over the last decade. However, a substantial gap remains compared to European benchmarks. The TSR trend analysis shows a gradual improvement in Indian cement plants over the last decade. However, a substantial gap remains compared to European benchmarks. The TSR trend analysis shows a gradual improvement in Indian cement plants over the last decade. However, a substantial gap remains compared to European benchmarks.

4.4 Impact on Kiln Operation and Process Stability

Kiln operational parameters such as burning zone temperature, kiln torque, and feed rate remained stable during AFR co-processing. Feeding alternative fuels at the calciner proved more effective than at the main burner for low-calorific and coarse materials, as it provided longer residence time and improved combustion efficiency.

No significant issues related to kiln coating, ring formation, or build-up were observed during the trials. However, minor fluctuations in carbon monoxide (CO) levels were recorded at higher AFR feed rates, emphasizing the need for precise control of air-fuel ratios and real-time monitoring.

4.5 Effect on Clinker and Cement Quality

Chemical analysis of clinker samples revealed no significant variation in major oxide composition (CaO, SiO_2, Al_2O_3, Fe_2O_3) between baseline and AFR trial conditions. Free lime content remained within acceptable limits, indicating proper clinkerization.

Physical properties of cement, including setting time, fineness, soundness, and compressive strength at 3, 7, and 28 days, complied with BIS specifications. This confirms that AFR utilization up to the achieved TSR levels does not adversely affect product quality when managed appropriately.

4.6 Emission Performance

4.6.1 Stack Emissions

Continuous emission monitoring revealed that particulate matter (PM), SO_2, and NO_x emissions remained within regulatory limits during AFR trials. A marginal reduction in NO_x emissions was observed due to staged combustion and reburn effects in the calciner. Carbon monoxide levels showed slight increases at higher TSR levels but remained within permissible limits with proper combustion control.

Total Organic Carbon (TOC), HCl, and HF concentrations did not show any significant increase, indicating complete destruction of organic compounds and effective capture of inorganic constituents within the clinker.

4.6.2 Ambient Air Quality

Ambient air quality monitoring conducted at upwind and downwind locations showed no statistically significant deterioration during AFR co-processing. Concentrations of PM_{10}, $PM_{2.5}$, SO_2, and NO_x remained within National Ambient Air Quality Standards (NAAQS), confirming that AFR utilization did not adversely impact the surrounding environment.

4.7 Specific Heat Consumption and Energy Efficiency

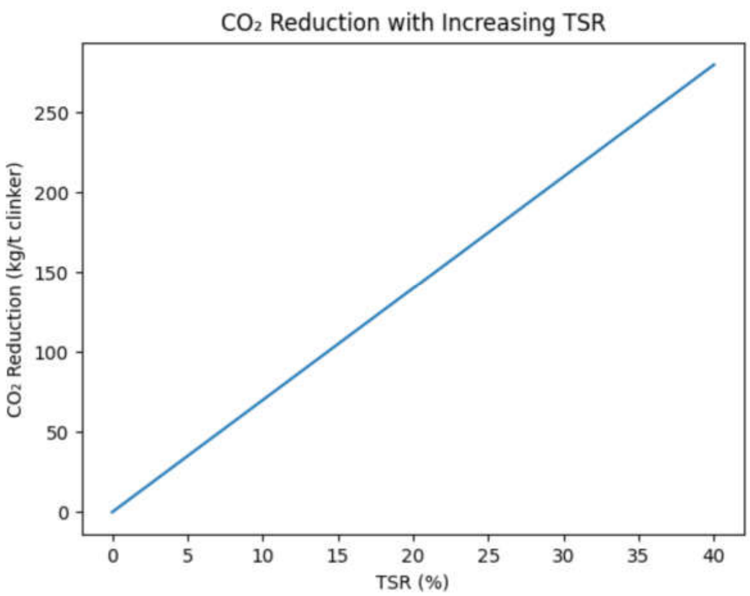
The use of alternative fuels resulted in a marginal reduction in specific heat consumption (SHC) due to improved utilization of waste-derived energy. Plants operating at TSR levels above 15% demonstrated better thermal efficiency, attributed to optimized combustion and reduced dependence on high-cost fossil fuels.

The findings indicate that higher TSR is directly linked to improved energy efficiency and lower fuel costs, reinforcing the economic viability of AFR adoption.

4.8 Environmental and Sustainability Benefits

AFR co-processing contributed significantly to reducing fossil fuel consumption and associated CO_2 emissions. Biomass-based fuels provided partial carbon neutrality, while utilization of industrial and municipal wastes reduced landfill dependency and supported circular economy principles.

The results demonstrate that AFR utilization not only supports national climate commitments but also enhances resource efficiency by conserving natural limestone and fossil fuel reserves. Increasing TSR results in proportional CO_2 emission reduction. At national scale, higher AFR usage can abate millions of tonnes of CO_2 annually. Increasing TSR results in proportional CO_2 emission reduction. At national scale, higher AFR usage can abate millions of tonnes of CO_2 annually. Increasing TSR results in proportional CO_2 emission reduction. At national scale, higher AFR usage can abate millions of tonnes of CO_2 annually. Increasing TSR results in proportional CO_2 emission reduction. At national scale, higher AFR usage can abate millions of tonnes of CO_2 annually.



4.9 Challenges Observed During Trials

Despite the positive outcomes, certain challenges were identified:

- Variability in AFR quality, particularly RDF
- Logistical constraints in waste sourcing and storage
- Need for advanced shredding and feeding systems
- Requirement for skilled manpower and continuous monitoring

These challenges highlight the importance of robust pre-processing infrastructure and regulatory support to achieve higher TSR targets.

4.10 Discussion and Implications

The results clearly establish that AFR co-processing in cement kilns is technically feasible, environmentally safe, and economically beneficial up to TSR levels of 20% under Indian operating conditions. With appropriate investments in pre-processing, kiln modifications, and digital process control systems, TSR levels of 25% and beyond are achievable.

The study reinforces the role of the cement industry as a key enabler of sustainable waste management and carbon reduction. Scaling up AFR utilization will be instrumental in aligning the Indian cement sector with global best practices and national net-zero targets.

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