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RESEARCH ARTICLE

Fueling Sustainability: A Cost-Benefit Analysis of RDF and Sewage Sludge as Alternative Fuels in Cement Production

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Abstract
With a substantial market share in the global cement industry, India ranks as the second-largest producer of cement. Cement is made by extracting and processing raw materials like shale, clay, and limestone, which are then heated to high temperatures in a kiln to create clinker. With the cement industry responsible for about 8% of all anthropogenic CO2 emissions, it is one of the largest contributors to global greenhouse gas emissions. Fuels are essential to the production of cement because they supply the heat required to burn the kilns, which turns raw materials into clinker, the main component of cement. Fossil fuels such as coal, oil, and natural gas have been used traditionally, but to lower energy costs and their negative effects on the environment, there is a growing trend toward alternative fuels, such as waste materials. Cement producers in many nations are already fuel switching from coal to alternative fuels. The cement industry combines material recycling and energy recovery to use waste as alternative fuels. Using Cost-Benefit Analysis, this study examines the use of Refuse Derived Fuel (RDF) from Municipal Solid Waste and treated Sewage Sludge (SS) as an alternative fuel for coal in cement production. Although both RDF and SS are more cost-effective and environmentally friendly alternatives to coal, this study emphasizes that RDF is a more sustainable option.

Keywords: Sewage Sludge, Refuse Derived Fuel, Municipal Solid Waste, Cost-Benefit Analysis, Cement production, Alternative fuel.

Introduction

The production of cement is an important industrial activity that is essential to the construction industry. There are several environmental effects linked to the cement production process, which raises questions regarding sustainability. Numerous factors, such as urbanization, population growth, economic development, and consumer purchasing patterns, have led to a sharp rise in waste production worldwide in recent decades. The production of municipal solid waste is expected to rise by nearly 90% by 2025, reaching 4.2 billion tons, and this trend is not expected to slow down (Kumari *et al*., 2023).

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The production of Municipal Solid Waste (MSW) is significantly rising, and the cement industry now frequently uses MSW as an alternative fuel. However, because of the waste's heterogeneity and the presence of elements that could raise quality and environmental issues, the majority of cement plants do not directly burn unsorted MSW. Rather, RDFs are employed. Depending on where they come from, the RDFs from MSW have varying physical and chemical characteristics, particularly about their water, ash, chlorine, and sulfur contents (Hajinezhad *et al*., 2016).

Every sewage sludge treatment plant produces sewage sludge, which has the potential to be a substantial source of heat, energy, or chemicals like fertilizers and macro and microelements. Sewage treatment processes around the world generate a significant amount of sewage sludge. The primary conventional disposal methods are landfills and agricultural use as organic fertilizer and soil conditioner, both of which are not environmentally friendly. Burning sewage sludge in a cement kiln and containing the ash in the clinker is an alternate method of disposal. 54,964 tons of dried sewage sludge were used by the Swiss cement industry in 2006, accounting for 22% of all alternative fuels used. The cement plant's maximum sewage sludge feed rate shouldn't exceed 5% of its clinker production capacity.

The wet sewage sludge is more suitable for use in wet process kilns and for mixing into wet process slurries. Before

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firing, the sludge in the dry cement process needs to be dried until the moisture content is less than 1%. The characteristics of the source and the sludge's treatment process determine the range of various elements in the sewage sludge as well as its calorific value. When sewage sludge is used as fuel in cement kilns instead of primary fossil fuels, NOx emissions are decreased (Zieri *et al*., 2018). For a year, using 10,000 tons of dry sewage sludge as an alternative fuel would save 60,000 tons of CO_2 emissions and replace about 25,000 tons of coal (Rusanescu *et al*., 2022).

About 3.3 GJ of energy is needed for every tonne of cement produced, making cement production a very energy-intensive process (Sharma *et al*., 2022). Fossil fuel combustion provides a substantial amount of this energy demand, between 85% and 90%. The cement industry's 7% global carbon dioxide emissions contribution (or about 2.9 billion tons of CO_2 annually in 2021) highlights the industry's role in climate change and the pressing need for mitigation measures. In the cement production process, the three main sources of CO_2 emissions are calcination (50%) fuel combustion in the kiln (40%), and manufacturing activities (10%) (Hanifa *et al*., 2023).

There are numerous challenges facing the cement industry today, and most of these relate to environmental factors or environmental degradation brought on by this particular region, such as carbon (greenhouse gas) emissions, freshwater consumption, and global warming. Lack of limestone, clinker production, and human safety issues (Elehinafe *et al*., 2022; Benhelal *et al*., 2021).

Fossil fuels, particularly coal, are the traditional energy source used in the cement industry and are linked to a significant environmental impact. Energy costs, on average, make up almost 40% of the total cost of production per ton of cement, highlighting the need for both economically and environmentally sound alternatives. Numerous studies have shown that there are promising prospects for replacing coal with alternative fuels like biomass, solid-derived fuel (SDF), and RDF. However, because it is difficult to incorporate additional fuel-saving techniques, the integration of such fuels presents operational challenges. In certain systems, the consumption of electricity is often close to 3000 MJ per ton of clinker. Greater fossil fuel savings and more stable kiln operations are made possible by thermal optimization through co-processing and pre-processing, which has been found to be an effective way to get past these obstacles. Through co-processing in cement factories, waste-to-energy relationships can be a viable and sustainable strategy, as evidenced by case studies from developing countries like Togo (Beguedou *et al*., 2023).

Since thermal energy alone accounts for almost 40% of the total production cost per ton of cement, cement production is acknowledged as one of the most energy-intensive and environmentally demanding industrial processes. Fossil fuels, like coal and pet coke, have historically been the main energy sources in rotary kilns, greatly increasing greenhouse gas emissions and production costs. In response, the cement industry has been investigating alternative fuels (AFs) made from waste streams more and more, such as SS, MSW, and RDF. By turning waste into useful energy, these AFs not only lessen reliance on finite fossil resources but also support the ideas of the circular economy. The dry process, which is used in the majority of contemporary cement plants, involves preheating, precalcining, and processing raw material in a rotary kiln at temperatures as high as 1450 °C. The rotary kiln burner and precalciner are the main locations where AF is introduced in this system. The high thermal profile required for clinker formation is maintained by the kiln burner, while the calciner stage provides high efficiency for solid-gas combustion and quick calcination. Cement plants can replace a sizable portion of coal with AFs at these stages without sacrificing the quality of the clinker, as long as the AF's calorific value and combustion characteristics are properly controlled. Beyond just being technically feasible, AF substitution has practical implications. From an environmental point of view, the substitution ratio of AFs helps to reduce carbon emissions, while from an economic point of view, it directly affects operating costs. Quantifying the financial savings and sustainability benefits linked to various substitution strategies thus requires the use of mathematical models and cost-benefit analyses. In the context of cement production economics, this study makes a contribution to this field by contrasting RDF and SS with conventional coal and highlighting their relative benefits and drawbacks (Kahawalage *et al*., 2023).

To address these issues, this work creates a mathematical model to assess the costs and environmental effects of replacing conventional fuels with alternative fuels in cement production, driven by the challenges of fuel price volatility and carbon reduction targets.

Mathematical Formulation

Notations

$AFCD$ Demand for all alternative fuels
TSR Rate of thermal substitution
AFD_{RSD} Total alternative fuel demand for RSD
AFD_{SS} Total alternative fuel demand for SS
CV_{RDF} RDF calorific value
CV_{SS} SS calorific value
MSW needed to produce RDF
∇ SS required to meet demand
E_{RDF} RDF efficiency
E_{SS} SS efficiency
Fuels consumed
CV Coal calorific value
Coal emission factor
RDF emission factor

SS emission factor
Cost of Coal
C_{RDF} Cost of RDF
C_{SS} Cost of SS
Coal cost
RDF amount
Ss price
Transportation cost
Preprocessing cost
NS_{RDF} Net savings for RDF
NS_{SS} Net savings for SS
Discount rate
Number of years
Initial investment
Annual savings

Problem Description

In recent decades, coal has been a key fuel in the manufacturing of cement. In order to analyze the replacement of coal from RDF and SS and determine which replacement produces better results, an 11-year data set of the cement manufacturing industry is gathered (MoSPI, 2025). The replacement of fuels is then examined using a Cost-Benefit Analysis (CBA) to determine which has a major contribution and whether both fuels are superior to sewage sludge. The equations given below are used to estimate the required values for the analysis (Neuwahl *et al*., 2019; Boardman *et al*., 2018; Hinkel *et al*., 2020).

$$AFCD = \Omega \times TSR$$

$$AFD_{RSD} = \frac{AFCD}{CV_{RDF} \times 1000}$$

$$AFD_{SS} = \frac{AFCD}{CV_{SS} \times 1000}$$

$$\nabla = \frac{AFD_{SS}}{E_{SS}}$$

$$\Delta = \frac{AFD_{RSD}}{E_{RDF}}$$

Coal Emission savings = $\left(\frac{\Omega}{CV_C}\right)\alpha$

RDF Emission savings = $AFD_{RSD} \times \beta$

SS Emission savings = $AFD_{SS} \times \gamma$

$$= \left(\frac{\Omega}{CV_c}\right)\phi$$

$$C_{RDF} = AFD_{RSD} \times (\varphi + \mu + \nu)$$

$$C_{SS} = AFD_{SS} \times (\chi + \mu + \nu)$$

$$NS_{RDF} = C_C - C_{RDF}$$

$$NS_{SS} = C_C - C_{SS}$$

Net Present Value for RDF = $\sum_{i=1}^{n} \frac{NS_{RDF}}{(1+D)^i}$

Net Present Value for SS = $\sum_{i=1}^{n} \frac{NS_{ss}}{(1+D)^i}$

Payback Period = $\frac{\sigma}{\omega}$

Since coal is typically used as a baseline fuel in kilns, it burns with high or complete efficiency. However, the composition and combustion behaviour of RDF and SS differ, necessitating the inclusion of its efficiency. The pre-processing costs for SS and RSD are ₹ 9500 and ₹ 6270, respectively, and the transportation cost is 500 per ton of waste (MoUD, 2016). The initial investment needed to set up infrastructure and pre-processing facilities is assumed to be ₹50 crore, which is a one-time investment, and the discount rate is 7% for the number of years 11. Using these described values and the Table 1 values the CBA is accomplished.

Result

Fuel consumption, carbon emissions, total output, gross value added, coal price, rdf price, ss price emission factors, and CO_2 savings are all taken into account in this analysis. The results were assessed using Python code. The outcome displays the Thermal Substitution Rate (TSR) values, which represent the proportion of thermal energy in the cement kiln that is replaced by alternative fuels rather than coal. An increased dependence on alternative fuels is indicated by a higher TSR of 0.4. This demonstrates how using RDF and SS can result in possible cost savings. Estimates of the RDF and SS requirements were made in order to assess the annual replacement of coal. The estimated CO_2 values show that using alternative fuels instead of coal reduces emissions.

Table 1: The input values

Factors	*Coal*	*RSD*	*SS*
Calorific value	27	15	12
Emission factors	2.5	1.0	1.6
Price	10,000	2,500	3000
Efficiency	0	0.6	0.7

The CO_2 savings increase as TSR rises, demonstrating that greater alternative fuel use leads to greater emission reduction. The Net Present Value illustrates the net financial benefits of using alternative fuels over 11 years, while the Net Saving Value reveals the cost savings from doing so. Due to the inclusion of large-scale industries in the model, the NPV value is ₹ 8,526.68 crore and ₹ 8,526.44 crore. The largest overall cost savings are indicated by a higher NPV value. Both fuels provide comparable financial gains. Here, the increased processing cost causes the NPV to decrease as TFR increases.

The payback value, which is 0.064 years or roughly 23 days, is also very short, according to the results, suggesting that investments in RDF or SS recover quickly. That is, cement plants are not financially burdened by alternative fuels, and the investment cost is promptly recouped. This indicates that early on, the savings outweigh the investment, which would encourage industry participants to use it.

Observations On Fuel Properties And Handling

Regarding the use of RDF and SS as alternative fuels in the production of cement, prior research has documented a number of operational and technical insights. These results offer crucial context for comprehending the possible effects of adopting alternative fuels.

According to reports, RDF, which is made from processed MSW, has a comparatively high calorific value. Paper, wood, and organic waste make up a sizable portion of its biogenic composition, which helps to lower CO_2 emissions in accordance with global decarbonization goals (Hemidat *et al*., 2019). However, one major issue that has been identified as affecting RDF's dependability as a fuel is the variability in its composition brought on by uneven waste segregation. Strong preprocessing, including shredding, screening, and inert material removal, is necessary to guarantee constant quality.

Sewage sludge demonstrates a unique set of properties. Despite having a lower calorific value than RDF, it has definite environmental benefits. SS can be efficiently co-fired in cement kilns at low blending ratios after being dried and processed, resulting in reliable combustion (Cheng *et al*., 2024). However, because of its high moisture content, untreated sludge requires energy-intensive drying, which raises operating costs. Despite this, SS provides a secure and effective way to get rid of leftovers from municipal wastewater because cement kiln temperatures above 1400°C can get rid of most organic pollutants and pathogens. To avoid clinker contamination and preserve product quality, continuous heavy metal monitoring is advised.

Additionally, research indicates that balancing energy production, emissions reduction, and operating expenses can be achieved by optimizing the blend of RDF and SS. The majority of calorific input is typically provided by RDF, whereas SS helps with waste management and other environmental advantages. The trade-off between financial and environmental goals is highlighted by the fact that increasing the thermal substitution rate (TSR) necessitates more extensive preprocessing, which could increase costs (Klarova *et al*., 2021). The financial feasibility of RDF and SS implementation at an industrial scale is supported by literature showing that lower coal purchases and waste disposal costs result in comparatively short payback periods, even though the initial capital investment for the necessary infrastructure can be substantial.

These observations from the literature give the current cost-oriented mathematical model context and guide the assumptions and parameter selections, guaranteeing a realistic evaluation of the economic and environmental consequences.

Discussion

The environmental benefits of using alternative fuels in cement kilns, such as SS and RDF, are well known. Research shows that using RDF in place of up to 90% of coal can divert about 40 Mg of RDF from landfills and save about 28.6 Mg of coal per hour. Similarly, it has been demonstrated that even small additions of sewage sludge, like 6% of heat input, reduce CO_2 emissions by almost 17 kg per ton of clinker. These results demonstrate how RDF and SS serve as both important instruments for reducing emissions in energy-intensive industries and efficient waste management techniques.

The economic potential of RDF utilization is also highlighted by external analyses, which align with the environmental benefits discussed. According to research centered on the Indonesian context, producing RDF yields a clear financial surplus, with each ton offering substantial financial gains in comparison to its production costs. This research supports the idea that switching to alternative fuels is not only a necessary environmental step but also a wise financial move. This supports RDF's feasibility as an alternative fuel, giving the cement industry a less expensive alternative to fossil fuels while also relieving pressure on municipal waste disposal (Wojtacha *et al*., 2022).

When combined, the data from the two studies and the current analysis point to the complementary advantages of using SS and RDF in cement production. Sewage sludge contributes to quantifiable CO_2 reduction and sustainable waste treatment, while RDF offers a high substitution potential and strong financial feasibility. By combining, they forge a path that promotes the ideas of the circular economy, lessens reliance on landfills, and improves the sustainability of the cement industry.

Coal substitution has wider societal benefits than just cost and emission reductions; these include better air quality, better public health, and less strain on landfills. This enhances the quality of life over the long run, in addition to creating cleaner urban environments. Even though the results are encouraging, there are still issues with waste availability, consistency of quality, and policy enforcement.

The findings of this research are further supported by a more comprehensive perspective from international case studies. Studies of the European cement industry, especially in Poland, show that incorporating industrial and municipal waste fractions as alternative fuels produces quantifiable ecological and economic advantages. Energy consumption averages 3.3 GJ per ton of cement, or roughly 120 kg of coal, according to production data from Polish cement plants. Even a partial switch from coal to alternative fuels offers substantial financial benefits, as energy costs account for 30–40% of the total costs of cement production.

In addition to the economic aspect, the ecological evaluation shows a steady decrease in CO_2 emissions without sacrificing clinker quality or production profitability. The fact that these plants' transition to alternative fuels did not result in an increase in dangerous heavy metal emissions is significant because it allayed stakeholders' worries about the possible health hazards of such substitutions (Niekurzak *et al*., 2024).

The cement industry in India uses a lot of energy; it accounts for 26% of industrial CO2 emissions and 15% of total energy demand. Alternative fuels (AFs) like municipal solid waste, biomass, used tires, plastics, and refuse-derived fuel (RDF) are being considered more and more as alternatives to coal and petcoke due to rising costs and fuel availability uncertainties. According to published research, when the right fuel mixtures are chosen, using AFs in cement kilns has several advantages, such as cost savings, CO2 emissions reduction, and comprehensive waste management, without posing significant environmental risks. In cement plants in India, the Thermal Substitution Rate (TSR), which measures the percentage of fossil fuels replaced with AFs, is steadily increasing, indicating expanding operational adoption. It has been noted that operational issues with AFs, like feeding and transfer chute jamming, greatly increase system downtime, underscoring the necessity of efficient handling and preprocessing. Additionally, according to environmental studies, properly blending AFs can safely co-process hazardous or high-calorific waste while lowering CO_2 and NOx emissions. Economic studies show that using AF can help offset the growing costs of fossil fuels, lessen reliance on imported coal, and offer a workable way to reach carbon neutrality targets by 2070. (Kukreja *et al*., 2023).

The present study is complemented by these findings, which show that the advantages of substituting RDF and SS go beyond local cost savings implications and represent a global trend toward sustainable cement production. They offer a useful basis for the assumptions and parameter selection in the current cost-oriented mathematical model. The use of alternative fuels is consistent with environmental regulations, the circular economy, and cement producers' long-term competitiveness, as demonstrated by the European case. Additionally, it highlights how waste-to-fuel conversion supports industry-wide decarbonization initiatives in addition to addressing growing waste volumes. When combined, the study's economic analysis and global data demonstrate that alternative fuels like RDF and SS are strategic assets rather than just supplemental ones. A vital first step in accomplishing sustainability goals, lowering reliance on fossil fuels, and advancing the creation of greener building materials is their incorporation into cement production systems. Overall, using RDF and SS in place of coal is an essential step toward producing cement in a sustainable manner that will help achieve global climate change mitigation objectives while also providing social, economic, and environmental advantages.

Conclusion

The potential of SS and RDF as environmentally friendly substitutes for coal, the traditional and most popular fuel in the manufacture of cement, is assessed in this study. The results of a thorough cost-benefit analysis show that although both RDF and SS perform better economically and environmentally than coal, RDF provides higher net and cost savings than SS. However, by reducing fuel costs and greenhouse gas emissions, SS is still a better alternative to coal, even though it requires a higher rate of substitution. These results demonstrate that the carbon intensity of cement production can be significantly decreased by substituting alternative fuels for coal. In areas with well-segregated municipal solid waste streams and processing infrastructure, RDF is especially beneficial because it requires a lower replacement ratio and produces higher cost efficiency, according to the comparative analysis. However, SS is advantageous in areas where sludge from wastewater treatment plants is plentiful, despite the logistical and operational difficulties posed by its higher consumption rate. But both examples show that switching from coal to fuels derived from waste has definite positive effects on the environment and solves urban waste management issues at the same time. This study offers verifiable proof that moving away from coal and toward RDF and SS helps achieve two goals: lowering reliance on fossil fuels and advancing a circular economy, as seen from an industrial and policy standpoint. Given the proven cost savings and sustainability benefits, cement manufacturers who are frequently wary of alternative fuels may feel more at ease. Governments and regulatory agencies can also use these insights to create incentives that promote the widespread use of RDF and SS in place of coal, such as tax breaks or emission credits.

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