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A Case Study on Energy Recovery in the Rexine Industry: Comparative Insights into RDF and Coal-Based Combustion Systems

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ABSTRACT

The growing interest in sustainable industrial solutions has motivated the development of refuse-derived fuel (RDF) as an alternative to traditional fossil fuels, which are non-renewable. This study aimed to assess the technical and environmental feasibility of using RDF as a substitute for coal in the production of rexine. The sample RDFs were subjected to proximate and ultimate analyses to determine their fuel properties. Proximate analysis indicated 34.24% moisture, 19.15% ash, and 24.61% volatile matter. The ultimate analysis revealed 30.47% carbon, 4.28% hydrogen, and a low sulfur content of 0.65%, suggesting a high combustion value with reduced pollutant emissions. Industrial trials were conducted in a 350 TPD boiler unit, and emissions were measured using continuous gas analyzers and gravimetric methods following the CPCB guidelines. The investigation confirmed that particulate matter (40.4 mg.Nm^{-3}), NOX (260.2 mg.Nm^{-3}), SO_2 (110.8 mg.Nm-^{3}), and CO (80 mg.Nm^{-3}) emissions were within acceptable limits. Cost-benefit analysis further demonstrated potential fuel cost savings of 40–60% when using RDF instead of coal. In conclusion, the results establish RDF as a clean, economical, and regulation-compliant energy feedstock for the rexin industry, aligning with the goals of a circular economy and sustainable energy transition.

INTRODUCTION

One of the critical issues associated with municipal solid waste (MSW) is rapid urbanization and increasing population, especially in developing countries such as India. The trends of this transformation are not cyclically developed but increasingly linear, causing exponential waste generation that usually outpaces infrastructure development(Ganesan et al. 2024). India produces over 150,000 metric tons of waste each day, the majority of which is untreated and dumped in an unhygienic manner (Sharma et al. 2024). These methods are not sustainable, as they cause long-term environmental pollution, soil and water contamination, air pollution through fugitive methane emissions, and other serious public health problems. Innovative waste-to-energy (WtE) technologies are rapidly emerging to address global sustainable development challenges. Among these, refuse-derived fuel (RDF) stands out as a viable alternative that minimizes landfill dependency and serves as a substitute for conventional industrial fuels (Moya et al. 2017).

Refuse-derived fuel (RDF) is a high-energy-content fuel extracted from various waste products, such as wood, plastics, textiles, and paper. It is treated to the extent that its physical characteristics allow it to easily burn as fuel. The end product is not only a commodity fuel of higher caloric quality than petcock, but can also replace coal in the future. RDF is inherently homogeneous, dry, and energy-rich, making it better suited for regulated incineration in industrial boilers and kilns than untreated raw waste (Sarquah et al. 2023). Globally, several countries, such as Germany, Sweden, and Japan, have successfully deployed RDF in their industrial energy infrastructures, such as cement kilns, power plants, and district heating systems (Sharma et al. 2024, Chyang et al. 2010).

The shift in Ireland from landfills to energy from incineration is an example of this evolution. However, India has not been very successful in adopting RDF so far, even though RDF is accepted across the globe. Although several policies, such as the Swachh Bharat Mission, Swachh Bharat Cess, and the National Policy on Solid Waste Management, have been introduced, several challenges hinder their practical implementation (Sangeetha et al. 2024). These challenges include poor source segregation, limited awareness among local authorities, lack of technical expertise and skilled labor, and inadequate financial incentives for RDF users (Sakri et al. 2021). Exacerbating the problem is India's long-standing dependence on coal, which is historically the least expensive and most accessible form of energy. Key industrial sectors, namely cement, textiles, and rexine (faux leather), still prefer coal owing to the existing infrastructure, established combustion technologies, and procurement practices (Parlikar et al. 2016). Despite the environmental and economic advantages of RDF, this structural inertia remains a barrier to its implementation.

Nevertheless, RDF possesses characteristics that qualify it as an alternative to coal-fired power generation. Although RDF typically has a relatively high moisture content, sophisticated drying and pretreatment processes can reduce it to acceptable levels, resulting in a calorific value of 4200 $caL.gm^{-1}$ for many waste feedstocks and treatment methods (Karpan et al. 2021). Its sulfur content is comparable to that of Indian coal (which contains 0.8–1.5% sulfur and contributes to high SO_2 pollution (Sharma et al. 2025). In contrast, RDF can have a sulfur content as low as 0.5%, leading to cleaner combustion. Additionally, RDF has a lower ash content than Indian sub-bituminous coal, reducing both the management and cost of disposing of combustion residues (Punin et al. 2014). The environmental impact of RDF availability is another advantage of this technology. First, the use of a binder in RDF treatment diverts MSW from landfills, limiting methane emissions from anaerobic degradation, which is 28 times more potent than CO_2 over 100 years (Makrygiannis et al. 2023). Second, net CO_2 emissions from RDF incineration are far less than those from coal, because RDF contains biomass-based materials, which are considered carbon neutral under international emissions accounting frameworks (Chyang et al. 2010). For example, coal combustion emits over 2.5 kg of CO_2 per kg of fuel burned, whereas RDF emissions are typically over 50% lower, depending on their organic content (Choudhury et al. 2022).

In addition to incineration, RDF can be used in gasification and pyrolysis, advanced thermal treatment technologies that produce syngas and liquid fuels from waste. These techniques result in lower pollutant generation, reduced energy waste, and less air pollution (Samolada et al. 2014). RDF is a clearly defined energy source that is compatible with circular economy principles and industrial decarbonization. However, high capital expenditure and the need for consistent feed material quality remain bottlenecks for large-scale RDF adoption in India(Bhatsada et al. 2023, Nema et al. 2021).

A comparative analysis of coal and RDF as industrial fuels revealed trade-offs from technical, economic, and disposal perspectives. Coal has a high fixed carbon content and stable combustion characteristics, but also produces high CO_2, SO_2, and particulate emissions, along with large amounts of fly ash due to unburned pyrite particles (Sharma et al. 2025). Although RDF is heterogeneous, proper pretreatment enables it to compete with coal in terms of energy value. RDF processing has become increasingly accurate and consistent. Moreover, RDF is becoming increasingly cost-effective. In light of fluctuating international coal prices and India's reliance on coal imports, locally generated RDF is emerging as a more stable and, in some cases, cheaper alternative (Sever et al. 2016). Additionally, industries adopting RDF can benefit from carbon credits, government subsidies, and CSR-related tax incentives, making the economic case even stronger.

The potential for RDF use in India is particularly significant in sectors such as rexine, where energy-intensive processes such as calendaring, lamination, and coating do not require high-grade fuel. Traditionally, rexine production is coal-based and environmentally detrimental because of the large furnaces used. Replacing coal with RDF in this sector could reduce India's coal dependency and help meet its climate goals as outlined in the Paris Agreement. Furthermore, the use of RDF could lower emissions of particulate matter, NO_X, and SO_2 while advancing municipal waste management objectives (Sharma et al. 2025, Makrygiannis et al. 2023).

However, the application of RDF in the rexine industry and similar fields is not without challenges. Companies must ensure RDF quality control, adopt advanced boilers and burners suited for RDF, and establish long-term RDF procurement systems. Local governments must also improve source-level waste segregation and develop modern waste processing infrastructure, which may require public-private partnerships (Nema et al. 2021). A multi-pronged approach is necessary to overcome these barriers to successful implementation. Regulations must go beyond intent and include legally binding RDF usage requirements for the industry. Monetary incentives, such as retrofit subsidies for RDF-compatible boilers and feed-in tariffs for electricity generated from RDF, should be considered. Training programs for plant personnel and municipal engineers on RDF handling and combustion optimization are essential. Independent RDF quality control and standardization are key to building industry confidence.

This study considers the feasibility of substituting coal with RDF in the production of rexine, focusing on the technical, environmental, and economic aspects of the transition. This comparison is essential for evaluating the environmental sustainability of RDF as a solution to India's growing waste and energy demands. It also explores the potential for co-firing RDF in industrial facilities and how RDF-blended fuels can help achieve climate targets, close resource loops, and support broader sustainability goals.

MATERIALS AND METHODS

Waste Segregation and RDF Collection

The mechanical separation of RDF and organic components is currently practiced in the Indian state of Uttar Pradesh. Fig. 1 illustrates the feedstock handling process at an RDF-oriented material recovery facility (MRF) for organic waste extraction. Waste is initially received at the incoming waste platform, where shallow pits are employed for treatment, especially at facilities processing 100 TPD or more. Various materials are deposited into the corresponding extraction bins, whereas flammable dry residues (such as mattresses and baskets) are ground and directed to the RDF processing line.

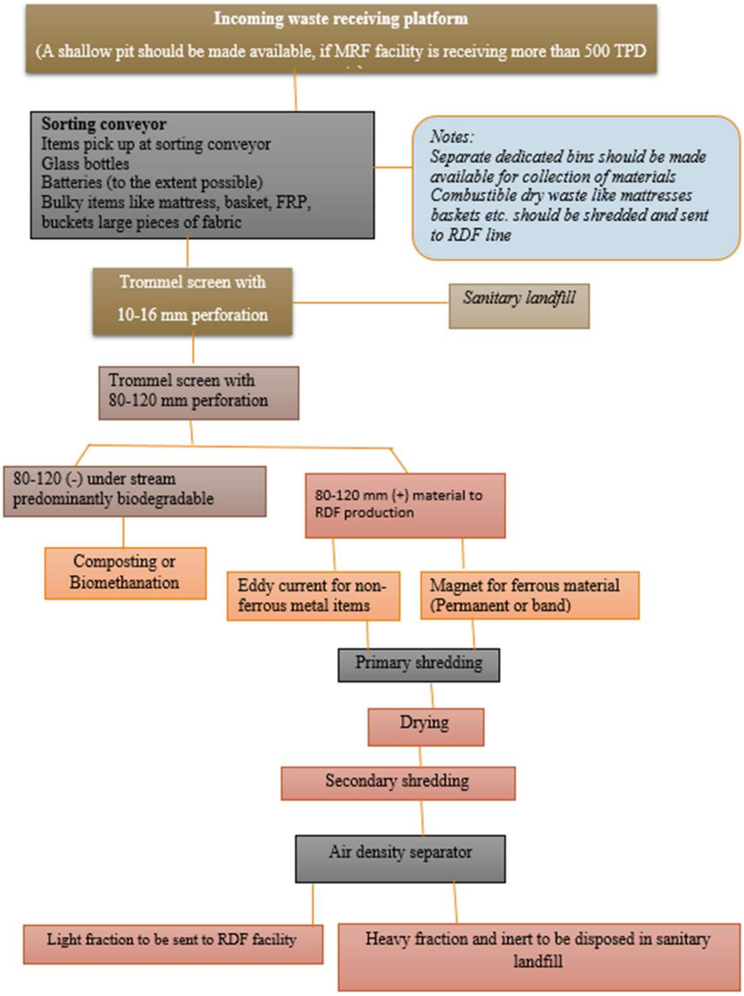

Fig. 1: Flow chart for the pre-processing of mixed municipal waste (CPHEEO 2005, CPCB 1998).

The waste is then conveyed along a sorting conveyor, where items such as glass, metals, batteries, and oversized articles (e.g., FRP buckets and mattresses) are removed. This is followed by trommel screening. The first trommel (10–16 mm apertures) separates fine inert fractions for landfilling, while the second trommel screen (80–120 mm perforations) separates biodegradable fines for composting or bio-methanation and coarser fractions for RDF production. Eddy Current Separation is used for non-ferrous metals, and Magnetic Separation is used for ferrous metals. The RDF is shredded, dried, and further processed with an air density separator, which separates light RDF fractions from heavy waste that is sent to sanitary landfills. The optimum system maximized resource recovery and RDF yield while minimizing landfill deposition.

The Ultimate and Proximate Analysis

Proximate analysis was performed using two methods, the muffle furnace method and thermogravimetric method, to determine the moisture content, volatile matter, fixed carbon, and ash. Elemental analysis (C, H, N, S, and O) was performed using a CHNS analyzer for ultimate analysis using ASTM methods (Dianda et al. 2018, CPHEEO 2005, CPCB 1998).

Stack Emission and Air Pollution Monitoring

The emissions of gaseous and particulate matter compounds (such as CO, SO_2, and NO_x) were measured using continuous gas analyzers and gravimetric methods. Sampling was carried out as per the guidelines of the EPA and CPCB, and analyzed for compliance with environmental standards (EPA 2005, CPHEEO 2005, CPCB 1998).

Working of Rexin Plant

This study investigated the application of refuse-derived fuel (RDF) in the rexine manufacturing industry, specifically examining environmental emissions and energy balance. RDF sampling was conducted at three sites in Uttar Pradesh (Morta Site, Morta Pipeline Site, and Sector 146, Noida) (Fig. 2). At each site, a 4 × 4 ft plot was demarcated, and RDF was collected to a depth of 6 in. Three replicates were taken from the edge, center, and stack regions and then composited to form representative samples. The composite mass per site was approximately 8–10 kg, which was homogenized using the quartering and coning method and sieved to control heterogeneity and ensure a uniform particle size distribution (<10 mm). Proximate analysis (moisture, volatile matter, ash, and fixed carbon) was performed in triplicate using a muffle furnace and thermogravimetric method (BIS 1994, Allen

Fig. 2: Geographical map illustrating the location of the test site.

1999). Ultimate analysis (C, H, N, S, and O) was carried out on a CHNS elemental analyzer (Perkin Elmer 2400 Series II), following (BIS 1994, Allen 1999). Higher heating value (HHV) was determined using bomb calorimetry (Allen 1999). This rigorous protocol ensured representative and statistically robust data on RDF fuel characteristics for subsequent comparative and combustion analyses. The calorific or energy value was assessed by determining the Higher Heating Value (HHV) using a bomb calorimeter. The emissions of gases and particulate matter (PM) during RDF combustion were measured to evaluate environmental performance. Gases such as CO_2, SO_2, and NO_x, along with PM, were measured using continuous gas analyzers and gravimetric methods. Sampling followed the CPCB and U.S. EPA guidelines to ensure data credibility (Dobkin et al. 2025, EPA 2005, CPHEEO 2005, CPCB 1998).

The operational process of the rexine manufacturing plants utilizing Refuse-Derived Fuel (RDF) as an energy source is illustrated in Fig. 3. RDF is collected from waste disposal sites, transported to the rexine-making facility, and moved via conveyor belts to the incineration unit. Incineration, carried out entirely with RDF, achieves up to 2.5 million calories, depending on fire conditions, fuel quality, and production efficiency. The chamber operates between 600 and 1200 °C, maintained by controlled RDF combustion. A compact moving-grate incineration system (2–4 m long, 1–2 m wide, and 2–3 m high) was installed in Uttar Pradesh; however, the exact site remains undisclosed as per company policy. Bottom ash was collected separately from the fly ash in designated chambers. Hi Tech Therm Oil 60 flowed into the pipeline through four consecutive ovens in the production line, as shown in Fig. 3, in line 8. Hi Tech Therm Oil 60 was used to make the rexine in the industry. Each oven in the production line was designed for a distinct operational function (Fig. 3). Oven-1 preheated the paper substrate, Oven-2 facilitated the drying and bonding of the rexine layer, Oven-3 applied and cured the paint coatings, and Oven-4 provided surface finishing, imparting smoothness and gloss to the final rexine sheet. Hot air, maintained at approximately 200°C and generated by heat transfer oil, circulated through coiled tubes within each oven, ensuring a uniform temperature distribution critical to each process stage. The exhaust air was subsequently routed through an air-pollution control system. The grate design supported a consistent airflow, stable combustion, and efficient heat recovery. The resulting hot gases were directed to a cyclone separator, where lime was introduced to neutralize acidic pollutants such as SO_2, thereby mitigating their environmental impact. Following neutralization, the gas stream passed through an air filtration unit, typically an electrostatic precipitator (ESP), to remove fine particulate matter and residual contaminants. The cleaned gases were then released through a chimney at an appropriate stack height to ensure safe dispersion and compliance with ambient air quality standards.

Stack emissions were measured using continuous gas analyzers and gravimetric methods, as per the CPCB and U.S. EPA guidelines (EPA 2005, CPCB 1998, Parlikar et

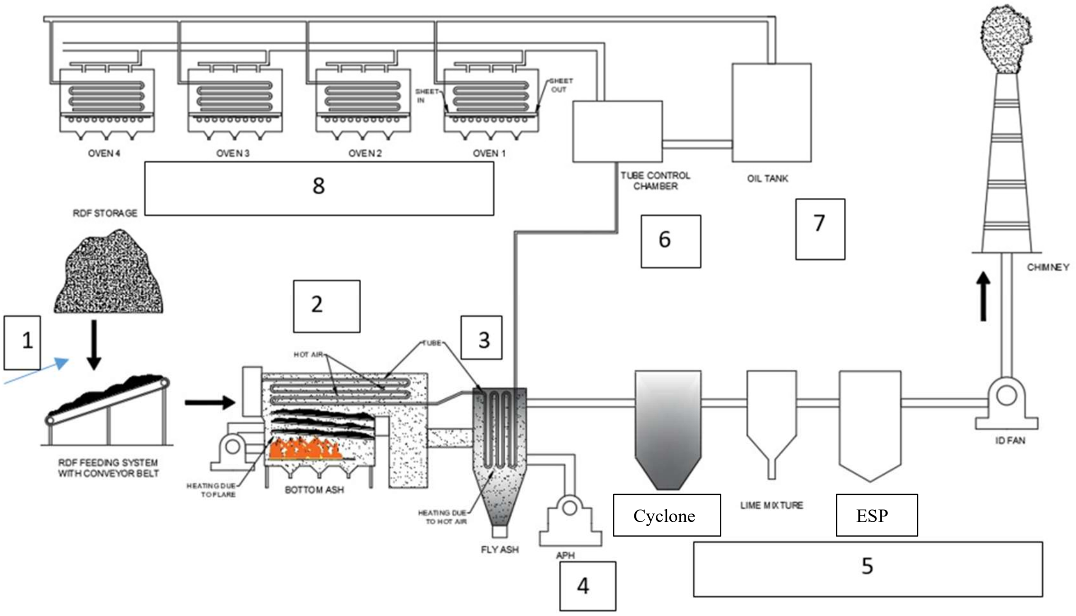

Fig. 3: Flow chart of utilization of RDF in the Rexin industry.

al. 2016). Gas velocity was determined using a Pitot tube traverse (BIS 1994) at 12 points across two perpendicular diameters (CPHEEO 2005, CPCB 1998). Corrections for temperature, barometric pressure, and moisture were applied to the data. The stack diameter was 2.7 m, and the mean velocity of 19.75 $m.s^{-1}$ was measured under actual conditions. The volumetric flow was normalized to standard conditions (0°C, 101.325 kPa, dry basis), yielding 219,175.76 $Nm^3.h^{-1}$. The air pollution control device (APCD) configuration used during the RDF trials consisted of a cyclone separator for coarse particulate removal, followed by a lime injection system and an electrostatic precipitator (ESP). This integrated arrangement effectively reduced both acid gases and fine particulates, thereby ensuring compliance with regulatory standards.

Total Nox was measured using CPCB emission standards and IS 11255 guidelines (BIS 1994). Stack gas monitoring was performed using a HORIBA PG-350 Portable Gas Analyzer, which employs chemiluminescence detection for NOx, nondispersive infrared for CO and CO_2, and electrochemical/paramagnetic sensors for O_2 and SO_2. The instrument was calibrated using certified span gases (NO, SO_2, and CO in N_2 balance) and zero checks with high-purity nitrogen before each sampling session. Each monitoring run was conducted for a minimum averaging period of 30 min, with three replicate runs performed on separate days. Mean values and 95% confidence intervals are now reported in the Results section to demonstrate the repeatability.

Particulate matter (PM) was measured using isokinetic sampling in accordance with the IS 11255 (Parts 1–7) and CPCB protocols (BIS 1994). An Envirotech APM 415 stack monitoring kit with pre-weighed glass fiber thimbles was used. The nozzle diameter was selected based on the stack gas velocity to maintain isokinetic sampling conditions, and each run lasted for 60 min. The filters were conditioned and weighed in a controlled environment before and after sampling, and the gravimetric mass was corrected for moisture to derive the PM concentration in $mg.Nm^{3-}$. This approach ensures that the reported PM values are fully compliant with the CPCB and IS 11255 requirements (BIS 1994, EPA 2005, CPHEEO 2005, CPCB 1998).

RESULTS AND DISCUSSION

Comparative Performance of RDF and Coal as Rexine Industries Fuels

RDF is being developed and utilized globally as a potential substitute fuel for coal in industries such as cement, textiles, and rexine. RDF is especially useful for urban communities where MSW is generated abundantly and can be converted into an attractive fuel, which is consistent with sustainable waste management and the circular economy. Nonetheless, a comprehensive characterization of RDF's physical and chemical properties, especially compared to coal data, is an essential step for its successful substitution or co-firing with coal.

According to the results obtained (Table 1) from the proximate and ultimate analyses, RDF has several beneficial characteristics; however, some limitations require suitable pretreatment. In the present study, the moisture content of RDF was reported as 34.24%, which is much higher than that of typical Indian coal (8–12%). A high moisture content results in a low heating value and poor combustion efficiency, which often leads to incomplete combustion, increased emissions of pollutants such as CO and VOCs, and impaired industrial boiler operations (Sarquah et al. 2023). Therefore, drying methods such as mechanical dewatering, sun drying, or newer methods (microwave, torrefaction) are needed to reduce the moisture content of RDF to an acceptable level for proper and sustained combustion.

RDF showed a volatile matter content of 24.61%, which is similar to that of Indian coal. This factor is important for the ignition and stability of the flame. The fixed carbon in RDF (21.97%) is much lower than that in coal (one-third to one-half, 35–45%), which indicates short combustion times and low energy content (Zahir et al. 2024). However, this shortfall can be balanced by co-firing RDF with high-carbon fuel or improving the burner design to ensure constant burning.

RDF has an ash content of 19.15%, which is lower than that of certain grades of Indian coal, particularly high-ash indigenous lignite and sub-bituminous coal. Less ash is better because it leads to less slag and clinker formation in the furnace, thereby reducing the disruption of operations. The golden rule is: the less, the better. However, RDF has a much lower bulk density (0.43 $g.cc^{-1}$) than coal (0.8–1.0 $g.cc^{-1}$), which influences the design of fuel handling and feeding systems, as well as storage, to ensure the efficient use of RDF(Makrygiannis et al. 2023). The analysis of RDF revealed that it contains hydrogen (4.28%), which is in the lignite coal range, which is beneficial for heating value and flame properties. Amounts of nitrogen and sulfur (0.95% and 0.65%, respectively) are permissible by regulations but necessitate SO_2 and NO_x emission controls (Ganesan & Vedagiri 2024). Finally, considering that coal has better stability during combustion because of its low moisture content and high fixed carbon content, RDF is a feasible alternative, particularly under controlled combustion conditions. Additionally, RDF helps divert large volumes of municipal waste from landfills, reduces greenhouse gas emissions, and promotes the sustainable use of resources.

Table 1: Comparative evaluation of RDF and coal based on proximate and ultimate analysis.

Parameter	Unit	RDF	*Coal (Typical Indian) **	Remarks
Proximate Analysis				
Moisture Content	%	34.24	8–12	RDF requires drying, whereas coal has better combustion efficiency owing to its low MC
Volatile Matter	%	24.61	18–25	It is comparable and essential for ignition and combustion
Fixed Carbon	%	21.97	35–45	Lower RDF impacts sustained combustion
Ash Content	%	19.15	20–35	Lower than some coal grades, favorable for slagging and fouling
Ultimate Analysis				
Carbon	%	30.47	40–55	Moderate: contributes to energy content
Hydrogen	%	4.28	3.5–4.5	Similar to coal
Nitrogen	%	0.95	1–2	Acceptable range
Sulphur	%	0.65	0.4–1.0	SO_2 scrubbers are needed within acceptable limits
Oxygen	%	10.26	5–15	Moderate, affects the combustion stoichiometry
Gross Calorific Value (GCV) On air dry basis)	$CaL.gm^{-1}$	4200	7000	Comparable, efficient with blending or pre-drying
Net Calorific Value (NCV) On air dry basis)	$CaL.gm^{-1}$	3800	6600	Within the usable range, depending on the system efficiency
Bulk Density	$g.cc^{-1}$	0.43	0.8–1.0	Lower temperatures affect storage and feed systems

When combined with emission control systems, RDF becomes a highly suitable partial or complete replacement for coal in the rexine industry and related thermal applications, while supporting sustainable operations and reducing environmental impact.

Stack Emission Performance Evaluation of RDF Usage in the Rexine Industry

In energy-consuming industries, such as the production of rexine, the changeover from conventional fossil fuel-based systems to waste-derived alternatives is a prime industry concern. In this study, the stack emissions and operational parameters of a 350 TPD industrial boiler burning RDF were compared with those of a conventional coal-powered boiler of similar capacity and operational time. This study aimed to assess the environmental impact of RDF as a clean and sustainable alternative fuel source in comparison with Indian (CPCB) guidelines and Indian Standard IS-11255 (BIS 1994, Sharma et al. 2025, CPCB 1998).

The stack surveillance of RDF operations was monitored at an industrial plant (350 TPD boiler). A set of parameters, including chimney height, temperature, velocity, and emissions of PM, NO_X, SO_2, and CO, was monitored as per CPCB guidelines and IS-11255 Parts 1, 2, 3, and 7 (BIS 1994, CPCB 1998, Chyang et al. 2010). An air pollution control device, including a baghouse, was used to efficiently collect and remove particulate and gaseous emissions from the system. The PM load was 40.4 $mg.Nm^{-3}$, which was well below the permissible CPCB standard of 50 $mg.Nm^{-3}$. Under the same conditions, emissions from a coal-fired boiler commonly lie in the range of 110–90 $mg.Nm^{-3}$ and often exceed the control limits owing to poor combustion efficiency and inadequate filtration devices (Sarquah et al. 2023). The NO_X and SO_2 values for RDF were 260.2 $mg.Nm^{-3}$ and 110.8 $mg.Nm^{-3}$, respectively, both within the prescribed limits of 400 $mg.Nm^{-3}$ for NO_X and 200 $mg.Nm^{-3}$ for SO_2. In comparison, NO_X levels for coal can often exceed 350–450 $mg.Nm^{-3}$, while SO_2 levels may range from 220–180 $mg.Nm^{-3}$, mainly due to the higher nitrogen and sulfur content in Indian grades of bituminous and sub-bituminous coal (Mateus et al. 2023). CO emission from RDF was 80 $mg.Nm^{-3}$, which is approximately the upper standard limit of 100 $mg.Nm^{-3}$ but still within the allowable range. In contrast, CO concentrations are relatively high during coal burning, especially when combustion is incomplete, resulting in CO concentrations of 120–150 $mg.Nm^{-3}$. This reflects incomplete combustion and a higher environmental risk (Ruhela et al. 2024).

The dynamic process of stack patterns in RDF operations also plays a role in the efficient dispersion of contaminants. During operation, an average mean-stack temperature of 280°C and a mean gas velocity of 19.75 $m.s^{-1}$ were obtained, which provides even higher release as well as upward movement of emissions, thereby reducing ground-level concentrations. In the case of coal-fired boilers, which have higher temperatures (300–320°C) but generally poorer velocity conditions, local pollution can be enhanced. Coal

Table 2: Comparative Table: Emission & Stack Performance RDF vs. Coal. (CPHEEO 2005, CPCB 1998, Karpan et al. 2021, Sarquah et al. 2023).

Parameter	RDF (Present Study)	Coal (Typical Indian Industrial Use)	CPCB Limit	Remarks
Boiler Capacity [TPD]	350	350–500	–	Comparable industrial capacity
Fuel Consumption [t.h^{-1}]	4–4.5	5–5.5	–	RDF has lower consumption → better thermal optimization
Stack Height (from ground, ft)	100	90–100	–	Similar design standard
Stack Diameter [m]	2.7	2.5–3.0	–	No major difference
Stack Temperature [°C]	280	300–320	–	Slightly lower in RDF—indicating controlled combustion
Average Stack Velocity [m.s^{-1}]	19.75	20–22	–	Comparable
Quantity of Emission [Nm^3.h^{-1}]	219,175.76	240,000–260,000	–	Lower for RDF → cleaner operation
Particulate Matter [PM, mg.Nm^{3-}]	40.4	90–110	50	RDF meets standards, coal often exceeds without high-end ESPs
Oxides of Nitrogen [NO_X, mg.Nm^{3-}]	260.2	350–450	400	RDF is within limit, coal sometimes exceeds
Sulphur Dioxide [SO_2, mg.Nm^{3-}]	110.8	180–220	200	RDF emission is lower, supporting low-sulfur combustion
Carbon Monoxide [CO, mg.Nm^{3-}]	80	120–150	100	RDF remains compliant, coal combustion leads to higher CO
Control Measures Used	Bag House	Electrostatic Precipitator (ESP) or Cyclone	–	Bag House shows excellent performance with RDF
Fuel Type	RDF (processed MSW)	Coal (bituminous/sub-bituminous)	–	RDF diverts waste, coal causes GHG and mining damage
Purpose of Monitoring	Pollution Load Assessment	Same	–	–

has a heating value of 7000 caL.gm^{-1} (raw basis), whereas RDF contains 4200 caL.gm^{-1}, depending on the biomass material and its pre-treatment. This difference indicates that, to produce the same amount of energy, RDF would require a mass flow approximately one order of magnitude higher. In line with these predictions, industrial trials demonstrated a specific RDF consumption of 8–10 t.h^{-1} versus 5–5.5 t.h^{-1} for coal. The higher consumption of RDF is consistent with its comparatively lower calorific density; however, its good combustion kinetics maximized its utilization. High volatile matter, low ash load, and low sulfur fraction were conducive to stable ignition, less fouling, and cleaner combustion despite the low energy density of coal, mitigating some of the adverse effects. Beyond thermal performance, the incineration of RDF removes large volumes of waste material from landfills, reduces the potential surface emissions of methane, and supports circular economy goals, including the controlled combustion of RDF waste.

Overall, this comparative analysis clearly demonstrates that RDF outperforms coal in key areas, such as emissions of regulated pollutants (PM, SO_2, NO_X, and CO), fuel consumption, and compliance with CPCB regulations (Table 2). The fact that RDF operates efficiently with conventional baghouse filtration gives it an edge as an alternative fuel source for the rexine industry to meet statutory and environmental commitments. The continued strengthening of policy frameworks and advancements in RDF processing and combustion technologies can significantly reduce the environmental footprint of India's industrial sector.

A limitation of this study is that the chloride content, along with emissions such as hydrogen chloride (HCl), hydrogen fluoride (HF), polychlorinated dibenzo-p-dioxins and furans (PCDD/F), and heavy metals, was not measured. The presence of these compounds poses potential environmental and health risks during RDF combustion. Future studies should comprehensively monitor chloride and associated emissions to better evaluate and control their impacts.

Benefits of RDF as Compared to Coal in the Rexine Industries

Economic, environmental, and operational comparisons of refuse-derived fuel (RDF) and lignite indicate that RDF is much more advantageous than conventional coal as an industrial fuel (Table 3). From a cost perspective, RDF offers substantial savings, with a fuel cost of only Rs. 3,000–Rs. 5,000 per ton compared to Rs. 8,000–Rs. 10,000 per ton for

Table 3: Comparative assessment: RDF vs. Coal across key performance metrics.

Parameter	RDF	Coal	Why RDF is Better
Fuel Price (Rs. /ton)	Rs. 3,000–Rs. 5,000	Rs. 8,000–Rs. 10,000	Lower costs significantly reduce fuel expenditures.
Government Incentives	Available (e.g., waste-to-energy subsidies, carbon credits)	Not applicable	RDF qualifies for multiple sustainability programs.
Operational & Lifecycle Cost	Moderate (handling + processing offset by savings)	Higher (ash disposal, emission treatment)	RDF reduces costs in the long term through the dual benefits of fuel and waste management.
Waste Disposal Costs	Eliminated (waste is utilized)	Additional ash handling and environmental penalties	RDF supports zero-waste goals.
Energy Density (CaL. gm^{-1})	4200	7000	Although lower, RDF can be optimized using additives such as plastics or biomass.
Combustion Temperature	850–1,100°C	900–1,500°C	It is adequate for most industrial processes, such as heating in the rexine industry.
System Adaptability	Requires optimized modern combustion systems	Works with standard boilers	RDF systems are becoming increasingly efficient and scalable.
Waste Heat Recovery	High potential, adaptable with modern tech	High	RDF-based systems support energy-saving integration.
Waste Management Impact	Supports landfill reduction and resource recovery	Contributes to mining and solid waste	RDF promotes a circular economy by valorizing waste.
Ash Production	15–25% (manageable with filters)	10–15% (often toxic and difficult to treat)	RDF ash can be reused and stabilized effectively.
Toxic Emissions (SO_2, NOx, CO)	Significantly lower with filtration systems	High unless expensive scrubbers are used	RDF meets the CPCB norms with simpler control systems.
Fuel Availability	None – Locally produced from domestic waste	Often reliant on imported coal (e.g., coking coal)	RDF supply is stable and future-proof.
Import Dependency	Requires tailored combustion setup	Readily compatible with existing systems	It reduces the foreign exchange burden.
Infrastructure Requirement			RDF infrastructure is evolving with increasing industry adoption.
Market Scalability	Rapidly growing due to policy and environmental pressures	Plateauing due to regulatory and environmental limitations	RDF aligns with future clean energy roadmaps and urban waste management strategies.

coal. In addition, the operational cost of RDF is effectively reduced by government policy support, such as incentives, grants, and carbon credits under waste-to-energy and circular economy policies. Special infrastructure may be necessary for RDF combustion; however, the overall lifecycle costs are calculated to be lower when ash handling and waste disposal costs are eliminated.

Although the calorific value of coal (7000 $cal.g^{-1}$) is higher than that of RDF (4200 $cal.g^{-1}$), the combustion temperature can still meet the requirements for applications such as heating in rexine production. The compatibility of RDF with existing combustion systems, combined with waste heat recovery technologies, increases its utilization efficiency. RDF may also be upgraded by co-treatment with biomass or plastic waste to enhance its energy content.

RDF also has a significant advantage in terms of environmental sustainability. RDF facilities produce much lower emissions of regulated pollutants such as SO_2, NOx, CO, and PM when equipped with a cyclone, lime mixture, and electrostatic precipitator (ESP). Additionally, RDF promotes better waste treatment by assisting in waste diversion from landfills and reducing the reliance on fossil fuels. Although the RDF ash content is relatively high (15–25%), it is less hazardous and easier to handle than coal ash.

Finally, RDF's scalability and sustainability stem from its local availability, increasing stock due to growing MSW generation, and limited dependence on imports. This makes RDF not only a technically viable solution but also a strategic resource for sustainable industrial growth, aligning with the circular economy philosophy.

Strategic Role of Refuse-Derived Fuel (RDF) in Advancing Sustainable Industrial Energy Systems

Refuse-derived fuel (RDF), derived from the combustible components of municipal solid waste, has attracted growing interest as a possible alternative to traditional fossil fuels for industrial use. Its integration with energy systems for the production of useful heat and other types of energy also meets the general targets of both environmental and economic sustainable development. With rising energy demand coupled with growing levels of waste, RDF serves as a pathway to cleaner, more circular energy. The feasibility of RDF is given below:

A. Economic Feasibility and Optimal Fuel Cost

Although the heat value of RDF is lower than that of conventional fuels such as coal or petcoke, it has cost advantages. Lower acquisition costs, lower tipping fees, and potential full government funding all reduce the operating costs. This financial encouragement has made RDF an attractive proposition and economically viable for industries, including those with high thermal energy requirements, such as cement kilns and textiles.

B. Environmental Benefits and Closed Resource Loops

There are significant environmental gains from using RDF. RDF diverts non-recyclable waste from landfills, thereby reducing methane generation and the leachate load on municipal waste systems. Upon combustion, there are reduced net CO_2 emissions compared to coal, which aligns with the international climate policies. In addition, the implementation of RDF supports the practical application of a circular economy by transforming waste into value-added energy.

C. Policy Alignment and Industrial Transformation

Government- and institution-led pressures are compelling industries to seek alternative, environmentally friendly options. RDF interest has been generated not only by the positive policy environment that surrounds it (carbon credits, tax incentives, and co-processing obligations) but also because of its economic interest. These measures not only improve the economics of RDF but also stimulate industries to reach sustainability and compliance targets more quickly.

D. Energy Security and Resource Independence

RDF also contributes to improved energy security by using domestic waste resources and decreasing the imports of fossil fuels. This is even more evident in fluctuating international fuel markets. RDF has the advantage of a reliable and uninterrupted supply chain. In combination with developments in waste sorting and pretreatment, this reliability makes uninterrupted industrial operations possible.

F. Regulatory Incentives and Corporate Sustainability

RDF is receiving policy support, and in India, state and central schemes are encouraging its adoption through financial and regulatory incentives. Businesses that adopt RDF may enjoy additional EPR credits, lower environmental fees, and an enhanced corporate image in sustainability reports. Taken together, these drivers make RDF a strategic tool for meeting net-zero carbon targets. RDF is much more than just an alternative fuel source: it is a convergence of energy insight, environmental responsibility, and economic sense. With the development of technology and the maturity of waste-to-energy concepts, RDF has the potential to change the eco-industrial pattern and move toward sustainability.

CONCLUSIONS

This study demonstrates that refuse-derived fuel (RDF) offers a technically sound and economically favorable alternative to coal in the rexine industry. While coal has traditionally been the primary energy source due to its high calorific value (7000 $CaL.g^{-1}$), RDF, with a calorific value of 4200 $caL.gm^{-1}$, is sufficient for industrial heating needs, especially when optimized combustion systems are employed. Importantly, RDF exhibits a much lower sulfur content (0.65%) than coal, along with manageable ash production (19.15%), thereby reducing environmental risks. Emissions from RDF combustion, including PM (40.4 $mg.Nm^{-3}$), NO_X (260.2 $mg.Nm^{-3}$), SO_2 (110.8 $mg.Nm^{-3}$), and CO (80 $mg.Nm^{-3}$), were well within the CPCB norms and notably lower than the typical coal emissions. Economically, RDF is more cost-effective, reducing raw fuel costs from ₹8,000–₹10,000/ton (coal) to ₹3,000–₹5,000/ton, making it attractive for long-term operational sustainability. In summary, although coal offers a higher energy density, RDF outperforms coal in terms of environmental compliance, cost savings, and alignment with sustainability goals. Its adoption can support waste valorization and reduce dependence on fossil fuels, paving the way for greener industrial-energy systems.

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