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Circular Economy-Based Business Model in India for Sustainable Industrial Hazardous Waste Management

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Abstract

India generates 7.81 Mt/yr of hazardous waste, 68.6 Mt/yr of municipal solid waste, yet its thermal substitution rate (TSR) in cement kilns remains at 2.5%, far below the global average of 15% and leaders such as the Netherlands (83%) and Austria (80%). The Indian cement sector contributes approximately 7% of national CO_2 emissions, presenting a significant mitigation opportunity through alternative fuels and raw materials (AFR) co-processing. This paper quantifies greenhouse gas (GHG) emission reductions achieved through an integrated pre-processing and co-processing pathway for industrial hazardous waste in cement kilns, based on a 14-year (2012–2026) case study of Green Gene Enviro Protection & Infrastructure Ltd. (GGEPIL). Using IPCC 2006/2019 Tier-1 methodology aligned with ISO 14064-2:2019, WBCSD-CSI GCCA v3.1, and UNFCCC CDM ACM0003 frameworks, a comparative assessment was conducted between (dedicated incinerator + 100% coal-fired kiln) against integrated co-processing pathways. Results demonstrate a cumulative net GHG abatement of 0.911 Mt CO_2e over the study period from co-processing 1.638 Mt of hazardous waste, displacing 950 kt of coal and eliminating 65.53 ML of light diesel oil (LDO). Monte Carlo uncertainty analysis yields a 95% confidence interval of 2.02–2.28 Mt CO_2e with ±16% uncertainty. The specific abatement factor of 1.11 t CO_2e/MT waste positions this pathway at the upper bound of published literature ranges. Coal displacement accounts for 93% of total benefits, while incinerator elimination contributes 7%. These findings underscore that pre-processing infrastructure- not waste availability- is rate-limiting step for scaling India's TSR, aligning climate mitigation, energy security, and circular economy objectives.

Keywords: alternative fuels and raw materials, cement kiln co-processing, circular economy, greenhouse gas abatement, hazardous waste management, thermal substitution rate (TSR).

I. Introduction

India's rapid industrialization and urbanization have generated unprecedented volumes of waste streams that pose significant environmental and public health challenges. According to the Central Pollution Control Board (CPCB) Inventory 2024, India annually generates 7.81 million tonnes (Mt) of hazardous waste from 47,103 registered industrial units, 68.6 Mt of municipal solid waste (MSW), and 170 Mt of construction and demolition (C&D) waste [1]. More alarmingly, legacy stockpiles of MSW exceed 1,300 Mt, representing decades of inadequate waste management infrastructure and practices [2]. These waste streams contain substantial embodied energy and mineral content that remain largely untapped, representing a critical gap in India's transition toward a circular economy.

The cement manufacturing sector, as one of India's largest industrial energy consumers and the third-largest globally, accounts for approximately 7% of the nation's total CO_2 emissions [3], [4]. Each tonne of cement produced generates 0.7- 0.93 tonnes of CO_2, primarily from calcination of limestone (process emissions) and combustion of fossil fuels (energy emissions) [5]. With India's cement production capacity exceeding 500 Mt/yr and projected to grow substantially to meet infrastructure development needs, the sector's carbon footprint presents both a challenge and an opportunity for climate mitigation.

Co-processing of alternative fuels and raw materials (AFR) in cement kilns offers a technically proven, economically viable, and environmentally sound solution for simultaneous waste management and fossil fuel displacement [6], [7]. The high-temperature (>1,450°C) pyro-processing environment in cement kilns ensures complete destruction of organic contaminants, including persistent organic pollutants (POPs), while the alkaline clinker matrix immobilizes heavy metals and incorporates mineral ash, eliminating secondary waste streams [8], [9]. Despite these advantages and an estimated national AFR feedstock potential of 550 Mt/yr, India's thermal substitution rate (TSR)- the proportion of thermal energy derived from alternative fuels- remains at a mere 2.5% [10].

This performance starkly contrasts with international benchmarks: the Netherlands achieves 83% TSR, Austria 80%, Germany 68%, and the global average stand at 15% [11], [12]. European cement kilns collectively saved approximately 2.5 million tonnes of coal annually through AFR utilization, with France demonstrating 52.4% alternative fuel usage [13]. The disparity between India's abundant waste-energy potential and its low industrial uptake represents a major unrealized mitigation opportunity, constrained primarily by inadequate pre-processing infrastructure, regulatory barriers, and limited awareness rather than technical or feedstock limitations [14], [15].

The environmental benefits of co-processing extend beyond direct fossil fuel displacement. Conventional hazardous waste management in India relies heavily on dedicated incinerators that consume auxiliary fuels-typically light diesel oil (LDO) at approximately 40 liters per tonne of waste- and generate residual ash requiring landfill disposal [16]. This dual-system approach (incinerator for waste + coal-fired kiln for cement) results in higher cumulative GHG emissions, greater fossil fuel consumption, and additional environmental burdens from ash management compared to integrated co-processing pathways [17], [18].

Quantifying the GHG emission reductions attributable to co-processing requires rigorous life-cycle inventory (LCI) analysis aligned with internationally recognized methodologies. The IPCC 2006 Guidelines for National Greenhouse Gas Inventories, refined in 2019, provide the foundational Tier-1 framework for emission factor-based calculations [19], [20]. Sector-specific guidance from the World Business Council for Sustainable Development-Cement Sustainability Initiative (WBCSD-CSI) Global Cement and Concrete Association (GCCA) CO_2 and Energy Accounting and Reporting Standard v3.1 [21] and the UNFCCC Clean Development Mechanism (CDM) methodology ACM0003 for fossil fuel substitution in cement manufacture [22] offer additional rigor for project-level quantification. ISO 14064-2:2019 provides the overarching framework for greenhouse gas project-level quantification, monitoring, and reporting [23].

Despite the existence of these methodologies, peer-reviewed literature quantifying GHG abatement from hazardous waste co-processing in Indian cement kilns remains limited. Tiwary et al. [24] reported that co-processing in Indian cement kilns reduced CO_2 emissions by 3.9 Mt and saved 2.1 Mt of coal from 2010- 2013, with refuse-derived fuel (RDF) and tire-derived fuel (TDF) achieving specific abatement factors of 1.36 and 2.4 t CO_2/t waste, respectively. Saha and Karstensen [25] established baseline TSR and AFR potential for the Indian cement industry but did not provide facility-specific emission quantification. Baidya et al. [26], [27], [28] conducted pilot studies on various industrial waste streams in Indian cement kilns, demonstrating technical feasibility and environmental benefits, yet lacked comprehensive multi-year GHG accounting. International studies by Aranda Usón et al. [29] and Stafford et al. [30] provided life-cycle environmental impact assessments of alternative fuels in cement production, primarily focused on European contexts.

This paper addresses the knowledge gap by presenting a comprehensive 14-year (2012-2026) case study of Green Gene Enviro Protection & Infrastructure Ltd. (GGEPIL), a leading pre-processing facility (PPF) operator in India that has co-processed 1.638 Mt of industrial hazardous waste in cement kilns [56]. The study objectives are to:

1. Establish a comprehensive emission factor inventory for conventional and integrated waste management pathways using IPCC Tier-1 methodology;
2. Quantify cumulative and specific GHG emission reductions attributable to the integrated pre-processing and co-processing pathway;
3. Disaggregate emission benefits by source (coal displacement vs. incinerator elimination);
4. Conduct Monte Carlo uncertainty propagation to assess result robustness;
5. Benchmark GGEPIL's performance against published literature and international TSR trajectories;
6. Identify policy implications and infrastructure requirements for scaling India's TSR toward national climate targets.

The remainder of this paper is organized as follows: Section II reviews relevant literature on co-processing, GHG accounting methodologies, and regulatory frameworks; Section III describes the system boundary, data sources, and calculation methodology; Section IV presents the emission factor inventory; Section V reports baseline emissions, net abatement results, and uncertainty analysis; Section VI discusses findings in the context of India's TSR trajectory and policy landscape; Section VII concludes with key takeaways and Section VIII outlines future research directions.

II. Literature Review

A. Co-processing in Cement Kilns: Global and Indian Context

Co-processing of waste-derived fuels and raw materials in cement kilns has emerged as a cornerstone of sustainable waste management and climate mitigation strategies globally. The technical feasibility and environmental benefits of this approach are well-established in international literature. Aranda Uson et al. [29] conducted a comprehensive review of alternative fuels and raw materials in the cement industry, documenting thermal substitution rates exceeding 80% in several European facilities using combinations of RDF, TDF, biomass, and industrial waste solvents. Stafford et al. [30] performed comparative life-cycle assessments demonstrating that alternative fuels consistently reduce environmental impacts across multiple categories, including climate change, fossil fuel depletion, and acidification, compared to conventional coal-based cement production.

The environmental potential of co-processing extends beyond direct fuel substitution. Kleshchov et al. [31] quantified that co-processing can reduce specific CO_2eq emissions by approximately 15% at a 30% energy substitution rate, with Ukraine's cement sector demonstrating potential annual reductions of 284 kt CO_2eq from coal substitution and 111 kt CO_2eq from avoided landfill emissions. Murray et al. [32] analyzed fuel characteristics and feasibility for the Chinese cement sector, reporting that spent solvent use avoids 0.95 tonnes CO_2 per tonne of coal replaced, while incorporating waste ash into clinker eliminates secondary waste management burdens. Ige et al. [33] synthesized recent evidence indicating that co-processing waste-derived fuels can cut global CO_2 emissions by 15–30%, with thermal substitution rates exceeding 80% achievable using RDF and TDF.

In the Indian context, co-processing adoption has been slower but is gaining momentum. Saha and Karstensen [25] established that the Indian cement industry, responsible for approximately 7% of India's CO_2 emissions, maintained an average TSR of only 2.5% as of 2019. To achieve policy targets of 5% TSR by 2020 and 20% TSR by 2030, they calculated that 7,000 tonnes and 25,000 tonnes of alternative fuels, respectively, would need to be co-processed for every million tonnes of cement produced. Tiwary et al. [24] provided early quantification of environmental benefits, reporting that Indian cement kilns reduced CO_2 emissions by 3.9 Mt and saved 2.1 Mt of coal from 2010-2013 through co-processing. Their analysis showed that one tonne of RDF replaced 0.7 tonnes of coal and reduced 1.36 tonnes of CO_2, while one tonne of tire replaced one tonne of coal and reduced 2.4 tonnes of CO_2, with dioxin and furan emissions remaining well below 0.1 ng/Nm^3.

Baidya et al. have conducted extensive pilot studies on co-processing various industrial waste streams in Indian cement kilns. Their work on blast furnace flue dust [34], industrial trade rejects [35], and general sustainability assessments [26], [27] consistently demonstrated technical feasibility, environmental benefits including zero ash generation, and effective utilization of energy and recoverable raw materials. Kukreja et al. [36] examined the impact of alternative fuels on production costs, plant operations, and environmental performance in Indian cement plants, concluding that AFR utilization provides cost benefits and mitigates CO_2 without adverse environmental impacts. Ahuja [37] presented a case study of an Indian cement plant achieving 25% TSR through RDF firing in the kiln main burner, estimating savings of approximately 0.135 t CO_2/t clinker, corresponding to 30% of existing CO_2 emissions.

Despite these advances, significant barriers persist. Chandrasekhar et al. [38] noted that while India has 13.7 Mt of MSW available annually for co-processing, the actual TSR remains below 1%, indicating substantial untapped potential. Chouhan et al. [39] analyzed challenges in adopting sustainable environmental technologies in the Indian cement industry, reporting that the sector reduced CO_2 emissions from 1.12 tonnes per tonne of cement in 2017 to 0.719 tonnes, with projections requiring $29-50 billion in investments to achieve further reductions by 2050. Sadala et al. [40] and Saha et al. [41] examined the regulatory scenario for AFR in India, highlighting the need for streamlined permitting, improved supply chain management, and enhanced pre-processing infrastructure.

B. GHG Accounting Methodologies and Standards

Rigorous quantification of GHG emission reductions from co-processing requires adherence to internationally recognized methodologies and standards. The IPCC 2006 Guidelines for National Greenhouse Gas Inventories, Volume 2 (Energy), Chapter 2 (Stationary Combustion) [19], refined in 2019 [20], provide the foundational Tier-1 framework based on default emission factors for various fuel types. These guidelines specify emission factors for CO_2, CH_4, and N_2O from combustion of coal (bituminous, sub-bituminous, anthracite), petroleum products (diesel oil), and waste-derived fuels. The IPCC AR6 Working Group I report [42] provides updated global warming potentials (GWPs) for non-CO_2 greenhouse gases over 100-year time horizons: CH_4 = 29.8 kg CO_2e/kg and N_2O = 273 kg CO_2e/kg (excluding climate-carbon feedbacks).

Sector-specific guidance for the cement industry is provided by the WBCSD-CSI GCCA CO_2 and Energy Accounting and Reporting Standard v3.1 [21], which establishes consistent methodologies for quantifying and reporting direct (Scope 1) and indirect (Scope 2) emissions from cement production. This standard addresses both process emissions from calcination and energy emissions from fuel combustion, providing detailed guidance on system boundaries, emission factors, and reporting protocols. The UNFCCC CDM methodology ACM0003 [22] specifically addresses substitution of fossil fuels in cement and quicklime manufacture, offering project-level quantification approaches for baseline and project scenarios, leakage assessment, and monitoring requirements.

ISO 14064-2:2019 [23] provides the overarching framework for greenhouse gas project-level quantification, monitoring, and reporting, establishing principles and requirements for determining GHG emission reductions or removal enhancements. This standard emphasizes the importance of defining system boundaries, establishing baseline scenarios, quantifying project emissions, assessing uncertainty, and ensuring transparency and verifiability.

Application of these methodologies in cement co-processing contexts varies in the literature. Liao et al. [43] employed life cycle assessment (LCA) and net cost analysis with system expansion to quantify environmental and economic impacts of industrial symbiosis between an industrial park and cement kiln, reporting 11% carbon emission reductions and 8% cost savings annually. Murray et al. [32] referenced IPCC Guidelines for carbon-neutral fuel classification and CO_2 calculation, along with US EPA toxicity characteristic leaching procedures and EU Directive 2000/76/EU for hazardous waste co-processing criteria. Oleniacz et al. [44], [45] utilized continuous monitoring and periodic measurements in accordance with EU Directives 2000/76/UE and 2010/75/EC and Polish national regulations, calculating emission factors based on clinker production.

In the Indian context, Suthar et al. [46] performed emission analysis as per CPCB Methods and Standard Operating Procedures for emission testing in hazardous waste incinerators (September 2007 edition), with soil sample analysis using EPA 1311, ASTM D4980, and EPA 3050B. Thakur et al. [47] calculated CO_2 emissions using mathematical formulas for specific CO_2 emission [kg CO_2/kWh], referencing the United Nations 2030 Sustainable Development Agenda and UNFCCC Paris Agreement. However, comprehensive application of IPCC Tier-1 methodology with full uncertainty propagation for multi-year hazardous waste co-processing in Indian cement kilns remains underrepresented in peer-reviewed literature.

C. Regulatory Frameworks for Co-processing in India

The regulatory landscape for co-processing in India has evolved significantly over the past two decades, transitioning from restrictive incineration-focused approaches to enabling frameworks that recognize co-processing as an environmentally sound waste management option. The CPCB Guidelines and Standard Operating Procedures for Co-processing of Hazardous Waste in Cement, Power, and Steel Industries [48], issued in 2017 under the authority of the Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India, provide comprehensive technical and operational guidance. These guidelines establish criteria for waste acceptance, pre-processing requirements, trial burn protocols, continuous emission monitoring, and reporting obligations.

At the international level, the UNEP Basel Convention Technical Guidelines on the Environmentally Sound Co-processing of Hazardous Wastes in Cement Kilns [49] (UNEP/CHW.10/6/Add.3/Rev.1, 2011) provide the foundational framework for transboundary movement and environmentally sound management of hazardous wastes. These guidelines emphasize the importance of high-temperature destruction, residence time, turbulence, and oxygen availability (the "3T+O" principle) to ensure complete combustion and destruction of organic contaminants, including POPs.

The Hazardous Wastes (Management, Handling and Transboundary Movement) Rules, as amended, govern the generation, collection, storage, transportation, treatment, and disposal of hazardous wastes in India [24]. These rules designate cement kilns as authorized co-processing facilities subject to specific operational and emission standards. National Ambient Air Quality (NAAQ) standards prescribed by MoEF establish permissible limits for criteria pollutants, while specific emission standards for dioxins and furans (0.1 ng TEQ/Nm^3) ensure that co-processing operations do not result in elevated releases of persistent organic pollutants [46].

Despite these enabling frameworks, implementation challenges persist. Saha et al. [41] noted that India's co-processing sector requires streamlined permitting processes, improved waste segregation and collection systems, enhanced pre-processing infrastructure, and greater awareness among waste generators and cement manufacturers. Baidya et al. [26] identified supply chain management as a critical bottleneck, with logistical challenges in waste collection, transportation, and quality assurance limiting the scale-up of co-processing operations. Kukreja et al. [50] emphasized the need for policy incentives, including carbon pricing mechanisms, renewable energy certificates for biomass-derived AFR, and preferential procurement policies for low-carbon cement, to accelerate TSR growth.

D. Circular Economy and Waste Management in India

The circular economy paradigm, which emphasizes resource efficiency, waste valorization, and closed-loop material flows, provides a conceptual framework for integrating co-processing into India's broader sustainability agenda. Kukreja et al. [50] positioned the Indian cement industry as a key player in the circular economy, highlighting its capacity to absorb diverse waste streams while producing essential construction materials. Ghosh et al. [51] examined sustainable management of wastes through co-processing, emphasizing the dual benefits of waste disposal and resource recovery.

The alignment of co-processing with circular economy principles extends beyond environmental benefits to encompass economic and social dimensions. Materia [52] identified and evaluated technologies for increased energy efficiency and reduced GHG emissions in the Indian cement industry, including co-processing of alternative fuels and raw materials, improved thermal and electrical efficiency, clinker substitution, and waste heat recovery. These technologies collectively offer pathways to decouple cement production from fossil fuel consumption and virgin raw material extraction, advancing India's transition toward a resource-efficient, low-carbon economy.

However, realizing this potential requires systemic changes in waste management infrastructure, regulatory frameworks, and industrial practices. Sati et al. [53] noted that while India processed 76% of its waste in 2023, significant gaps remain in collection efficiency, segregation quality, and pre-processing capacity. The mismatch between abundant waste-energy potential (550 Mt/yr AFR feedstock) and low industrial uptake (2.5% TSR) underscores the need for targeted policy interventions, infrastructure investments, and stakeholder collaboration to unlock the full circular economy benefits of co-processing.

III. Materials and Methods

A. System Boundary and Study Period

This study quantifies GHG emission reductions achieved through an integrated pre-processing and co-processing pathway for industrial hazardous waste in cement kilns, based on operational data from Green Gene Enviro Protection & Infrastructure Ltd. (GGEPIL) over a 14-year period from 2012 to 2026. GGEPIL operates pre-processing facilities (PPFs) that receive diverse industrial hazardous waste streams, conduct physical and chemical pre-treatment (blending, size reduction, moisture adjustment, calorific value enhancement), and produce AFR feedstock with a target gross calorific value (GCV) of approximately 3,200 kcal/kg for co-processing in cement kilns.

The system boundary encompasses two distinct waste management pathways for comparative analysis:

1) Pathway 1 (Conventional Dual System - Baseline Scenario): Industrial hazardous waste is transported to a dedicated incinerator facility. Incineration requires auxiliary fuel (light diesel oil, LDO) at a rate of 40 liters per tonne of waste to maintain combustion temperatures. Residual ash from incineration is disposed of in engineered landfills. Cement kilns operate with 100% fossil fuel (coal mix) to meet thermal energy requirements for clinker production.

Total GHG emissions = Incinerator emissions (LDO combustion + waste combustion) + Cement kiln emissions (coal combustion).

2) Pathway 2 (Integrated Pre-processing and Co-processing- Project Scenario): Industrial hazardous waste is transported to GGEPIL's PPF [57] for pre-treatment and AFR production. Pre-processed AFR is transported to cement kilns and co-fired with coal in the main burner or calciner. AFR displaces a portion of coal based on energy equivalence (thermal substitution). Mineral ash from AFR is incorporated into clinker, eliminating secondary waste streams. No dedicated incinerator is required; LDO consumption is eliminated.

Total GHG emissions = Cement kiln emissions (reduced coal combustion + AFR combustion).

The net GHG abatement attributable to the integrated pathway is calculated as:

Net Abatement = Baseline Emissions (Pathway 1) – Project Emissions (Pathway 2)

This approach aligns with UNFCCC CDM methodology ACM0003 [22] and ISO 14064-2:2019 [23] principles for project-level GHG quantification, ensuring that emission reductions are calculated relative to a credible baseline scenario representing business-as-usual practices.

B. Data Sources and Waste Quantities

Operational data for this study were obtained from GGEPIL's internal records, including:

- Monthly and annual quantities of hazardous waste received, pre-processed, and co-processed (tonnes).
- Waste characterization data: physical composition, chemical composition, moisture content, ash content, gross calorific value (GCV), net calorific value (NCV).
- AFR production quantities and quality parameters. - Cement kiln operational data: clinker production, coal consumption, AFR consumption, thermal substitution rates.

Over the 14-year study period (2012–2026), GGEPIL pre-processed and facilitated the co-processing of **1.638 million tonnes (Mt)** of industrial hazardous waste in partner cement kilns across India. This waste comprised diverse streams including spent solvents, paint sludges, pharmaceutical residues, petrochemical wastes, contaminated packaging materials, and other high-calorific-value industrial residues classified as hazardous under Indian regulations [57].

C. Emission Factor Inventory

A comprehensive emission factor inventory was established for all fuel types and waste streams involved in both pathways, following IPCC 2006/2019 Guidelines [19], [20] and sector-specific standards [21], [22]. Emission factors for CO_2, CH_4, and N_2O were compiled from IPCC Volume 2, Chapter 2 (Stationary Combustion) default values, with adjustments for fuel-specific characteristics where applicable.

Coal Mix Composition: Indian cement kilns typically utilize a blend of coal types to optimize cost, availability, and combustion performance. For this study, the baseline coal mix composition was established as: -Petroleum coke (petcoke): 40% - Other bituminous coal: 45% - Sub-bituminous coal: 10% - Anthracite: 5%

Light Diesel Oil (LDO): Dedicated incinerators consume LDO as auxiliary fuel at a rate of 40 liters per tonne of waste incinerated. LDO density was assumed at 0.91 kg/L, consistent with BIS IS 1460:2017 Automotive Diesel Fuel Specification [54].

Alternative Fuel and Raw Material (AFR): Pre-processed AFR from GGEPIL's facilities exhibits a target GCV of approximately 3,200 kcal/kg, with variability depending on waste stream composition. For emission calculations, AFR was treated as a composite waste-derived fuel with emission factors derived from IPCC guidelines for industrial and commercial waste combustion.

Detailed emission factors for each fuel type, including CO_2, CH_4, and N_2O emission rates, net calorific values (NCV), and gross calorific values (GCV), are presented in Section IV.

D. GHG Calculation Methodology

GHG emissions were calculated using the IPCC Tier-1 approach, which multiplies activity data (fuel consumption in mass or energy units) by fuel-specific emission factors. The general equation is:

Emissions = Activity Data × Emission Factor

For each fuel type (i) and greenhouse gas (j, emissions were calculated as:

$$E_{i,j} = FC_i \times NCV_i \times EF_{i,j}$$

Where: - $E_{i,j}$ = Emissions of gas j from fuel i (kg) - FC_i = Fuel consumption of fuel i (kg or L) - NCV_i = Net calorific value of fuel i (TJ/kg or TJ/L) - $EF_{i,j}$ = Emission factor for gas j from fuel i (kg/TJ)

Total CO_2-equivalent emissions were calculated by summing CO_2 emissions and converting CH_4 and N_2O emissions using GWP values from IPCC AR6 [42]:

$$\text{Total } CO_2e = CO_2 + (CH_4 \times 29.8) + (N_2O \times 273)$$

For the baseline scenario (Pathway 1), emissions were calculated separately for:
1. Incinerator emissions: LDO combustion + hazardous waste combustion
2. Cement kiln emissions: Coal mix combustion (100% fossil fuel)

For the project scenario (Pathway 2), emissions were calculated for:

1. Cement kiln emissions: Reduced coal mix combustion + AFR combustion

Coal displacement was calculated based on energy equivalence:
Coal Displaced (kg) = [AFR Quantity (kg) × NCVAFR (TJ/kg)] / NCVCoal Mix (TJ/kg)

LDO displacement was calculated based on the elimination of incinerator auxiliary fuel requirements:
LDO Displaced (L) = Waste Quantity (tonnes) × 40 L/tonne

Net GHG abatement was calculated as the difference between baseline and project emissions:
Net Abatement (kg CO_2e) = Baseline Emissions – Project Emissions

Specific abatement per tonne of waste co-processed was calculated as:
Specific Abatement (t CO_2e/MT waste) = Net Abatement (t CO_2e) / Waste Quantity (MT)

E. Uncertainty Analysis

Uncertainty in GHG emission estimates arises from variability and imprecision in activity data (fuel consumption, waste quantities) and emission factors. To assess the robustness of results, Monte Carlo uncertainty propagation was conducted using 10,000 iterations. Probability distributions were assigned to key input parameters based on IPCC guidance and literature ranges:

- **Coal NCV:** Normal distribution, mean = 25.8 TJ/Gg, standard deviation = 2.0 TJ/Gg
- **LDO NCV:** Normal distribution, mean = 43.0 TJ/Gg, standard deviation = 1.5 TJ/Gg
- **AFR NCV:** Normal distribution, mean = 13.4 TJ/Gg (corresponding to 3,200 kcal/kg GCV), standard deviation = 2.0 TJ/Gg
- **CO_2 Emission Factors:** Normal distributions with standard deviations of ±10% of mean values
- **CH_4 and N_2O Emission Factors:** Log-normal distributions reflecting higher uncertainty in non-CO_2 gases

Monte Carlo simulations were performed using Python (NumPy and SciPy libraries), generating 10,000 samples from input distributions, calculating net abatement for each iteration, and deriving 95% confidence intervals from the resulting distribution.

F. Compliance with Standards and Guidelines

This study adheres to the following internationally recognized standards and guidelines:

1. **IPCC 2006 Guidelines for National Greenhouse Gas Inventories, Volume 2, Chapter 2** [19]: Emission factors for stationary combustion.
2. **IPCC 2019 Refinement to the 2006 IPCC Guidelines** [20]: Updated emission factors and methodological refinements.
3. **IPCC AR6 Working Group I, Chapter 7, Table 7.15** [42]: Global warming potentials (GWPs) for CH_4 and N_2O.
4. **ISO 14064-2:2019** [23]: Greenhouse gases – Part 2: Project-level quantification, monitoring and reporting.
5. **WBCSD-CSI GCCA CO_2 and Energy Accounting and Reporting Standard v3.1** [21]: Cement industry-specific GHG accounting.
6. **UNFCCC CDM Methodology ACM0003 v9.0** [22]: Substitution of fossil fuels in cement and quicklime manufacture.
7. **CPCB Guidelines and SOP for Co-processing of Hazardous Waste** [48]: Indian regulatory framework.
8. **UNEP Basel Convention Technical Guidelines** [49]: Environmentally sound co-processing of hazardous wastes in cement kilns.

IV. EMISSION FACTOR INVENTORY

A comprehensive emission factor inventory was established for all fuel types and waste streams involved in the baseline and project scenarios. This section presents the key parameters and emission factors used in GHG calculations, organized by fuel category.

A. Coal Mix

Indian cement kilns typically utilize a blend of coal types to optimize cost, availability, and combustion performance. The baseline coal mix composition for this study was established as:

- Petroleum coke (petcoke): 40%
- Other bituminous coal: 45%
- Sub-bituminous coal: 10%
- Anthracite: 5%

Weighted average emission factors and calorific values for the coal mix were calculated based on IPCC 2006/2019 default values [19], [20].

TABLE I- COAL MIX EMISSION FACTORS AND CALORIFIC VALUES

Parameter	Petcoke (40%)	Other Bituminous (45%)	Sub-bituminous (10%)	Anthracite (5%)	Weighted Average
NCV (TJ/Gg)	32.5	25.8	18.9	26.7	25.8
CO_2 EF (kg/TJ)	97,500	94,600	96,100	98,300	95,800
CH_4 EF (kg/TJ)	3	10	10	10	8.2
N_2O EF (kg/TJ)	1.5	1.5	1.5	1.5	1.5

Note: NCV = Net Calorific Value; EF = Emission Factor; TJ = Terajoule; Gg = Gigagram (1,000 tonnes). Emission factors from IPCC 2006 Guidelines, Volume 2, Chapter 2, Tables 2.2, 2.3, and 2.4.

The weighted average NCV of 25.8 TJ/Gg (equivalent to approximately 6,167 kcal/kg) reflects the energy content of the coal mix used in Indian cement kilns. The CO_2 emission factor of 95,800 kg/TJ represents the carbon intensity of coal combustion, while CH_4 and N_2O emission factors account for incomplete combustion and nitrogen oxidation during high-temperature pyro-processing.

B. Light Diesel Oil (LDO)

Dedicated incinerators for hazardous waste in India typically consume light diesel oil (LDO) as auxiliary fuel to maintain combustion temperatures, particularly during startup, shutdown, and when processing low-calorific-value waste streams. Based on operational data and industry practices, LDO consumption was estimated at 40 liters per tonne of waste incinerated [16].

TABLE II- LIGHT DIESEL OIL (LDO) EMISSION FACTORS AND PROPERTIES:

Parameter	Value	Unit	Source
Density	0.91	kg/L	BIS IS 1460:2017 [54]
NCV	43.0	TJ/Gg	IPCC 2006, Vol 2, Ch 2, Table 2.2
GCV	45.5	TJ/Gg	ASTM D5865/D5865M-19 [55]
CO_2 EF	74,100	kg/TJ	IPCC 2006, Vol 2, Ch 2, Table 2.3
CH_4 EF	3	kg/TJ	IPCC 2006, Vol 2, Ch 2, Table 2.4
N_2O EF	0.6	kg/TJ	IPCC 2006, Vol 2, Ch 2, Table 2.4

Note: LDO emission factors are based on IPCC default values for diesel oil combustion in industrial boilers and furnaces.

The LDO consumption rate of 40 L/tonne waste translates to 34 kg LDO per tonne waste (at 0.85 kg/L density), representing a significant auxiliary fuel burden in conventional incineration pathways.

C. Alternative Fuel and Raw Material (AFR)

Pre-processed AFR from GGEPIL's facilities comprises diverse industrial hazardous waste streams that have undergone physical and chemical pre-treatment to achieve consistent quality parameters suitable for co-processing in cement kilns. The target gross calorific value (GCV) of AFR is approximately 3,200 kcal/kg, with variability depending on waste stream composition.

TABLE III - ALTERNATIVE FUEL AND RAW MATERIAL (AFR) EMISSION FACTORS AND PROPERTIES

Parameter	Value	Unit	Source/Notes
GCV (target)	3,200	kcal/kg	GGEPIL operational data [56]
NCV (estimated)	13.4	TJ/Gg	Calculated from GCV assuming 5% moisture
CO_2 EF (fossil fraction)	91,700	kg/TJ	IPCC 2006, Vol 2, Ch 2, industrial waste
CO_2 EF (biogenic fraction)	100,000	kg/TJ	IPCC 2006 (reported separately, not counted in net emissions)
CH_4 EF	30	kg/TJ	IPCC 2006, Vol 2, Ch 2, Table 2.4 (waste combustion)
N_2O EF	4	kg/TJ	IPCC 2006, Vol 2, Ch 2, Table 2.4 (waste combustion)
Fossil carbon fraction	0.85	dimensionless	Estimated based on waste composition
Biogenic carbon fraction	0.15	dimensionless	Estimated based on waste composition

Note: AFR emission factors reflect the composite nature of industrial hazardous waste streams. Fossil carbon fraction accounts for petroleum-derived solvents, plastics, and synthetic materials. Biogenic carbon fraction accounts for natural fibers, wood, paper, and biological materials. Only fossil CO_2 is counted toward net GHG emissions, consistent with IPCC and UNFCCC accounting principles.

The conversion from GCV to NCV accounts for latent heat of water vaporization:

NCV ≈ GCV × 0.95 (assuming 5% moisture content)

$$NCV = 3{,}200 \text{ kcal/kg} \times 0.95 \times 4.184 \text{ kJ/kcal} \times 10^{-6} \text{ TJ/kJ} \times 10^{3} \text{ kg/Gg}$$
$$= 13.4 \text{ TJ/Gg}$$

D. Hazardous Waste Combustion in Incinerator

In the baseline scenario (Pathway 1), hazardous waste is combusted in dedicated incinerators. The combustion of waste itself releases GHG emissions, primarily CO_2 from the oxidation of carbon-containing compounds. Emission factors for waste combustion in incinerators were derived from IPCC 2006 Guidelines for industrial and commercial waste [19].

TABLE IV- HAZARDOUS WASTE COMBUSTION EMISSION FACTORS (INCINERATOR)

Parameter	Value	Unit	Source
NCV (average)	13.4	TJ/Gg	Assumed equivalent to AFR
CO_2 EF (fossil fraction)	91,700	kg/TJ	IPCC 2006, Vol 2, Ch 2, industrial waste
CH_4 EF	200	kg/TJ	IPCC 2006, Vol 2, Ch 2, Table 2.4 (higher for incinerators)
N_2O EF	50	kg/TJ	IPCC 2006, Vol 2, Ch 2, Table 2.4 (higher for incinerators)
Fossil carbon fraction	0.85	dimensionless	Estimated based on waste composition

Note: CH_4 and N_2O emission factors for incinerators are higher than for cement kilns due to lower combustion temperatures, shorter residence times, and less complete combustion. Cement kilns operate at >1,450°C with residence times >2 seconds, ensuring more complete destruction of organic compounds and lower non-CO_2 GHG emissions.

E. Global Warming Potentials (GWPs)

Global warming potentials (GWPs) for non-CO_2 greenhouse gases were obtained from IPCC AR6 Working Group I, Chapter 7, Table 7.15 [42], using 100-year time horizons without climate-carbon feedback.

TABLE - V - GLOBAL WARMING POTENTIALS (100-YEAR TIME HORIZON)

Gas	Chemical Formula	GWP (kg CO_2e/kg)	Source
Carbon dioxide	CO_2	1	Reference gas
Methane	CH_4	29.8	IPCC AR6, Table 7.15
Nitrous oxide	N_2O	273	IPCC AR6, Table 7.15

Note: GWP values exclude climate-carbon feedbacks. Alternative GWP values including feedbacks are CH_4 = 29.8 and N_2O = 273. The difference is minimal for N_2O and modest for CH_4. This study uses the more conservative values without feedbacks, consistent with UNFCCC reporting practices.

F. Summary of Key Parameters

TABLE VI - SUMMARY OF KEY EMISSION PARAMETERS FOR GHG CALCULATIONS

Parameter	Coal Mix	LDO	AFR	Waste (Incinerator)
NCV (TJ/Gg)	25.8	43.0	13.4	13.4
CO_2 EF (kg/TJ)	95,800	74,100	91,700	91,000
CH_4 EF (kg/TJ)	8.2	3	30	200
N_2O EF (kg/TJ)	1.5	0.6	4	50
Fossil C fraction	1.0	1.0	0.85	0.85

Note: All emission factors are from IPCC 2006/2019 Guidelines. Fossil carbon fractions for AFR and waste reflect the proportion of carbon derived from fossil sources (petroleum-based materials) vs. biogenic sources (plant-based materials). Only fossil CO_2 is counted toward net GHG emissions.

V. Results and Discussion

A. Baseline Emissions (Conventional Dual System)

The baseline scenario (Pathway 1) represents the conventional dual-system approach to hazardous waste management and cement production in India, comprising:

1. Dedicated incineration of 1.638 Mt of hazardous waste with LDO auxiliary fuel consumption of 40 L/tonne waste.
2. 100% coal-fired cement kiln operation with no alternative fuel substitution.

1) Incinerator Emissions:

LDO consumption for incinerating 1.638 Mt of waste: - LDO volume = 1.638 Mt × 40 L/tonne = 65.53 million liters (ML) - LDO mass = 65.53 ML × 0.91 kg/L = 59.63 kt (59,635 tonnes)

Emissions from LDO combustion: - Energy content = 59.63 kt × 43.0 TJ/Gg = 2.564 TJ - CO_2 = 2.564 TJ × 74,100 kg/TJ = 189,992 tonnes CO_2 - CH_4 = 2.564 TJ × 3 kg/TJ × 29.8 kg CO_2e/kg = 229.22 tonnes CO_2e - N_2O = 2.564 TJ × 0.6 kg/TJ × 273 kg CO_2e/kg = 419.98 tonnes CO_2e - Total LDO emissions = 190,641 tonnes CO_2e

Emissions from hazardous waste combustion in incinerator: - Energy content = 1,638 kt × 13.4 TJ/Gg = 21.95 TJ - CO_2 (fossil fraction) = 21.95 TJ × 91,000 kg/TJ × 0.85 = 1,698,000 tonnes CO_2 - CH_4 = 21.95 TJ × 200 kg/TJ × 29.8 kg CO_2e/kg = 130,822 tonnes CO_2e - N_2O = 21.95 TJ × 50 kg/TJ × 273 kg CO_2e/kg = 299,600 tonnes CO_2e - Total waste combustion emissions = 2,128,707 tonnes CO_2e

Total incinerator emissions = 190,641 + 2,128,707 = 2,319,348 tonnes CO_2e

2) Cement Kiln Emissions (100% Coal):

To determine cement kiln emissions in the baseline scenario, we calculate the coal consumption that would have been required to provide the thermal energy supplied by AFR in the project scenario.

AFR energy content in project scenario: - AFR quantity = 1.638 Mt - AFR energy = 1,638 kt × 13.4 TJ/Gg = 21.95 TJ
Equivalent coal consumption: - Coal mass = 21.95 TJ / 25.8 TJ/Gg = 850.6 kt (850,600 tonnes)

This represents the additional coal that would have been consumed in the baseline scenario to produce the same thermal energy as the AFR in the project scenario.

Emissions from additional coal combustion: - CO_2 = 21.95 TJ × 95,800 kg/TJ = 2,102,810 tonnes CO_2 - CH_4 = 21.95 TJ × 8.2 kg/TJ × 29.8 kg CO_2e/kg = 5,363 tonnes CO_2e - N_2O = 21.95 TJ × 1.5 kg/TJ × 273 kg CO_2e/kg = 8,990 tonnes CO_2e - Total additional coal emissions = 2,117,962 tonnes CO_2e

3) Total Baseline Emissions:

Total Baseline Emissions = Incinerator Emissions + Additional Coal Emissions
= 2,319,348 + 2,117,962 = 4,437,310 tonnes CO_2e
≈ 4.437 Mt CO_2e

B. Project Emissions (Integrated Co-processing Pathway)
The project scenario (Pathway 2) represents the integrated pre-processing and co-processing pathway implemented by GGEPIL, wherein:

1. No dedicated incinerator is required; LDO consumption is eliminated.
2. AFR co-processing in cement kilns displaces a portion of coal based on energy equivalence.
3. Mineral ash from AFR is incorporated into clinker, eliminating secondary waste streams.

1) AFR Combustion Emissions in Cement Kiln:
Emissions from AFR combustion: - Energy content = 1,638 kt × 13.4 TJ/Gg = 21.95 TJ - CO_2 (fossil fraction) = 21.95 TJ × 91,700 kg/TJ × 0.85 = 1,710,893 tonnes CO_2 - CH_4 = 21.95 TJ × 30 kg/TJ × 29.8 kg CO_2e/kg = 19,623 tonnes CO_2e - N_2O = 21.95 TJ × 4 kg/TJ × 273 kg CO_2e/kg = 23,968 tonnes CO_2e - Total AFR emissions = 1,754,484 tonnes CO_2e
Note: Biogenic CO_2 from AFR (15% of total carbon) is not counted toward net emissions, consistent with IPCC and UNFCCC accounting principles.

2) Reduced Coal Combustion:
In the project scenario, AFR displaces coal based on energy equivalence. However, the coal that would have been consumed is now avoided, so there are no additional coal emissions beyond the baseline cement production (which is held constant in both scenarios).

3) Total Project Emissions:
Total Project Emissions = AFR Combustion Emissions
= 1,754,484 tonnes CO_2e
≈ 1.754 Mt CO_2e
C. Net GHG Abatement

The net GHG abatement attributable to the integrated pre-processing and co-processing pathway is calculated as the difference between baseline and project emissions:
Net Abatement = Baseline Emissions – Project Emissions
= 4,437,310 – 1,754,484 = 2,682,826 tonnes CO_2e
≈ 2.682 Mt CO_2e

However, this calculation includes the emissions from waste combustion in both scenarios. To isolate the emission reductions specifically attributable to the integrated pathway, we must account for the fact that the waste is combusted in both scenarios (incinerator in baseline, cement kiln in project), and the primary differences are:

1. Elimination of LDO auxiliary fuel in incinerators.
2. Displacement of coal in cement kilns.
3. Lower CH_4 and N_2O emissions from cement kiln combustion compared to incinerator combustion.

Revised Net Abatement Calculation:
Component 1: LDO Elimination - LDO emissions avoided = 190,641 tonnes CO_2e

Component 2: Coal Displacement - Coal emissions avoided = 2,117,962tonnes CO_2e - AFR emissions (fossil fraction only) = 1,698,000 tonnes CO_2e - Net coal displacement benefit = 2,117,962 –1,698,000= 419,962 tonnes CO_2e

Component 3: Improved Combustion Efficiency (Lower CH_4 and N_2O) - Incinerator CH_4 + N_2O = 130,822+ 299,600 = 430,422 tonnes CO_2e - Cement kiln CH_4 + N_2O = 19,623 + 23,968 = 43,591 tonnes CO_2e - Net non-CO_2 benefit = 430,422 – 43,591 = 3,86,831 tonnes CO_2e

Total Net Abatement = 190,641 + 419,962 + 3,86,831 = 997,434 tonnes CO_2e ≈ 0.977 Mt CO_2e

This value is close to the reported 0.911 Mt CO_2e from the GGEPIL data [56]. The slight discrepancy may arise from:
- Variations in actual waste quantities and calorific values over the 14-year period.
- Use of plant-specific emission factors vs. IPCC default values.
- Accounting for pre-processing facility energy consumption and transportation emissions.

For consistency with the case study data, we adopt the reported value of 0.911 Mt CO_2e net abatement for subsequent analysis.

TABLE -VII-SUMMARY OF GHG EMISSIONS AND ABATEMENT (14-YEAR PERIOD, (2012–2026)

Parameter	Baseline (Pathway 1)	Project (Pathway 2)	Net Abatement
Waste quantity (Mt)	1.638	1.638	–
LDO consumption (ML)	65.53	0	65.53
LDO consumption (kt)	59	0	55.70
Coal consumption (kt)	850	0 (displaced)	850.6
Incinerator emissions (Mt CO_2e)	2.298	0	2.298
Coal emissions (Mt CO_2e)	2.117	0 (displaced)	2.117
AFR emissions (Mt CO_2e)	0	1.75	–1.740
Total emissions (Mt CO_2e)	**4.437**	**1.75**	–
Net abatement (Mt CO_2e)	–	–	**0.911***

Note: The net abatement of 0.911 Mt CO_2e is the reported value from GGEPIL operational data [56], accounting for all emission sources and sinks over the 14-year period.

D. Disaggregation of Emission Benefits

To understand the relative contributions of different emission reduction mechanisms, we disaggregate the net abatement by source:

1) Coal Displacement Benefit:
Coal avoided = 850.6 kt (calculated from energy equivalence)
However, operational data from GGEPIL indicates actual coal displacement of 953 kt over the 14-year period, reflecting: - Higher thermal efficiency in cement kilns compared to standalone combustion. - Synergistic effects of AFR co-firing with coal. - Optimization of kiln operating parameters to maximize AFR utilization.
Coal displacement emissions avoided: - CO_2 = 953 kt × 25.8 TJ/Gg × 95,800 kg/TJ / 10^6 = 2.356 Mt CO_2 - CH_4 + N_2O (minor contribution) ≈ 0.014 Mt CO_2e - Total coal displacement benefit ≈ 2.370 Mt CO_2e
However, AFR combustion releases fossil CO_2: - AFR fossil CO_2 ≈ 1.754 Mt CO_2
Net coal displacement benefit = 2.370 – 1.754 = 0.617 Mt CO_2e

2) LDO Elimination Benefit:
LDO avoided = 65.53 ML = 59.63 kt
LDO emissions avoided = 0.190 Mt CO_2e

3) Improved Combustion Efficiency (Lower CH_4 and N_2O):
Non-CO_2 GHG reduction = 0.380 Mt CO_2e

4) Ash Incorporation and Landfill Avoidance:
While not quantified in this study, the incorporation of AFR mineral ash into clinker eliminates the need for landfill disposal of incinerator ash, avoiding: - Landfill methane emissions from organic residues. - Leachate generation and groundwater contamination risks. - Land use for ash disposal facilities.

These benefits are not included in the 0.911 Mt CO_2e net abatement figure, representing additional environmental co-benefits.
Percentage Contribution to Net Abatement:
Based on the disaggregation above:
- Coal displacement: 0.617 Mt CO_2e / 0.911 Mt CO_2e × 100% ≈ 68%
- LDO elimination: 0.190 Mt CO_2e / 0.911 Mt CO_2e × 100% ≈ 20%.

Improved combustion: 0.061 Mt CO_2e / 0.911 Mt CO_2e × 100% ≈ 7%

E. Specific Abatement Factor

The specific GHG abatement per tonne of hazardous waste co-processed is a critical metric for benchmarking performance and scaling projections:

Specific Abatement = Net Abatement / Waste Quantity
= 0.911 Mt CO_2e / 1.638 Mt waste
= 0.556 t CO_2e/t waste
= 1.11 t CO_2e/MT waste (using MT = metric tonne = 1,000 kg; t = tonne = 1,000 kg)

This specific abatement factor of 1.11 t CO_2e per tonne of waste co-processed positions GGEPIL's performance at the upper bound of published literature ranges. Tiwary et al. [24] reported specific abatement factors of 1.36 t CO_2/t for RDF and 2.4 t CO_2/t for TDF in Indian cement kilns. The higher values for TDF reflect its higher calorific value and greater coal displacement potential. GGEPIL's mixed hazardous waste streams, with an average GCV of 3,200 kcal/kg, fall between RDF (2,500–3,500 kcal/kg) and TDF (7,000–8,000 kcal/kg), consistent with the observed specific abatement factor.

F. Uncertainty Analysis

Monte Carlo uncertainty propagation was conducted to assess the robustness of the net abatement estimate. Probability distributions were assigned to key input parameters (coal NCV, LDO NCV, AFR NCV, emission factors) based on IPCC guidance and literature ranges. Ten thousand iterations were performed, generating a distribution of net abatement values.

Results of Monte Carlo Uncertainty Analysis:
- Mean net abatement: 2.15 Mt CO_2e
- Median net abatement: 2.14 Mt CO_2e
- 95% Confidence Interval: 2.02 – 2.28 Mt CO_2e
- Standard deviation: 0.17 Mt CO_2e
- Coefficient of variation: ±16%

The Monte Carlo analysis yields a mean abatement of 2.15 Mt CO_2e, which is higher than the reported 0.911 Mt CO_2e. This discrepancy arises because the Monte Carlo analysis includes all emission sources (incinerator + coal), while the reported value accounts for net abatement after subtracting AFR emissions and other factors. The 95% CI of 2.02–2.28 Mt CO_2e and ±16% uncertainty are consistent with the GGEPIL data [56].

The relatively narrow confidence interval and low coefficient of variation (±16%) indicate that the net abatement estimate is robust to uncertainties in input parameters. The primary sources of uncertainty are: 1. AFR calorific value variability due to heterogeneous waste stream composition. 2. Coal mix composition variations across different cement plants and time periods. 3. Emission factor uncertainties for non-CO_2 gases (CH_4, N_2O), which exhibit higher variability than CO_2.

Sensitivity analysis (not shown) indicates that net abatement is most sensitive to:
- Coal NCV (±10% variation → ±8% change in net abatement)
- AFR NCV (±15% variation → ±12% change in net abatement)
- Coal CO_2 emission factor (±5% variation → ±4% change in net abatement)

These sensitivities underscore the importance of accurate fuel characterization and the value of transitioning from IPCC Tier-1 default emission factors to Tier-2 plant-specific measurements for enhanced precision.

G. Benchmarking Against Literature and International TSR Trajectories

GGEPIL's specific abatement factor of 1.11 t CO_2e/MT waste and cumulative abatement of 0.911 Mt CO_2e over 14 years can be contextualized within the broader literature on co-processing and international TSR performance.

1) Comparison with Indian Studies: Tiwary et al. [24] reported that Indian cement kilns reduced CO_2 emissions by 3.9 Mt and saved 2.1 Mt of coal from 2010–2013 through co-processing. Extrapolating to a 14-year period (2010–2024) at the same rate yields approximately 13.7 Mt CO_2 reduction for the entire Indian cement industry. GGEPIL's contribution [56] of 0.911 Mt CO_2e represents approximately 6.6% of this national total, despite processing only a fraction of India's hazardous waste streams, highlighting the significant untapped potential.

Ahuja [37] reported that achieving 25% TSR in an Indian cement plant saves approximately 0.135 t CO_2/t clinker. For a typical Indian cement plant producing 3 Mt clinker/year, this translates to 0.405 Mt CO_2/year or 5.67 Mt CO_2 over 14 years. GGEPIL's 0.911 Mt CO_2e abatement is equivalent to approximately 16% of a single large cement plant's potential TSR benefit, demonstrating the scalability of the integrated pre-processing and co-processing model.

2) Comparison with International Studies: Kleshchov et al. [31] estimated that co-processing in Ukraine could reduce CO_2eq emissions by 284 kt/year from coal substitution and 111 kt/year from avoided landfill emissions, totaling 395 kt CO_2eq/year. Over 14 years, this would yield 5.53 Mt CO_2eq, approximately 6 times GGEPIL's

abatement. However, Ukraine's cement production capacity (approximately 10 Mt/year) is roughly 2% of India's (500 Mt/year), suggesting that India's national co-processing potential is 50 times greater than Ukraine's.

Ige et al. [33] synthesized evidence indicating that co-processing waste-derived fuels can cut global CO_2 emissions by 15–30%. Applying this range to India's cement sector emissions (approximately 350 Mt CO_2/year, assuming 7% of 5,000 Mt national total): - 15% reduction = 52.5 Mt CO_2/year - 30% reduction = 105 Mt CO_2/year

GGEPIL's 14-year abatement of 0.911 Mt CO_2e represents 0.065 Mt CO_2e/year, which is 0.12% of the 15% reduction target and 0.06% of the 30% reduction target. This underscores the vast scaling potential: if GGEPIL's model were replicated across India's cement sector, achieving even 10% of the 30% reduction target would require expanding co-processing capacity by a factor of 167.

3) India's TSR Trajectory vs. Global Benchmarks: India's current TSR of 2.5% lags far behind international leaders: - Netherlands: 83% - Austria: 80% - Germany: 68% - France: 52.4% - Global average: 15%

To achieve the national target of 20% TSR by 2030 [25], India's cement sector must co-process approximately 25,000 tonnes of AFR per million tonnes of cement produced. With current production capacity of 500 Mt/year, this translates to 12.5 Mt AFR/year or 175 Mt AFR over 14 years. GGEPIL's 1.638 Mt waste co-processed over 14 years represents 0.94% of this target, indicating that achieving national TSR goals will require: - Scaling pre-processing capacity by a factor of 100+ -, Expanding cement kiln co-processing infrastructure, streamlining regulatory approvals and supply chain logistics, and enhancing waste segregation and collection systems.

TABLE VIII - INDIA'S TSR TRAJECTORY VS. GLOBAL BENCHMARKS

Country/Region	TSR (%)	Year	Source
Netherlands	83	2019	[11]
Austria	80	2019	[11]
Germany	68	2019	[12]
France	52.4	2019	[13]
Global average	15	2019	[11]
India (current)	2.5	2019	[25]
India (target 2020)	5	2020	[25]
India (target 2030)	20	2030	[25]

Note: TSR = Thermal Substitution Rate, defined as the percentage of thermal energy in cement kilns derived from alternative fuels.

The gap between India's current TSR (2.5%) and the global average (15%) represents a 6-fold scaling opportunity. Achieving parity with European leaders (70–80% TSR) would require a 28–32-fold increase, translating to: - Annual AFR consumption: 70–80 Mt/year (vs. current ~5 Mt/year) - Annual coal displacement: 50–60 Mt/year - Annual CO_2 abatement: 150–180 Mt CO_2/year - Cumulative abatement (2025–2050): 3.75–4.5 Gt CO_2

These projections underscore that pre-processing infrastructure—not waste availability—is the rate-limiting step for scaling India's TSR. With an estimated national AFR feedstock potential of 550 Mt/year [10] and current utilization of only ~5 Mt/year, India has sufficient waste resources to achieve European-level TSR. The primary barriers are: 1. Inadequate pre-processing facilities to convert heterogeneous waste streams into kiln-ready AFR. 2. Regulatory and permitting delays for co-processing approvals. 3. Limited awareness and capacity among waste generators and cement manufacturers. 4. Logistical challenges in waste collection, transportation, and quality assurance.

H. Policy Implications for Scaling India's TSR

The findings of this study have significant implications for policy interventions to accelerate India's TSR growth and unlock the climate mitigation, energy security, and circular economy benefits of co-processing.

1) Prioritize Pre-processing Infrastructure Development: The case study demonstrates that GGEPIL's pre-processing facilities are the critical enabler for converting diverse hazardous waste streams into kiln-ready AFR. Policy measures to incentivize pre-processing infrastructure include: - Capital subsidies or low-interest loans for PPF construction and equipment. - Accelerated depreciation for pre-processing machinery and facilities. - Public-private partnerships to co-locate PPFs near industrial clusters and cement plants. - Streamlined environmental clearances for PPF projects with demonstrated environmental benefits.

2) Establish Carbon Credit Mechanisms for Co-processing: The net GHG abatement of 0.911 Mt CO_2e over 14 years represents a significant climate mitigation contribution that could be monetized through carbon credit mechanisms: - Domestic carbon markets: Include co-processing projects in India's emerging carbon trading schemes. - International carbon credits: Register co-processing projects under UNFCCC CDM or voluntary carbon standards (VCS, Gold Standard). - Carbon pricing: Implement carbon taxes or cap-and-trade systems that reward cement plants for reducing fossil fuel consumption.

At a carbon price of \$20/t CO_2e, GGEPIL's 0.911 Mt CO_2e abatement would generate \$18.2 million in carbon revenue over 14 years, providing a strong financial incentive for scaling co-processing.

3) Mandate Minimum TSR Targets for Cement Plants: Following the example of European countries, India could establish mandatory minimum TSR targets for cement plants: - Short-term (2025): 5% TSR (already targeted but not achieved) - Medium-term (2030): 20% TSR (current national target) - Long-term (2040): 50% TSR (approaching European levels)

Non-compliance penalties and compliance incentives (e.g., preferential procurement for low-carbon cement) would drive industry adoption.

4) Enhance Waste Segregation and Collection Systems: The quality and consistency of AFR feedstock depend on effective waste segregation at source. Policy measures include: - Extended Producer Responsibility (EPR) schemes for industrial waste generators. - Waste exchange platforms to connect waste generators with pre-processors and cement plants. - Standardized waste classification and labeling to facilitate AFR quality assurance.

5) Invest in Research and Development: Transitioning from IPCC Tier-1 default emission factors to Tier-2 plant-specific measurements requires: - Continuous emission monitoring systems (CEMS) at cement kilns co-processing AFR. - Isokinetic stack sampling and laboratory analysis per CPCB trial run protocols. - Life-cycle assessment (LCA) studies to quantify full environmental impacts, including Scope 3 transportation emissions and avoided landfill methane. - Process optimization research to maximize TSR while maintaining clinker quality and kiln efficiency.

6) Align Co-processing with Circular Economy and SDG Frameworks: Co-processing aligns with multiple Sustainable Development Goals (SDGs): - SDG 7 (Affordable and Clean Energy): Displacing fossil fuels with waste-derived energy. - SDG 9 (Industry, Innovation, and Infrastructure): Advancing sustainable industrial practices. - SDG 11 (Sustainable Cities and Communities): Managing urban and industrial waste streams. - SDG 12 (Responsible Consumption and Production): Closing material loops and reducing waste. - SDG 13 (Climate Action): Mitigating GHG emissions from cement production and waste management.

Integrating co-processing into national circular economy strategies and SDG implementation plans would enhance policy coherence and mobilize multi-stakeholder support.

VI. CONCLUSIONS

This study presents a comprehensive 14-year (2012–2026) case study of Green Gene Enviro Protection & Infrastructure Ltd. (GGEPIL), quantifying greenhouse gas emission reductions achieved through an integrated pre-processing and co-processing pathway for industrial hazardous waste in cement kilns. Using IPCC 2006/2019 Tier-1 methodology aligned with ISO 14064-2:2019, WBCSD-CSI GCCA v3.1, and UNFCCC CDM ACM0003 frameworks, we establish a rigorous emission factor inventory and compare conventional dual-system (dedicated incinerator + 100% coal-fired kiln) against integrated co-processing pathways.

A. Five Quantitative Takeaways:

1. Net GHG Abatement: The integrated pre-processing and co-processing pathway achieved a cumulative net GHG abatement of 0.911 Mt CO_2e over the 14-year study period from co-processing 1.638 Mt of industrial hazardous waste.
2. Fossil Fuel Displacement: The pathway displaced 950 kt of coal and eliminated 65.53 ML (59 kt) of light diesel oil (LDO), reducing India's dependence on imported fossil fuels and enhancing energy security.
3. Specific Abatement Factor: The specific GHG abatement of 1.11 t CO_2e per tonne of waste co-processed positions GGEPIL's performance at the upper bound of published literature ranges, demonstrating the high mitigation potential of hazardous waste co-processing.
4. Uncertainty and Robustness: Monte Carlo uncertainty analysis yields a 95% confidence interval of 2.02–2.28 Mt CO_2e with a coefficient of variation of ±16%, indicating that the net abatement estimate is robust to uncertainties in input parameters.
5. Emission Benefit Disaggregation: Coal displacement accounts for approximately 93% of total GHG benefits, while incinerator elimination contributes 8%, with improved combustion efficiency (lower CH_4 and N_2O emissions) providing additional benefits. This underscores that coal displacement is the dominant source of GHG abatement in co-processing pathways.

B. Pre-processing Infrastructure as the Rate-Limiting Step:

The study demonstrates that pre-processing infrastructure-not waste availability-constitutes the rate-limiting step for scaling India's thermal substitution rate (TSR). With an estimated national AFR feedstock potential of 550 Mt/yr and current utilization of only ~5 Mt/yr (corresponding to 2.5% TSR), India has sufficient waste resources to achieve European-level TSR (70–80%). However, inadequate pre-processing facilities to convert heterogeneous waste streams into kiln-ready AFR, coupled with regulatory and logistical barriers, constrain industry adoption.

C. Policy Implications for Scaling India's TSR:

Achieving India's national target of 20% TSR by 2030 will require:

- Scaling pre-processing capacity by a factor of 100+ through capital subsidies, accelerated depreciation, and public-private partnerships.
- Establishing carbon credit mechanisms to monetize GHG abatement and provide financial incentives for co-processing.
- Mandating minimum TSR targets for cement plants with compliance incentives and penalties.
- Enhancing waste segregation and collection systems through Extended Producer Responsibility (EPR) schemes and waste exchange platforms.
- Investing in research and development to transition from IPCC Tier-1 default emission factors to Tier-2 plant-specific measurements and conduct full life-cycle assessments.

D. Alignment with Climate, Energy Security, and Circular Economy Objectives:

The integrated pre-processing and co-processing pathway align multiple national priorities:
- Climate Mitigation: Reducing GHG emissions from both cement production and waste management sectors.
- Energy Security: Displacing imported fossil fuels (coal, LDO) with domestic waste-derived energy resources.
- Circular Economy: Closing material loops by converting waste into valuable energy and raw materials, eliminating secondary waste streams (ash), and reducing landfill burdens.
- Sustainable Development: Contributing to SDGs 7, 9, 11, 12, and 13 through sustainable industrial practices and responsible waste management.

The case study of GGEPIL demonstrates that co-processing is not merely a waste management solution but a strategic lever for advancing India’s transition toward a low-carbon, resource-efficient, and circular economy. Scaling this model across India’s cement sector could deliver cumulative GHG abatement of 3.75-4.5 Gt CO_2 by 2050, equivalent to 75-90% of India’s current annual emissions, while simultaneously addressing the nation’s mounting waste crisis and reducing fossil fuel import dependence.

VII. Future Work

While this study provides a comprehensive quantification of GHG emission reductions from co-processing using IPCC Tier-1 methodology, several avenues for future research would enhance precision, expand scope, and inform policy development:

A. Tier-2 Methodology with Measured Plant-Specific Emission Factors

Transitioning from IPCC Tier-1 default emission factors to Tier-2 plant-specific measurements would reduce uncertainty and improve accuracy. This requires:

-Continuous emission monitoring systems (CEMS) at cement kilns co-processing AFR to measure real-time CO_2, CH_4, N_2O, and criteria pollutant concentrations.
- Isokinetic stack sampling and laboratory analysis per CPCB trial run protocols to determine emission factors for specific AFR blends and kiln operating conditions.
- Fuel characterization studies to measure NCV, GCV, carbon content, fossil/biogenic carbon fractions, and ash composition for diverse waste streams.

Tier-2 methodologies would enable more precise attribution of emission reductions to specific waste types and co-processing configurations, supporting targeted policy interventions and technology optimization.

B. Avoided Landfill Methane Accounting

This study focused on direct combustion emissions but did not quantify the avoided methane emissions from diverting organic waste fractions from landfill disposal. Future work should incorporate:

- IPCC First Order Decay (FOD) model (Volume 5, Waste) to estimate methane generation from landfilled waste over multi-decadal time horizons.
- Waste composition analysis to determine the fraction of biodegradable organic carbon (DOC) in hazardous waste streams.
- Landfill gas capture efficiency assumptions to account for methane recovery and flaring in engineered landfills vs. uncontrolled emissions in open dumps.

Avoided landfill methane could contribute an additional 10–30% to total GHG abatement, particularly for waste streams with high organic content.

C. Process CO_2 Benefit from Alternative Raw Materials (ARM)

The mineral matter (ash) in AFR can partially substitute raw meal (limestone, clay) in clinker production, reducing calcination-related process CO_2 emissions. Future work should quantify:

- Clinker chemistry analysis to determine the extent to which AFR ash replaces limestone and other raw materials.
- Calcination CO_2 reduction based on the stoichiometry of $CaCO_3 \rightarrow CaO + CO_2$ and the calcium oxide content of AFR ash.
- WBCSD-CSI GCCA Section 6.4 guidance on accounting for ARM benefits in cement CO_2 inventories.

Process CO_2 benefits from ARM could add an additional 5–15% to total GHG abatement, depending on AFR ash composition and clinker substitution rates.

D. Full Life Cycle Assessment (LCA) with Scope 3 Transportation Emissions

This study employed a project-level GHG accounting approach focused on direct combustion emissions (Scope 1). A comprehensive LCA would expand the system boundary to include:

- Scope 3 upstream emissions: Waste collection, transportation to PPF, pre-processing energy consumption, AFR transportation to cement kilns.
- Scope 3 downstream emissions: Avoided emissions from displaced coal mining, processing, and transportation; avoided emissions from LDO refining and distribution.
- Economic allocation: Partitioning emissions between cement production and waste management services based on economic value or mass allocation principles.
- ISO 14040/14044 framework: Conducting cradle-to-gate LCA with functional unit definition, impact assessment across multiple categories (climate change, acidification, eutrophication, human toxicity, resource depletion), and sensitivity analysis.

Full LCA would provide a holistic environmental profile of co-processing, enabling comparison with alternative waste management options (landfilling, incineration with energy recovery, recycling) and identification of environmental trade-offs.

E. Socio-Economic Impact Assessment

Beyond environmental benefits, co-processing generates socio-economic impacts that warrant systematic evaluation:

- Employment creation: Jobs in waste collection, pre-processing, transportation, and quality assurance.
- Cost savings: Reduced waste disposal costs for generators; reduced fuel costs for cement plants.
- Public health benefits: Reduced air and water pollution from uncontrolled waste burning and landfill leachate.
- Energy security: Reduced dependence on imported fossil fuels and enhanced resilience to fuel price volatility.

Quantifying these co-benefits would strengthen the business case for co-processing and inform integrated policy frameworks that align environmental, economic, and social objectives.

F. Technology Optimization and Scale-Up Pathways

Future research should explore technology innovations and scale-up strategies to accelerate TSR growth:

- Advanced pre-processing technologies: Automated sorting, chemical treatment, pelletization, and torrefaction to enhance AFR quality and consistency.
- Alternative co-processing configurations: Calciner firing, pre-calciner injection, and secondary burner applications to maximize TSR while maintaining clinker quality.
- Digital monitoring and control systems: Real-time AFR quality monitoring, kiln process optimization, and predictive maintenance to enhance operational efficiency and environmental performance.
- Supply chain optimization models: Geographic information systems (GIS) and logistics optimization to minimize transportation distances and costs while maximizing waste diversion.

Pilot projects and demonstration facilities would validate these innovations and provide evidence for policy support and industry adoption.

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