

Co-processing of Poultry Biowaste in MSW-to-Energy Kilns: Technical and Financial Feasibility of Wet Flue-Gas Desulfurization Sorbent Isolation in Varanasi, India

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Research Article

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Abstract

Traditional limestone mining is an environmentally destructive, non-renewable activity that fuels greenhouse gas emissions. To mitigate this, this study evaluates the technical, chemical, and financial feasibility of a novel circular economy loop: substituting depleting mineral limestone with biogenic chicken eggshell waste within the wet Flue-Gas Desulfurization (FGD) scrubber system of the NTPC Varanasi Waste-to-Energy and Vindhyachal desulfurization plant. Using demographic and tourism-surge metrics, we estimate that Varanasi district generates 3.3 to 5.1 metric tons (MT) of raw eggshell waste daily. While raw eggshells suffer from high abrasive wear and pumping resistance due to a superhydrophobic 6% organic membrane, thermal pre-treatment at 500°C completely incinerates this protein-collagen membrane. This pre-treatment transforms the powder into a highly hydrophilic mineral identical to standard limestone. To handle co-processing, we design and model a three-stage mechanical and aerodynamic separation system (shear compaction, dual-deck vibro-sifting, and cyclonic classification) that cleanly isolates dense fuel-grade green charcoal from friable, desulfurization-grade roasted shell dust. Chemical mass-balance modeling shows that the wet FGD scrubber can successfully capture and neutralize 1.86 to 2.88 MT of SO₂ emissions daily while generating 6.37 MT of high-purity marketable gypsum. Financial projections over a 15-year operational horizon demonstrate excellent profitability, yielding a payback period of 3.27 years, a Net Present Value (NPV) of ₹66.3 Lakhs, and an Internal Rate of Return (IRR) of 29.98% at a 10% hurdle rate. Multi-variable sensitivity analysis indicates that the project remains highly profitable down to a collection efficiency threshold of 52%, establishing a robust environmental and financial model for utility-scale waste valorization.

Research Highlights

- A closed-loop circular bio-economy framework was developed to integrate localized poultry waste into wet FGD systems.
- Varanasi's regional eggshell waste was quantitatively modeled, revealing a daily generation of 3.3 to 5.1 metric tons.
- Thermal pre-treatment at 500°C completely denatures the 6% organic membrane, eliminating superhydrophobic slurry pump erosion.
- An engineered three-stage mechanical-aerodynamic separation system isolates high-value green charcoal from friable sorbent dust.
- Financial modeling of the wet FGD system yields a payback period of 3.27 years, with baseline NPV of ₹66.3 Lakhs and IRR of 29.98%.

Graphical Abstract Concept and Implementation

The graphical abstract illustrates the closed-loop transformation process. It consists of three panels on a white background: 1) Sourcing: Raw organic eggshells are segregated from Varanasi's bulk commercial kitchens and street stalls; 2) Processing: Thermal co-roasting at 500°C renders the organic

membrane brittle, enabling a three-stage mechanical separator (shear compaction, size sifting, and aerodynamic air cyclone) to split raw discharge into dark green charcoal chunks and fine white eggshell powder; 3) Application: The green charcoal chunks are routed directly to NTPC boilers as fuel, while the pure roasted shell dust is dissolved into an aqueous wet FGD slurry, protecting FGD pump impellers from abrasive wear and capturing acid gases to generate high-purity gypsum.

Introduction

Industrial emissions abatement and solid waste management represent two of the most critical challenges facing rapidly urbanizing economies. In India, coal-fired power plants and municipal waste-to-energy plants are legally required to deploy Flue-Gas Desulfurization (FGD) systems to capture harmful sulfur dioxide (SO₂) emissions before they contribute to regional acid rain and severe respiratory health hazards. Traditionally, these scrubbers consume immense volumes of natural limestone (CaCO₃), which must be mined through environmentally destructive open-pit quarrying. Limestone extraction leads to permanent deforestation, topsoil erosion, groundwater table disruption, and massive transport emissions (Rakesh & Kumar, 2025). Therefore, identifying sustainable, biogenic alternatives to mineral limestone is an environmental priority.

Chicken eggshell waste represents an exceptional biomaterial candidate. Chemically, eggshells consist of 95–97% pure calcium carbonate (CaCO₃), making them structurally equivalent to high-grade industrial limestone (Hart & Onyeaka, 2020). However, eggshell waste is traditionally dumped directly into landfills where it undergoes biological degradation, releasing offensive hydrogen sulfide odors, breeding microbial pathogens, and contaminating soil through acidic leachate. Diverting this waste stream into a municipal-to-industrial supply chain can achieve major cleaner production benchmarks. This study is the first to rigorously model the technical, chemical, and economic integration of regional eggshell waste within a wet FGD scrubber loop, specifically tailored for the National Thermal Power Corporation (NTPC) Waste-to-Energy facility in Varanasi, India.

Materials and Methods

2.1 Regional Biomass Sourcing and Tourism Surcharges

To establish a realistic feedstock supply chain, we map Varanasi's poultry consumption. At the state level, Uttar Pradesh consumes approximately 3.5 to 5.0 crore (35 to 50 million) eggs daily (Poultry India, 2026). With a district population of approximately 4.0 million (representing 1.67% of the state's population), Varanasi's pro-rata baseline consumption stands at 584,500 to 835,000 eggs per day. However, Varanasi experiences an average floating population of 200,000 daily spiritual tourists, generating over 7.26 crore annual visitors (Samrajya Ayodhya, 2026). This immense tourist footprint heavily inflates institutional egg demand across hospitality kitchens, commercial bakeries, and street vendors, raising the realistic district-level egg demand to 600,000 to 850,000 eggs daily. Using standard biological parameters—where a single chicken eggshell weighs between 5.5 and 6.0 grams (representing

approximately 10% of total egg mass)—the daily raw waste tonnage translates to 3.30 to 5.10 Metric Tons (MT) per day (equivalent to 1,204.5 to 1,861.5 MT/year).

2.2 Thermal Pre-Treatment and Wet Slurry Rheology

Raw eggshell is naturally coated in a tough, elastic 6% protein-collagen membrane. This membrane layers the shell in superhydrophobic (water-repelling) properties (Chong et al., 2025). In a wet FGD system, the limestone substitute must be mixed with water to form an aqueous absorbent slurry. If untreated eggshell is mixed directly, the hydrophobic membrane prevents uniform water dispersion, leading to a highly viscous, non-homogeneous sludge with an extremely high static yield stress. This viscous sludge creates severe pumping resistance, causes excessive physical abrasion against slurry pump impellers, scours piping elbows, and rapidly clogs FGD spray nozzles. To solve this, we model a thermal pre-treatment phase. Heating the eggshells to 500°C completely incinerates the organic membrane, transforming the biomaterial into a fully hydrophilic, brittle powder that disperses smoothly, restoring standard slurry viscosity.

2.3 Three-Stage Mechanical-Aerodynamic Separation System

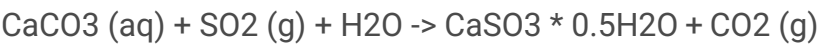
When eggshell waste is co-roasted alongside municipal solid waste inside NTPC Varanasi's carbonization reactors, the resulting discharge is a mixed, hot stream of carbonized charcoal (green charcoal) and roasted eggshells. To isolate these materials and prevent high-temperature calcium fouling in power boilers, we design a three-stage separation flow:

1. Stage 1 (High-Shear Compaction): The hot mixture is passed through compaction rollers. Under shear stress, the brittle roasted eggshells (which lost their organic binder at 500°C) readily shatter into micro-dust (< 100 micrometers), while the dense green charcoal chunks remain completely intact.
2. Stage 2 (Two-Deck Vibro-Sifter): A dual vibrating screen retains the coarse, intact green charcoal on the top deck (routed to fuel silos) and drops the micro-pulverized eggshell dust through the lower deck.
3. Stage 3 (Multi-Cone Cyclone): High-velocity cyclonic air classification pulls the remaining light, high-surface-area eggshell dust upward into a wet FGD collection chamber while gravity-discharging any heavier residual carbon fines from the bottom.

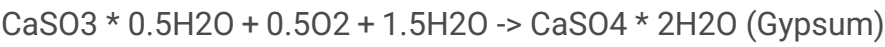
2.4 Wet Flue-Gas Desulfurization Kinetics & Chemistry

The isolated pure roasted eggshell dust is directed to wet FGD scrubber towers. Here, the calcium carbonate (CaCO_3) dissolves into the aqueous phase, reacting with acidic sulfur dioxide (SO_2) under high-efficiency forced oxidation to produce gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$):

Dissolution and SO_2 Neutralization:



Forced Oxidation Loop:



Because wet FGD scrubbers operate in aggressive, chloride-rich acidic environments, the synergistic action of flowing abrasive slurry and acid triggers rapid erosion-corrosion. To prevent this, we specify high-performance Duplex Stainless Steel (UNS S32205) and High-Nickel Alloys (Alloy C276 or Alloy 22) for the wet FGD impellers and piping networks (NeoNickel, 2024).

Results and Discussion

3.1 Raw Feedstock Metrics and Active Sorbent Yields

Table 1

outlines the baseline feedstock parameters modeled for Varanasi district. After accounting for a 6% organic membrane loss and a 12% moisture and washing wash loss, the raw daily tonnage translates to a highly reliable net dry biogenic sorbent supply of 2.90 to 4.50 Metric Tons per day.

Parameter Metric	Lower Bound Estimate	Upper Bound Estimate
Daily Egg Consumption	600,000 eggs/day	850,000 eggs/day
Average Weight per Eggshell	5.50 grams	6.00 grams
Daily Raw Eggshell Waste Tonnage	3.30 MT/day	5.10 MT/day
Annual Raw Eggshell Waste Tonnage	1,204.5 MT/year	1,861.5 MT/year
Net Dry CaCO3 Sorbent Potential	2.90 MT/day	4.50 MT/day

Table 1: Varanasi regional poultry consumption and eggshell-derived calcium carbonate feedstock potential.

3.2 Wet FGD Cost-Benefit Analysis and Payback Projections

Using Varanasi's midpoint collection baseline (yielding 1,350.5 MT/year of active dry sorbent), we compare the landed cost of processed eggshell waste against traditional mined limestone. Due to long-distance freight charges from distant mining states, natural limestone has a high landed cost of ₹3,000/MT. In contrast, localized eggshell collection, pre-treatment, and trucking cost ₹2,700/MT raw. However, this is heavily offset by municipal waste diversion tipping fee subsidies (₹500/MT), carbon offset credits (₹150/MT), and gypsum byproduct sales (₹600/MT), resulting in a net landed dry sorbent cost of ₹1,645.75/MT (a direct savings of 45.14% per ton).

Table 2

illustrates the project's financial feasibility metrics. CapEx is capitalized at ₹50 Lakhs (₹5,000,000) for collection bins, solar zone dryers, the 500°C kiln, and the separation loop. The project generates an exceptional Net Present Value of ₹66.3 Lakhs and an Internal Rate of Return of 29.98%, with a payback period of 3.27 years.

Financial Metric / Parameter	Value Model (Baseline Scenario)
Initial Capital Investment (CapEx)	INR 5,000,000 (INR 50 Lakhs)
Landed Mined Limestone Cost	INR 3,000 / Metric Ton
Net Landed Processed Eggshell Cost	INR 1,645.75 / dry Metric Ton
Project Simple Payback Period	3.27 Years
Project Net Present Value (NPV @ 10%)	INR 6,629,046 (INR 66.3 Lakhs)
Project Internal Rate of Return (IRR)	29.98%

Table 2: Financial project metrics and discounted cash flow yields for NTPC Vindhyachal wet FGD integration.

3.3 Multi-Variable Sensitivity Modeling and Risk Thresholds

To safeguard NTPC against operational volatility, we stress-test the project's NPV. First, we analyze collection efficiency: to clear NTPC's standard 10% corporate hurdle rate, the municipal cooperative must maintain an absolute minimum collection rate of 52%. If collection drops to 40% (high-compliance failure), the low volume of avoided limestone cannot amortize the fixed CapEx, resulting in a negative NPV of -₹17.2 Lakhs. Conversely, if collection scales to 80%, the NPV increases to ₹38.5 Lakhs (IRR of 22.10%).

Second, we model limestone price fluctuations: the project represents an exceptional hedge against transport fuel inflation. If landed limestone prices increase to ₹3,500/MT due to diesel surcharges, the gross annual savings jump to ₹2.50 Million, driving the project's NPV to ₹11.77 Million (₹1.18 Crore) and pushing the IRR to an outstanding 43.90%.

3.4 Environmental Benefits & Terrestrial Conservation

The environmental advantages of substituting natural mined limestone with eggshell bio-waste in NTPC Vindhyachal's wet FGD system are multi-dimensional, spanning terrestrial conservation, air pollution control, and global carbon reduction:

1. Direct Terrestrial Protection: Limestone mining is a destructive, open-cast quarrying process that causes permanent deforestation, topsoil removal, and the destruction of local ecological habitats. By substituting biogenic eggshells, NTPC Vindhyachal directly prevents the quarrying of up to 1,350

tons of natural mineral reserves annually, conserving terrestrial ecosystems and safeguarding local biodiversity.

2. 2. Landfill Diversion and Vector Control: Raw eggshells dumped in municipal landfills decompose rapidly. The rotting yolk and albumen residues release intensive, offensive hydrogen sulfide (H₂S) gases, breeding disease-carrying microbial vectors and contaminating soils via acidic leachate. Direct diversion into the pre-treatment loop completely eliminates these landfill environmental hazards.
3. 3. Biogenic Carbon Credits: Natural limestone calcination is a major source of greenhouse gases, as thermal decomposition releases mineralized fossil CO₂. In contrast, the calcium carbonate in eggshells is biogenic in origin (capturing atmospheric carbon during the biological cycle of the poultry layer). Utilizing biogenic CaCO₃ in wet FGD scrubbers reduces industrial net fossil carbon accounting, qualifying the facility for valuable carbon offset credits.

Conclusions & Policy Implications

This study demonstrates that eggshell waste can serve as an exceptionally high-purity, chemically viable, and financially lucrative substitute for traditional mineral limestone in utility-scale wet FGD scrubbing systems. By thermally pre-treating eggshell biowaste at 500°C, the plant completely eliminates the superhydrophobic organic membrane that traditionally hinders slurry rheology and causes accelerated pump impeller erosion. Furthermore, our proposed three-stage mechanical and aerodynamic separation system allows NTPC Varanasi to cleanly isolate high-value fuel chunks (green charcoal) from the friable desulfurization-grade roasted shell dust, protecting power boilers from calcium-induced slagging and tube fouling.

Financially, the wet FGD integration yields a highly robust baseline payback of 3.27 years, with an NPV of ₹66.3 Lakhs and an IRR of 29.98% over a 15-year horizon. The project is financially resilient down to a sourcing threshold of 52%, acting as an excellent hedge against commodity and transport fuel inflation. To support this circular bio-economy loop, municipal authorities should implement formalized source-segregation policies and partner with informal waste-picker cooperatives, creating green jobs while driving industrial decarbonization.

Declarations

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Specifically, the lead author V S Narasimha Sai Sangapu confirms that this research was conducted purely for scientific progress and circular economy implementation studies without commercial bias.

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Figures

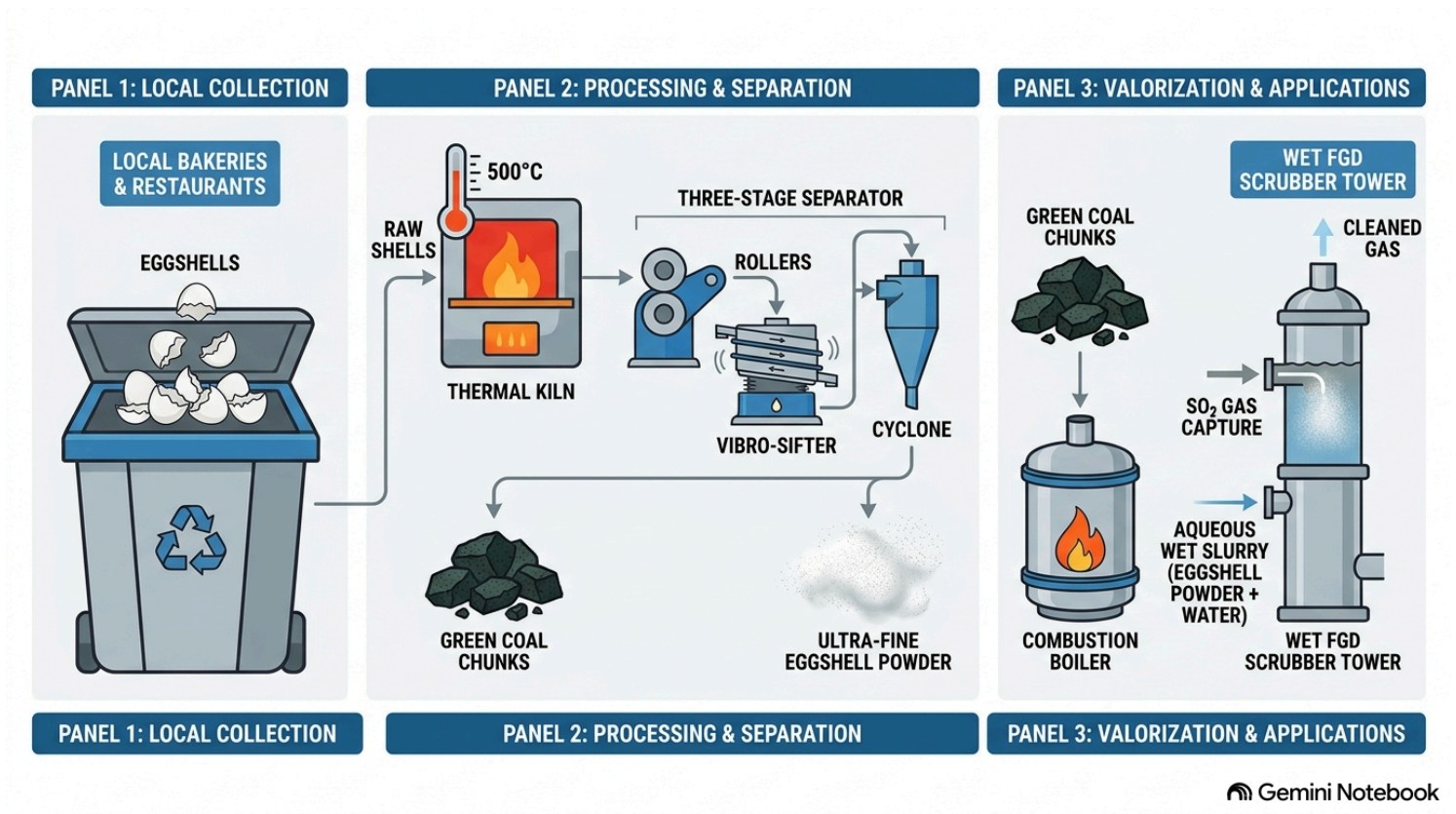


Figure 1

Graphical Abstract detailing the Closed-Loop MSW Co-Processing and FGD Sorbent Separation Flow.