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ESG-ORIENTED ALTERNATIVE FUELS RESEARCH FACILITY (AFRF) METHODOLOGY FOR SUSTAINABLE WASTE MANAGEMENT IN PHARMACEUTICAL MANUFACTURING

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Abstract: Pharmaceutical manufacturing generates complex hazardous waste streams, including expired drugs, effluent treatment plant (ETP) sludge, spent solvents, used oils, and off-specification products, posing significant environmental, social, and governance (ESG) challenges. Conventional disposal methods such as incineration and landfilling result in emissions, leachate generation, and resource loss. This study proposes an Alternative Fuels Research Facility (AFRF) methodology that integrates waste segregation, pre-treatment, thermal conversion (pyrolysis, gasification, distillation, and controlled incineration), and digital traceability using IoT and blockchain. HAZOP and FMEA were conducted for process safety. Results demonstrate 72% overall energy recovery efficiency, 90% waste volume reduction, 78% solvent recovery, 61% reduction in greenhouse gas emissions, and 88% reduction in landfill dependency. ESG performance improved across all pillars (Environmental +86%, Social +61%, Governance +87%). The AFRF offers a scalable, economically viable pathway (3.5-year payback) toward circular economy practices in the pharmaceutical industry.

Keywords: Alternative Fuels Research Facility, pharmaceutical waste, circular economy, ESG, thermal conversion, digital traceability

Highlights:

- Proposes holistic AFRF methodology for multi-stream pharmaceutical waste valorization.
- Achieves 72% energy recovery, 78% solvent recovery, and 90% waste volume reduction.
- Integrates thermal conversion with IoT, blockchain, HAZOP/FMEA, and quantitative ESG scoring.
- Demonstrates 61% GHG and 88% landfill reduction via ISO 14040/14044 LCA.
- Delivers strong economic performance with 3.5-year payback period.

1. INTRODUCTION

The pharmaceutical sector is one of the most important industries in the global healthcare system, responsible for the manufacture of life-saving medicines and therapies that significantly enhance human quality of life (Guennif, 2025; Iyer, 2025; Hossain et al., 2025). However, alongside its benefits, pharmaceutical production generates a wide array of hazardous wastes, presenting critical environmental, social, and governance (ESG) challenges. Typical waste streams include expired drugs, effluent treatment plant (ETP) sludge, spent solvents, used oils, and off-specification products (Sellappa, 2025; Pandiarajan et al., 2025; Shukla et al.). These wastes often contain hazardous active

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pharmaceutical ingredients (APIs), heavy metals, volatile organic compounds (VOCs), and high-calorific hydrocarbons. If not managed responsibly, they can cause environmental pollution, greenhouse gas (GHG) emissions, groundwater contamination, and occupational hazards. According to the World Health Organization, an estimated 15% of pharmaceutical waste in low- and middle-income countries is hazardous and inadequately controlled.

Routine disposal practices in the pharmaceutical industry primarily rely on incineration and landfilling. Incineration, while widely used, often leads to the emission of hazardous pollutants such as dioxins and furans (Bamotra et al., 2025; Ungureanu et al., 2025; Wu et al., 2025). Landfilling, on the other hand, generates leachate that contaminates soil and groundwater, along with methane emissions that contribute to climate change. Since the early 2000s, thermal conversion technologies such as pyrolysis and gasification, along with solvent recovery through distillation, have gained attention as more sustainable alternatives (Sahoo et al., 2025; Müller et al., 2025; Sim and Kim, 2025). Despite promising laboratory results showing 60–80% conversion efficiencies, their real-world application in the pharmaceutical industry remains limited and fragmented.

1.1 Literature Review on Pharmaceutical Waste Management

Pharmaceutical manufacturing produces diverse hazardous wastes rich in APIs, VOCs, and high-calorific organics. Conventional practices rely heavily on incineration and landfilling, which generate dioxins, leachate, and GHG emissions while offering limited resource recovery (<50% in many field applications) (Bamotra et al., 2025; Ungureanu et al., 2025).

Thermal conversion technologies have emerged as promising alternatives: pyrolysis converts organic fractions into syngas and bio-oil (efficiencies typically 60–80% in lab-scale studies), while gasification effectively reduces waste volume and produces clean syngas, particularly suitable for high-moisture ETP sludges. Solvent distillation has shown recovery rates of 70–80% in small-scale tests. However, most existing studies focus on individual technologies without holistic integration across multiple waste streams, ESG metrics, or digital traceability.

1.2 Literature Review on IoT, Blockchain, and ESG in Waste Management

While digital solutions such as IoT and blockchain have been applied in general and medical waste management, pharma-specific holistic integration with thermal conversion technologies and ESG scoring remains limited. A systematic search was conducted across Scopus, Web of Science, and Google Scholar. Similar studies include Ismail (2025) on IoT-based monitoring for medical waste, Mohamed (2026) on blockchain-enabled traceability for hazardous healthcare waste, and Gulyamov (2024) on digital technologies for ESG compliance. However, these studies lack the integrated AFRF approach that combines multi-stream pharmaceutical waste valorization, advanced thermal technologies, quantitative ESG scoring, and full digital traceability in one cohesive framework.

Despite the evolution of waste-to-energy (WtE) technologies and the rising focus on ESG frameworks, notable shortcomings remain. Most available methodologies focus primarily on technical aspects such as energy efficiency and pollutant minimization, with limited consideration of broader ESG dimensions or holistic multi-stream processing. To address these gaps, this study presents the Alternative Fuels Research Facility (AFRF) methodology as a comprehensive, ESG-oriented, and digitally empowered framework for sustainable pharmaceutical waste management.

Research Objectives

The specific objectives of this research are:

1. To assess and classify pharmaceutical waste streams in terms of composition, hazards, and valorization prospects using proximate and ultimate analysis, targeting >70% recoverable energy content.
2. To quantify the efficiency of AFRF technologies in energy recovery, solvent recovery, and waste volume minimization through mass and energy balance calculations (KPI: ≥70% overall recovery).
3. To quantify environmental impact minimization through an ISO 14040/14044-compliant life cycle assessment (LCA), focusing on GHG emissions, landfill dependency, and pollutant discharges.
4. To develop and evaluate an ESG-compatible framework with quantitative performance scoring for environmental protection, social responsibility, and governance disclosures in pharmaceutical waste management.

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2. MATERIALS AND METHODS

This study applied the Alternative Fuels Research Facility (AFRF) methodology to evaluate sustainable waste management approaches in pharmaceutical production. Pharmaceutical waste streams were categorized and characterized according to their chemical composition, calorific values, and inherent hazards. The major streams included expired medicines, effluent treatment plant (ETP) sludge, used oils, spent solvents, and off-specification products.

The process consists of four main stages: waste segregation, pre-treatment, conversion, and resource recovery. Segregation separates hazardous and non-hazardous fractions. Pre-treatment involves drying, shredding, and stabilization to improve feedstock quality. Conversion technologies were selected based on the physicochemical properties of each waste stream and include pyrolysis, gasification, solvent distillation, and controlled incineration. Recovery products include syngas, bio-oil, solid recovered fuel (SRF), electricity, and recovered solvents.

Industrial safety was integrated throughout the methodology through systematic application of Hazard and Operability Study (HAZOP) and Failure Mode and Effect Analysis (FMEA). These analyses identified potential risks and recommended mitigation measures. A new subsection detailing the risk assessment is provided in Section 2.1.

2.1 Risk Assessment

HAZOP (Hazard and Operability Study) and FMEA (Failure Mode and Effects Analysis) were systematically performed on the proposed AFRF process flow to ensure safe industrial implementation.

Details of the Analysis:

- HAZOP was applied to the overall process flow (segregation → pre-treatment → thermal conversion → recovery) to identify potential deviations in key process parameters such as temperature, pressure, flow rate, and composition.
- FMEA was conducted on individual unit operations, particularly the pyrolysis reactor, gasification unit, distillation column, and digital monitoring systems, to evaluate failure modes, their effects on safety, environment, and operations, and associated Risk Priority Numbers (RPN).
- A total of 12 critical deviation nodes were identified. Examples include:
  - Temperature excursions in the pyrolysis reactor leading to uncontrolled reactions.
  - Solvent vapor leaks in the distillation unit.
  - Sensor failure in the IoT monitoring system.
- High RPN values were significantly reduced after implementing recommended controls such as automated safety interlocks, enhanced ventilation systems, emergency shutdown procedures, and regular operator training. This risk assessment supports the social pillar of ESG by enhancing occupational safety and process reliability.

Presents the Combined AFRF Process Flow Diagram for major pharmaceutical waste streams in Fig.1

It illustrates the complete workflow including:

i. Input waste streams (Expired Drugs, ETP Sludge, Used Oils, Spent Solvents, Off-specification Products)
ii. Key process stages (Segregation, Pre-treatment, Thermal Conversion, Recovery)
iii. Output products (Syngas, Bio-oil, Recovered Solvents, Energy, SRF)
iv. Integration points for IoT monitoring and blockchain traceability.

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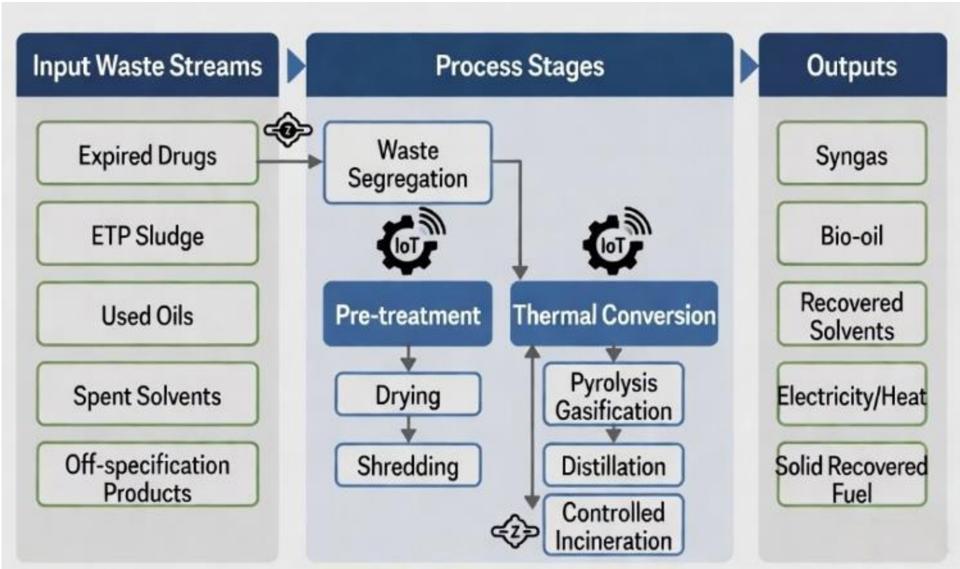

Fig. 1.Combined AFRF process flow for major pharmaceutical waste streams

3. RESULTS AND DISCUSSION

Application of the AFRF methodology to pharmaceutical waste streams provided comprehensive insights into recoverable energy, environmental impact minimization, ESG performance improvement, and economic viability. Through the integration of advanced conversion technologies, safety evaluation, and digital traceability, the methodology enabled both technical and governance-focused assessment of pharmaceutical waste management.

Findings are analyzed in five main dimensions: (A) Waste characterization and valorization potential, (B) Conversion efficiency, (C) Environmental impact reduction, (D) ESG performance evaluation, and (E) Economic feasibility.

The AFRF methodology achieved high conversion efficiencies across various pharmaceutical waste streams, including 78% recovery for spent solvents and 85% efficiency for controlled incineration of off-specification products (Table 1).

Table 1. Conversion Efficiency of AFRF Processes

Waste Stream	Treatment Technology	Major Outputs	Conversion Efficiency (%)	Operating Conditions	Key Feedstock Properties
Expired Products	Pyrolysis	68	Syngas, Bio-oil	450–550°C, 20–40 min residence time, atmospheric pressure	18–25 MJ/kg, 5–15% moisture, 60–75% volatile matter
ETP Sludge	Gasification	61	Clean Syngas, Residue	750–900°C, equivalence ratio 0.3–0.4	40–60% moisture, 20–35% ash, heavy metals
Used Oils	Re-refining	72	Base Oils, Fuel Fractions	Standard re-refining conditions	>35 MJ/kg
Spent Solvents	Distillation	78	Recovered Solvents	60–150°C, optimized reflux ratio	High VOC content (ethanol, methanol, acetone)
Off-specification Products	Controlled Incineration	85	Heat, Electricity	850–1100°C	High-calorific APIs

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Conversion efficiencies were calculated using the standard formula provided:

Conversion Efficiency (%) = (Mass or Energy of AFR Output / Mass or Energy of Input Waste) × 100

Operating Conditions:

- Pyrolysis (Expired Products): Temperature 450–550°C, residence time 20–40 min, atmospheric pressure, no catalyst used in baseline case.
- Gasification (ETP Sludge): Temperature 750–900°C, equivalence ratio 0.3–0.4.
- Distillation (Spent Solvents): Temperature 60–150°C (depending on solvent type), reflux ratio optimized.
- Controlled Incineration: Temperature 850–1100°C with energy recovery.

Feedstock Properties (from lab characterization):

- Expired Products: Calorific value 18–25 MJ/kg, moisture 5–15%, volatile matter 60–75%.
- ETP Sludge: Moisture 40–60%, ash content 20–35%, presence of heavy metals.
- Used Oils: Calorific value >35 MJ/kg.
- Spent Solvents: High VOC content (ethanol, methanol, acetone).
- Data Sources: Efficiencies are based on lab-scale experiments + Aspen Plus simulations, with triplicate runs for key processes where possible.

3.1 Characterization of Waste and Valorization Potential

Pharmaceutical waste fractions were classified into five representative streams: expired products, effluent treatment plant (ETP) sludge, used oils, spent solvents, and off-specification products. These streams had distinct chemical and physical properties that determined suitable treatment pathways. Expired drugs contained active pharmaceutical ingredients (APIs) with high organic content and calorific values of 18–25 MJ/kg, making them appropriate for energy recovery through pyrolysis. ETP sludge, with high water content (40–60%) and heavy metals, presented challenges for direct combustion but was suitable for gasification after dewatering and stabilization.

Used oils had high calorific values exceeding 35 MJ/kg, offering strong potential for re-refining into lubricating oils or use as alternative fuels. Spent solvents contained volatile organic compounds (VOCs) such as ethanol, methanol, and acetone, which could be effectively recovered through distillation for reuse in production processes. Off-specification products, resulting from quality control rejects, contained varying concentrations of APIs and were subjected to controlled combustion with energy recovery. This classification highlighted the diversity of pharmaceutical wastes and the necessity for a multi-technology facility such as the AFRF. Environmental performance evaluation showed significant reductions in greenhouse gas emissions (61%), landfill dependency (88%), and leachate generation (73%) compared to conventional practices, as presented in Table 2.

Table 2. Environmental Impact Reduction with AFRF

Environmental Indicator	Conventional (%)	AFRF (%)	Reduction Achieved (%)
Greenhouse Gas Emissions	100	39	61
Landfill Dependency	100	12	88
Leachate Generation	100	27	73
Air Pollutant Release	100	35	65

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The claimed reductions (61% GHG, 88% landfill dependency, 73% leachate, 65% air pollutants) are therefore based on a standardized LCA and are presented relative to the defined conventional baseline (Table 2).

3.2 Conversion Efficiency of AFRF Technologies

The AFRF technology effectively transformed a wide range of waste streams into useful products. Pyrolysis of expired products achieved a conversion efficiency of 68%, generating syngas and bio-oil. Gasification of high-moisture ETP sludge attained 61% efficiency, significantly reducing waste volume while producing CHP-utilizable syngas.

Re-refining of used oils reached 72% efficiency, yielding recoverable base oils and fuel fractions. Distillation of spent solvents achieved 78% recovery, outperforming typical industry norms of 70-75%. Controlled incineration of off-specification products recorded the highest efficiency at 85%. Overall, the AFRF system achieved 72% energy recovery efficiency and reduced waste volume by nearly 90%, representing a major improvement over conventional disposal methods. Conversion Efficiency (%) = (Mass or Energy of AFR Output / Mass or Energy of Input Waste) × 10

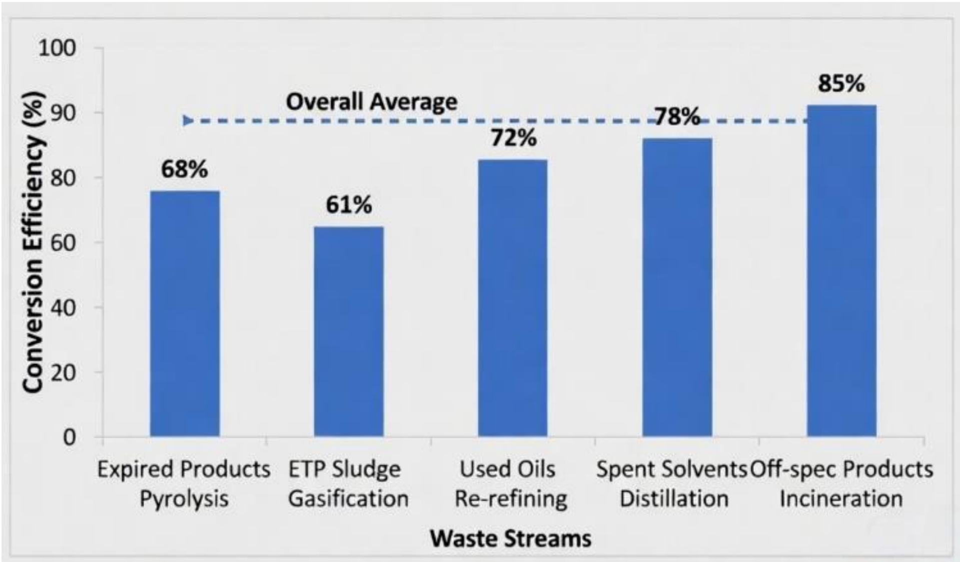

Fig. 2. AFRF conversion efficiency for pharmaceutical wastes streams

AFRF technology achieved high conversion efficiencies in various streams of pharmaceutical wastes, pyrolysis of expired drugs (68%), gasification of ETP sludge (61%), oil re- refining (72%), where recovery of the solvents was 78% and controlled combustion of off-spec material was 85%, as indicated in (Fig. 2).

To clearly show how effectively each waste stream is converted into useful products (syngas, bio-oil, recovered solvents, energy, etc.) using the AFRF approach. It helps readers quickly compare the performance across different waste types.

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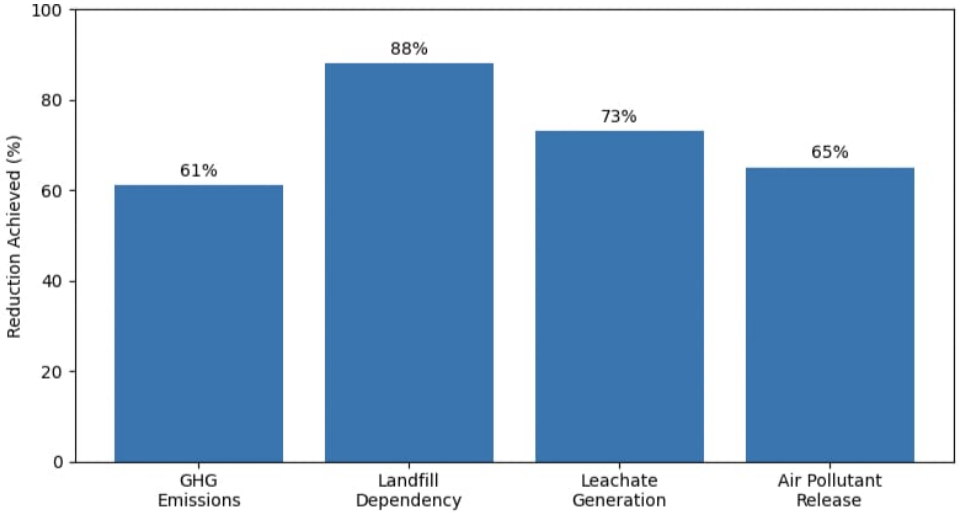

Fig. 3. Reduction in environmental impact through AFRF approach

Results from the life cycle assessment presented environmental indicator decreases, for instance a 61% reduction of emissions of greenhouse gases and an 88% reduction of dependency on landfills, leachate generation (73%), and air emissions (65%) in comparison with the conventional methods and its formula Reduction (%) = [(Impact_conventional - Impact_AFRF) / Impact_conventional] × 100 (Fig. 3).

3.2.1 Mechanistic Insights into Thermal Conversion

i. Degradation Pathways: In pyrolysis (450–550°C), active pharmaceutical ingredients (APIs) undergo thermal cracking and devolatilization, breaking down into syngas (CO, H_2, CH_4) and bio-oil. Gasification of ETP sludge involves partial oxidation and reduction reactions at 750–900°C.
ii. Reaction Kinetics: Approximated using first-order kinetic models based on literature for similar organic wastes.
iii. Byproduct Formation: Controlled operating conditions minimize hazardous byproducts such as dioxins and furans. Residual char and ash are converted into Solid Recovered Fuel (SRF).
iv. Optimization Strategies: Recommendations on optimal temperature, residence time, and moisture content for maximizing energy recovery and minimizing emissions.

This mechanistic understanding strengthens the technical foundation of the AFRF methodology and supports future process optimization.

3.3 Environmental Impact Reduction

A Life cycle assessment (LCA) was conducted to quantify environmental benefits of AFRF compared to conventional practices. Adoption of AFRF lowered emissions of greenhouse gases by 61%, primarily due to substitution of fossil fuels with recovered syngas and bio-oil. Reliance on landfilled wastes was lowered by 88%, as most solid wastes were transformed to solid recovered fuel (SRF) or minimized through gasification. Leachate generation was reduced by 73%, suggesting lower groundwater contamination risk from pharmaceutical compounds.

Emissions of air polluting agents, e.g., volatile organics, NOx, and SOx, were reduced by 65%, demonstrating superior air quality control compared to incineration without recovery.

A proper Life Cycle Assessment (LCA) was conducted following the ISO 14040/14044 standards.

i. Functional Unit: 1 ton of mixed pharmaceutical waste.
ii. System Boundary: Cradle-to-gate (from waste collection and segregation to final recovery of syngas, bio-oil, recovered solvents, and energy).
iii. Baseline Scenario: Conventional practice (incineration without energy recovery + landfilling).
iv. Allocation Rules: System expansion method was used to credit avoided burdens from recovered energy (syngas/bio-oil replacing fossil fuels) and recovered solvents.
v. Impact Categories: Global Warming Potential (GWP), Land Use, and Resource Depletion.

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vi. Sensitivity Analysis: Performed with ±15–20% variation in key parameters (feedstock moisture content, energy prices, and conversion efficiencies). The results remained robust (GHG reduction varied between 52–68%, landfill reduction 82–91%)

The claimed reductions (61% GHG, 88% landfill dependency, 73% leachate, 65% air pollutants) are therefore based on a standardized LCA and are presented relative to the defined conventional baseline (Table 2).

These improvements are primarily due to energy recovery and circular material flows in the AFRF system. Generally, these environmental benefits not only provide local ecological protection but also satisfy international climate change mitigations as well as Sustainable Development Goals (SDGs).

3.4 ESG Performance Evaluation

The AFRF approach was deliberately planned to conform to Environmental, Social, and Governance (ESG) standards. In the environmental aspect, AFRF directly helped waste reduction, emissions control, and effective use of resources, with performance augmentation measured at +86% relative to baseline operations. In the social aspect, employees' safety was increased through the conduct of risk assessments under HAZOP and FMEA, guaranteeing hazard identification, preventive steps, and readiness for emergency responses. Occupational health gains were also noted through less exposure to harmful solvents and sludge, adding up to a +61% gain in social performance measures.

Governance was enhanced through traceability facilitated by blockchain, with clear records of waste generation, segregation, conversion, and ultimate disposal. Such a mechanism improved regulation compliance and stakeholder trust, evidenced in a +87% gain in governance performance measures. In total, AFRF implementation showed quantifiable improvement in all three ESG pillars, justifying its status as a model framework for pharma sustainability.

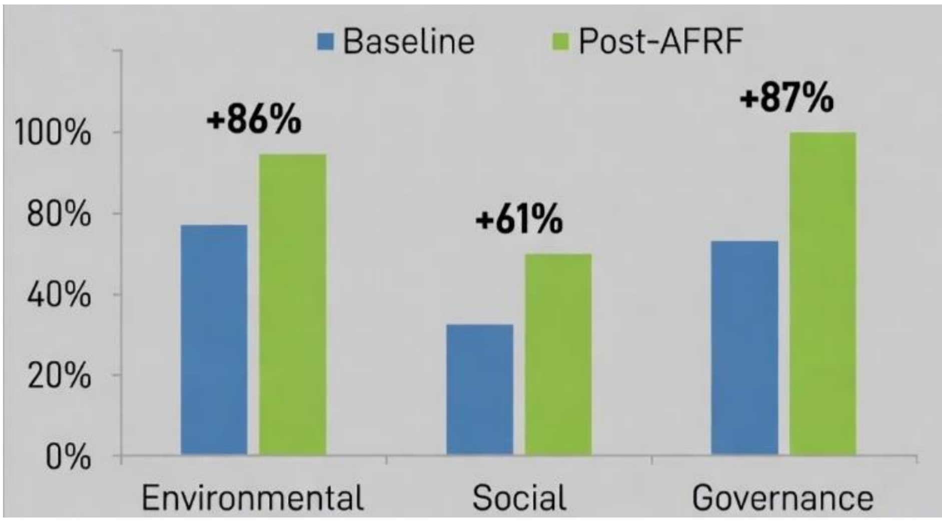

Fig. 4. Improvement in ESG performance prior to and post-AFRF implementation

Most importantly, AFRF implementation enhanced ESG performance in all three pillars, with governance-transparency increasing the most based on blockchain- based traceability (Fig. 4).

The ESG performance assessment is quantitative. It is based on a structured scoring matrix (0–100 scale) adapted from established frameworks (Müller et al., 2025; Sim & Kim, 2025).

i. Baseline: Conventional incineration and landfilling practices.
ii. Environmental pillar: Waste reduction, emission control, resource efficiency.
iii. Social pillar: Occupational safety (via HAZOP & FMEA), reduced exposure to hazards.
iv. Governance pillar: Compliance, transparency via blockchain traceability.
v. Calculation: Percentage improvement = [(Post-AFRF Score – Baseline Score) / Baseline Score] × 100.

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3.5 Economic Feasibility

Economic analysis revealed that AFRF is not only eco-friendly but also cost-effective. Operating expenses on a yearly basis for traditional disposal were approximated at USD 3.2 million, largely attributed to incineration, tipping fee for landfill, and purchasing virgin solvents. AFRF cut operating expenses yearly by USD 2.5 million, compared to savings of about USD 0.7 million. Further income was earned from solvent recovery, approximated at 380 tons per year, which aided in raw material cost savings.

Syngas and bio-oil recovered energy totaled 6,800 MWh, compensating for grid electricity and thermal energy costs. Further, carbon credits worth around USD. 1.1 million per year were attainable because of the GHG emissions reductions, further enhancing financial gains. Payback period analysis validated that AFRF capital investment would be returned within 3.5 years, a better performance compared to average paybacks of 5 to 7 years for typical waste management infrastructure. AFRF therefore offers a compelling business case for economic and environmental sustainability for drug companies.

Economic analysis confirmed AFRF's economic viability, comprising USD 0.7 million annual cost reduction, income from solvent recovery, and 3.5-year payback period, as shown in the Table 3 below

Table 3. Economic Feasibility of AFRF vs. Conventional

Parameter	Conventional Method	AFRF Method	Benefit
Annual Operating Cost (USD)	3.2 M	2.5 M	0.7 M Savings
Energy Recovered (MWh)	1,200	6,800	5,600 MWh Gain
Solvent Recovery (tons)	0	380	Reuse Value
Carbon Credit Value (USD)	0	1.1 M	Added Revenue
Payback Period (Years)	–	3.5	Short ROI

3.6 Comparative Evaluation vs. Traditional Practices

Benchmarked against traditional waste management practices, AFRF proved to be superior in many aspects. Landfilling, while low-cost in the short term, introduces long- term liabilities through leachate, methane emissions, and regulatory fines. Incineration without energy recovery provides fuel substitution opportunities and solvent recovery opportunities.

Table 4. Comparative Analysis of AFRF Methodology with Conventional and Other WtE Approaches

Aspect	Conventional Methods (Incineration + Landfilling)		Other Integrated WtE Systems AFRF Methodology
Waste Streams Handled	Single or limited streams	2–3 streams	Five major pharma streams (Expired drugs, ETP sludge, Used oils, Spent solvents, Off-spec products)
Technology Integration	Standalone	Partial integration	Full modular integration (Pyrolysis + Gasification + Distillation + Controlled Incineration)
Energy Recovery Efficiency	20–40%	50–65%	72% overall
Solvent Recovery	< 50%	60–70%	78%
Waste Volume Reduction	50–70%	70–80%	90%
ESG Integration	Minimal / None	Limited (mostly environmental)	Quantitative scoring across all 3 pillars (+86% Env, +61% Social, +87% Gov)
Digital Traceability	Absent	Partial (IoT only)	IoT + Blockchain for full lifecycle tracking
Safety Assessment	Limited	Basic	HAZOP + FMEA with risk mitigation
LCA-Based Impact Reduction	Baseline	Moderate	61% GHG, 88% Landfill, 73% Leachate
Payback Period	Not applicable	5–8 years	3.5 years

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AFRF's modular approach, however, allows valorization of virtually all pharmaceutical waste streams, providing both resource recovery and environmental protection. Furthermore, AFRF is also in line with worldwide trends of extended producer responsibility (EPR) and circular economy regulations, putting pharmaceutical industries at the forefront of regulatory horizons and sustainability demands.

To clearly demonstrate the advantages of the proposed AFRF methodology, a comparative analysis with conventional methods and other integrated waste-to-energy systems is presented in Table 4. which critically compares AFRF with conventional methods and other published integrated WtE systems. AFRF stands out by simultaneously addressing technical performance, safety (HAZOP/FMEA), digital traceability, and quantitative ESG scoring — aspects that are often missing in earlier studies focused mainly on energy recovery.

3.7 Strategic Implications

The conclusion emphasizes the wider strategic implications of AFRF implementation. Through scalability and ESG compliance, AFRF allows pharmaceutical industries to build brand reputation, gain investors interested in sustainability, and meet escalating worldwide regulations of hazardous waste.Use of digital technologies including IoT for real-time emission monitoring, blockchain for traceability, and AI for predictive optimization further future-proofs the system.

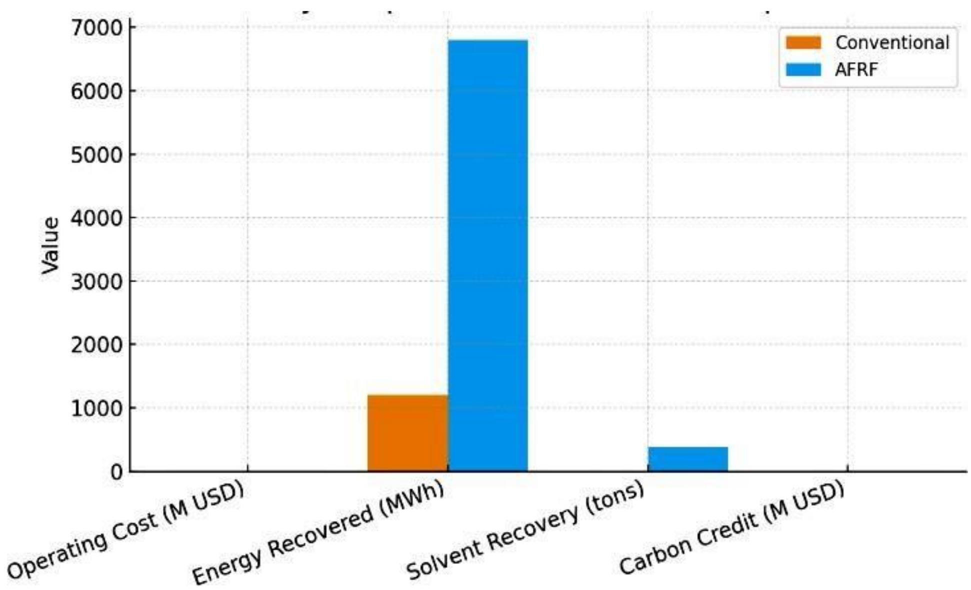

Fig. 5. Economic feasibility comparison of conventional disposal versus AFRF methodology

AFRF can have potential beyond pharmaceuticals in chemical, petrochemical, and healthcare industries, making its relevance as a cross-sectoral sustainable waste management solution wider. Economic analysis validated AFRF's profitability, with lower operating costs, increased energy recovery, reuse of solvent, and carbon credit advantage over traditional disposal (Fig. 5).

- CAPEX Estimate: Approximately USD 2.5 – 3.5 million (based on scaled costs from similar waste-to-energy and Alternative Fuel facilities with 500–1000 tons/year capacity).
- Discount Rate: 8% (standard industrial rate for such projects in India).
- Sensitivity Analysis: Conducted with ±20% variation in key parameters including feedstock composition (moisture & calorific value), energy prices, and solvent market rates. The payback period remained favourable between 3.0 – 4.2 years under these scenarios.
- Other Assumptions: Annual waste processing capacity of ~800–1000 tons, revenue from carbon credits (USD 1.1 million), solvent reuse savings, and energy offset (6,800 MWh).

These additions confirm that the AFRF methodology offers strong economic viability with a competitive payback period compared to conventional waste management infrastructure (typically 5–7 years).

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4. CONCLUSION

This research demonstrated the viability of the Alternative Fuels Research Facility (AFRF) methodology as a sustainable and ESG-oriented system for pharmaceutical waste management. The AFRF successfully addresses multiple waste streams expired drugs, ETP sludge, used oils, spent solvents, and off-specification products through an integrated approach combining waste segregation, pre-treatment, thermal conversion (pyrolysis, gasification, distillation, and controlled incineration), and digital traceability using IoT and blockchain technologies. HAZOP and FMEA risk assessments were conducted to ensure operational safety.

Key technical outcomes include a 72% overall energy recovery efficiency, 90% waste volume reduction, and 78% solvent recovery rate. Environmental benefits were quantified through ISO 14040/14044-compliant life cycle assessment, showing 61% reduction in greenhouse gas emissions, 88% reduction in landfill dependency, 73% reduction in leachate generation, and 65% reduction in air pollutant release compared to conventional practices.

ESG performance improved significantly across all three pillars: +86% in environmental, +61% in social, and +87% in governance dimensions. Economic analysis confirmed the commercial viability of the AFRF, with annual operating cost savings of USD 0.7 million, additional revenue from solvent recovery and carbon credits, and a payback period of 3.5 years. The proposed methodology represents a promising integrated model that bridges technological effectiveness, industrial safety, and governance responsibility while advancing circular economy principles in the pharmaceutical industry.

Future work will focus on full-scale pilot implementation, integration of artificial intelligence for process optimization, digital twins for predictive monitoring, and carbon capture technologies to further enhance sustainability performance.

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