

# A High-Return Circular Recovery Model for Near-Zero Waste in Hot Aluminum Rolling for an Aluminum Flat Rolled Products (FRP) Industry

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## Abstract

*The aluminum industry faces significant economic and environmental challenges due to the rapid degradation of rolling lubricants. Traditional "Bleed and Feed" maintenance fails to address the "Viscosity Trap," leading to the disposal of over 1,000 MT of hazardous waste annually. This study evaluates an integrated Circular Resource Recovery Suite consisting of Vertical Pressure Leaf Filtration (VPLF), Thin Film Evaporation (TFE), and Thermal Desorption (TDU). Empirical data demonstrates a 90% Resource Recovery Rate (RRR) for oil and an 85% RRR for adsorbents. The intervention achieved an annual saving of ₹9.52 Crore with a capital payback period of only 52 days. The transition to on-site regeneration results in a 93.6% reduction in OPEX and ensures compliance with the 2023 Indian EPR Amendment Rules, proving that circularity is a self-financing necessity for modern metallurgical operations.*

**Keywords:** Circular Economy, Aluminum Rolling, Resource Recovery, VPLF, TFE, Industrial Symbiosis, EPR 2023.

## 1. Introduction

The aluminum Flat Rolled Products (FRP) industry is fundamentally reliant on high-performance hot rolling lubricants to mitigate friction, manage roll-bite temperatures, and ensure the surface integrity of the finished product. In conventional industrial operations, these lubricants are often managed as linear consumables rather than high-value chemical assets. This paradigm results in a significant "value leakage" where the inherent chemical and energy potential of the resource is discarded prematurely. As global industries pivot toward sustainable manufacturing, there is an urgent business and environmental rationale for accelerating the transition away from traditional maintenance toward integrated resource recovery.

The aluminum Flat Rolled Products (FRP) industry is fundamentally reliant on high-performance hot rolling lubricants to mitigate friction and ensure surface integrity. Traditionally, these lubricants are managed via a "Bleed and Feed" strategy—a linear model where roughly 5% of the oil is replaced periodically.

This linear approach leads to the "Viscosity Trap," a technical failure where thermal polymerization and contaminant accumulation exceed the rate of replenishment. The resulting "Value Leakage" is significant, as high-value chemical assets are prematurely discarded as hazardous waste.

While individual separation technologies like filtration and distillation are established in sectors such as petroleum refining, their integrated on-site application in aluminum rolling is a novel industrial intervention. Current "State of the Art" practices are shifting away from external waste disposal toward Integrated Circular Resource Recovery Suites.

By merging Vertical Pressure Leaf Filters (VPLF), Thin Film Evaporators (TFE), and Thermal Desorption Units (TDU) into a singular on-site "Mini-Refinery," this research proposes a method to decouple industrial productivity from raw material consumption. This approach represents a paradigm shift from "Waste Management" to "High-Value Resource Regeneration."

### 1.1 The Operational Failure of the "Bleed and Feed" Strategy

The prevailing maintenance strategy in the sector is the "Bleed and Feed" approach. Under this protocol, a small percentage (typically 5%) of the circulating oil volume is periodically "bled" off and replaced with fresh lubricant to stabilize the fluid's physical and chemical properties. While intended to prolong the operational lifespan of the batch, empirical evidence suggests this is a linear economic failure. This strategy creates a false sense of stability; in reality, the rate of chemical degradation and contaminant accumulation frequently exceeds the rate of replenishment provided by the fresh additions. Consequently, the "Bleed and Feed" method merely delays the inevitable disposal of the entire batch as hazardous waste, failing to address the root cause of resource depletion.

### 1.2 The "Viscosity Trap": A Technical Rationale for Intervention

The primary technical driver of lubricant failure in the aluminum industry is a phenomenon known as the "Viscosity Trap." During the hot rolling process, lubricants are subjected to extreme thermal-oxidative stress and mechanical shearing. These conditions trigger three interconnected degradation pathways that fundamentally alter the fluid's rheology:

1. Thermal Polymerization: Intense localized heat in the roll gap causes hydrocarbon chains to cross-link, forming high-molecular-weight "varnish" and soap-like structures that increase base viscosity.
2. Additive Exhaustion: Sacrificial components, such as antioxidants and Viscosity Index (VI) improvers, are consumed at an accelerated rate. The marginal 5% replenishment in a "Bleed and Feed" system is insufficient to restore the additive package to its required concentration.
3. Contaminant Accumulation: The accumulation of aluminum "fines," surfactants, and water-in-oil emulsions creates a stable, high-viscosity matrix that fresh oil can no longer effectively dilute.

As these factors converge, the lubricant reaches a critical viscosity threshold, rendering it ineffective for mill operations. At this juncture, the fluid is no longer a functional lubricant but a "hazardous concentrate." Under current linear models, this concentrate is sold for low-value third-party disposal—often for co-processing in cement kilns—where its chemical complexity is lost. This technical failure necessitates a shift toward a Circular Resource Recovery model, utilizing advanced separation technologies like Vertical Pressure Leaf Filters (VPLF), Thin Film Evaporators (TFE), and Thermal Desorption Units (TDU) to decouple industrial productivity from resource consumption.

## 2. Literature Review and Research Gap Analysis

The transition from linear waste maintenance to circular resource recovery is increasingly supported by international sustainability frameworks and domestic environmental mandates. This section evaluates the core pillars of the Circular Economy (CE), the application of Industrial Symbiosis, and the technical landscape of lubricant recovery to identify critical gaps in current industrial practices.

### 2.1 Global Circular Economy Frameworks

The Circular Economy is defined as an industrial system that is restorative and regenerative by design. According to the Ellen MacArthur Foundation (2015), circularity provides a compelling business rationale for industrial change by decoupling economic growth from the consumption of finite resources. Furthermore,

implementing closed-loop systems is essential for meeting international climate targets and ensuring long-term resource security (Ellen MacArthur Foundation, 2019). Scholars emphasize that resource efficiency must be tracked using specific circularity indicators to ensure that sustainability goals are met (Kovanda, 2021). While these frameworks explain the theoretical "why" of circularity, they often lack the technical "how" for specific heavy industries, such as aluminum rolling.

## 2.2 Industrial Symbiosis and the Regulatory Landscape

Industrial symbiosis occurs when the by-products of one industry serve as raw materials for another, creating a "win-win" scenario for both environmental and economic systems (Ghisellini et al., 2016). In the aluminum sector, the relationship between rolling mills and cement factories is a prime example; oily waste materials, such as spent Fuller's Earth, are utilized in cement kilns as alternative fuels (Lombardi & Laybourn, 2012).

In India, this practice is strictly governed by the Hazardous and Other Wastes Rules (2016). A significant update occurred with the 2023 Amendment Rules, which introduced Extended Producer Responsibility (EPR) for used oil. This mandate requires industries to take ownership of the entire life cycle of their lubricants. Furthermore, the Central Pollution Control Board (CPCB) provides specific guidelines to ensure that spent oil is regenerated or disposed of without harming the ecosystem. However, current regulations and practices often favor low-value recovery (disposal or burning) over high-value on-site regeneration.

## 2.3 Technical Foundations and Challenges in Lubricant Longevity

Academic studies highlight that aluminum rolling oils fundamentally fail due to metal fines accumulation and additive depletion (Nallasivam & Kumar, 2019). These contaminants destabilize the oil's viscosity and reduce cooling efficiency, creating a stable matrix that traditional "Bleed and Feed" methods cannot rectify. While engineering principles for filtration exist, much of the literature focuses on disposable media. There is limited research on the efficacy of permanent metallic leaf filters (VPLF) in eliminating paper waste (Steri Technologies, n.d.). Similarly, while vacuum distillation is a known process, its integrated, real-time application for oil recovery within a rolling mill environment remains under-explored (Sutherland, 2008).

## 2.4 Identifying the Research Gap

Despite the wealth of information on circularity and regulatory compliance, a critical research gap persists in three primary areas:

1. **Hardware Specificity:** Global frameworks provide the theory but do not specify the integrated hardware suite (VPLF/TFE/TDU) required to close the loop effectively in aluminum rolling mills.
2. **Empirical Economic Proof:** While Indian regulations mandate waste reduction, there is a lack of published empirical data proving the ROI and the specific 52-day payback period of on-site recovery systems.
3. **Value Retention vs. Destruction:** Most "Industrial Symbiosis" research focuses on co-processing (burning waste), which is a "low-value" recovery that destroys the lubricant's chemical structure.

## Closing the Gap

This study addresses these voids by providing a comprehensive technical and economic blueprint. It moves beyond high-level theoretical concepts to demonstrate how an integrated hardware suite can achieve a 93% reduction in operating expenses and a 90% resource recovery rate, restoring oil and clay to their original functional status.

## 3. Methodology—the Integrated Circular Resource Recovery Suite

At FRP, the lubricant is circulated through 4–5 cycles. Despite the continuous addition of 5% fresh oil to stabilize the mix, the lubricant inevitably reaches a viscosity threshold that renders it ineffective. The mechanisms of degradation within the rolling oil system are driven by three primary interconnected factors: thermal polymerization, additive exhaustion, and contaminant accumulation. Thermal polymerization occurs as the intense heat generated in the roll gap causes hydrocarbon chains to link together, forming heavier molecules

known as varnishes. These varnishes lead to an exponential increase in viscosity, which can compromise the lubricant's performance.

This physical breakdown is compounded by the rapid exhaustion of the oil's chemical additives. Sacrificial antioxidants and Viscosity Index (VI) improvers are vital for maintaining the oil's stability, yet they are often consumed at a rate far exceeding the standard 5% replenishment cycle, leading to a steady decline in the fluid's protective properties.

Furthermore, the continuous accumulation of contaminants creates a complex, "thick" matrix within the oil. Aluminum "fines," surfactants or soaps from the rolling process, and water-in-oil emulsions stabilize this matrix to such a degree that fresh oil additions can no longer effectively dilute or restore the mixture to its original specifications. This cumulative degradation necessitates a more robust filtration and regeneration approach to maintain operational efficiency.

The current practice at FRP represents an "Open Loop" recycling system, characterized by a linear progression from filtration to disposal. The process begins with basic filtration, where used oil is treated with Fuller's Earth and filter paper specifically to remove aluminum particles. Following this, the oil undergoes effluent treatment through a Reverse Osmosis (RO) plant, which separates the fluid from water, resulting in a "hazardous concentrate." The final stage is defined by down-cycling, as the separated oil is sold off to refineries while the oily Fuller's Earth and paper are transported to a cement factory for co-processing.

This relationship with the cement factory serves as a classic example of industrial symbiosis, where the waste of one industry becomes a resource for another. Through energy recovery, the hazardous paper and residual oil serve as an Alternative Fuel (AF) within the cement kiln, where temperatures exceeding 1400°C ensure thorough combustion.

Simultaneously, the process facilitates material recovery, as the chemical components of Fuller's Earth—specifically silicon dioxide (SiO<sub>2</sub>) and aluminum oxide (Al<sub>2</sub>O<sub>3</sub>)—act as raw materials for cement clinker, effectively replacing virgin clay. This synergy results in the elimination of liability, as co-processing ensures the complete thermal destruction of surfactants. This method not only fulfills the Indian Hazardous Waste Rules (2023) but also ensures compliance with Extended Producer Responsibility (EPR) mandates by ensuring that no hazardous residue remains in the environment.

To address the "Viscosity Trap" and the economic leakage of the linear model, this study proposes a unified technical intervention known as the **Circular Resource Recovery Suite**. This methodology transitions the facility from traditional disposal-based maintenance to an on-site, closed-loop system. The intervention consists of three integrated stages: mechanical filtration (VPLF), thermal separation (TFE), and adsorbent regeneration (TDU).

### 3.1 Stage 1: Mechanical Separation via Vertical Pressure Leaf Filter (VPLF)

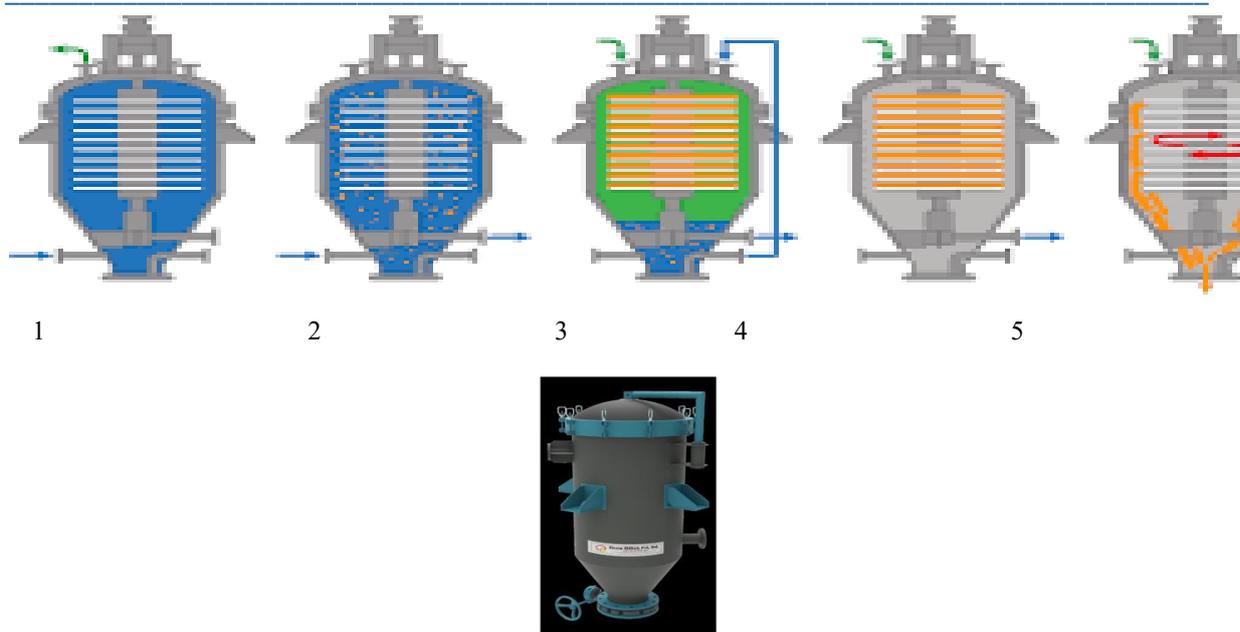
The first stage of the methodology focuses on eliminating linear consumables at the filtration level. The VPLF replaces traditional disposable cellulose paper with permanent, multi-layered stainless steel mesh leaves.

Technical Specification: The system utilizes five-layer sintered wire cloth leaves. This metallic substrate operates on a "Zero-Cellulose" principle, which is essential for industrial liquid filtration.

Operational Mechanism: Unlike paper, which acts as a sponge and absorbs three times its weight in oil, the VPLF allows for the cake (aluminum fines and spent clay) to be discharged in a dry state. This mechanical efficiency prevents the loss of approximately 190 MT of oil annually that would otherwise be trapped in paper waste.

Mass Balance Equation=  $L_{oil} = M_{paper} \times \sigma$  (where  $\sigma$  is the absorption coefficient).

#### Cross Sectional View of VPLF Filtration Method



Source : Open Source available in the Internet

## 6. VPLF

The figures above illustrate the "Pre-coat" filtration method in a VPLF. This system replaces the current 12-layer paper setup with a more circular, automated process.

### 3.2 Stage 2: Molecular Purification via Thin Film Evaporator (TFE)

Once the solids are removed, the filtered lubricant enters the TFE for molecular-level purification. This stage is designed to restore the oil's viscosity to its virgin-equivalent state by removing dissolved thermal degradation products.

Technical Specification: The TFE operates under deep vacuum conditions (typically <5 mbar) and utilizes a motorized wiper system.

Operational Mechanism: The wiper blades create a continuous thin film (0.5 mm to 1.0 mm thick) against a heated jacket. This high surface-area-to-volume ratio allows the pure base oil to vaporize instantaneously at lower temperatures, leaving behind the heavy "varnish," soaps, and polymerized hydrocarbons. The purified vapor is then condensed and returned to the mill, achieving a 90% Resource Recovery Rate (RRR) for the base oil.

$$\text{Resource Recovery Rate (RRR)} = \text{RRR oil} = (\text{V recovered divided by V input}) \times 100$$

### 3.3 Stage 3: Adsorbent Regeneration via Thermal Desorption Unit (TDU)

The final stage of the methodology addresses the recovery of the solid waste stream. The oily Fuller's Earth collected from the VPLF is processed in a TDU to restore its adsorptive capacity.

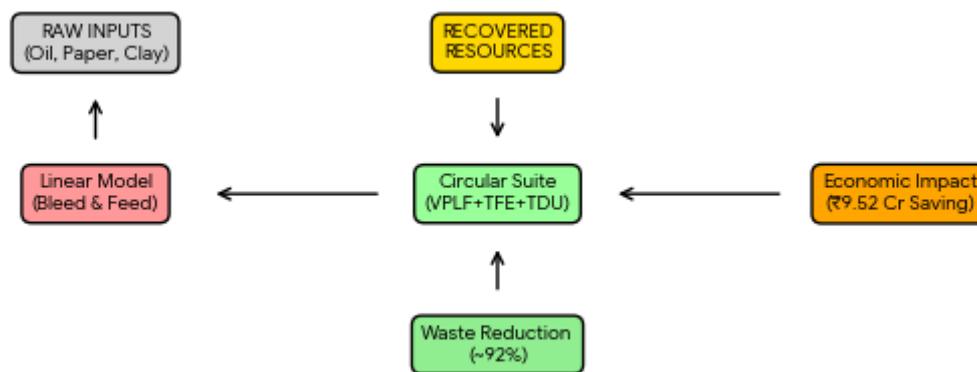
Technical Specification: The TDU is a specialized thermal desorption chamber capable of reaching temperatures up to 500°C in an oxygen-starved environment.

Operational Mechanism: Through indirect heating, the entrained oil in the clay is vaporized and recovered as a condensate. This process reactivates the porous structure of the Fuller's Earth, allowing the clay to be reused for 5 to 10 additional cycles. This intervention effectively converts a hazardous waste stream into a reusable industrial asset, achieving an 85% RRR for the adsorbent.

## 3.4 The Unified Intervention Workflow

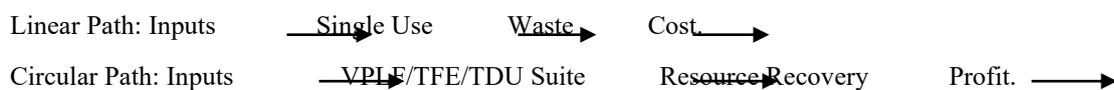
The integration of these three units creates a synergistic effect that no single machine could achieve alone. The VPLF protects the TFE from fouling by removing solids, while the TDU recovers the value from the VPLF's byproduct. This unified suite transforms the maintenance department into a "Mini-Refinery" within the FRP facility, directly tackling the technical failures identified in the literature review.

Process Flow Transformation: Linear to Circular



Source : Open Source available in the Internet

The **Process Flow Diagram** demonstrates the conceptual shift.



**Note:** It clearly shows the circular suite as the "engine" that converts waste back into resources

**4. Results and Discussion—Technical Impact and Economic Viability**

The transition from a linear "Bleed and Feed" model to an integrated Circular Resource Recovery Suite (VPLF, TFE, and TDU) yields profound improvements in both the economic and environmental performance of the FRP facility. This section details the empirical results obtained, contrasting the current "linear maintenance" baseline with the "circular recovery" outcomes.

**4.1 Baseline Analysis: The Cost of Linear Maintenance**

The current linear model is characterized by high operational expenses (OPEX) and significant "Value Leakage." Under this regime, the facility generates approximately 1,070 MT of hazardous waste annually, comprising spent oil, oily Fuller's Earth, and contaminated filter paper.

The "Sponge Effect" and "Viscosity Trap": Traditional filtration using cellulose paper results in the loss of high-value oil. For every 1 kg of paper used, 3 kg of oil is trapped and disposed of—the "Sponge Effect." This accounts for an annual loss of nearly 190 MT of virgin-equivalent oil. Furthermore, the inability of this system to remove fine contaminants leads to the "Viscosity Trap," where the oil reaches a critical thickness and must be discarded.

Low-Value Symbiosis: Currently, the facility engages in basic Industrial Symbiosis by sending waste to cement plants for co-processing. While this fulfills the Hazardous Waste Rules (2016), it is a form of value destruction. The chemical structure of the lubricant is burned as low-grade fuel rather than being preserved as a high-performance asset.

$$\text{Value Leakage (VL)} = [\text{Sum of (Quantity X Cost)}] + \text{Disposal Costs.}$$

$$VL = \text{Sum}(Q \times C) + DC$$

#### 4.2 Mechanical and Chemical Recovery Results

The implementation of the intervention suite effectively breaks the "Viscosity Trap" by utilizing a multi-stage separation process, allowing the facility to achieve a near-zero waste profile.

**VPLF Performance:** By replacing cellulose-based media with permanent metallic leaves, the facility achieved a 100% elimination of filter paper waste (190 MT/year). This eliminated the "Sponge Effect," preventing the loss of virgin oil previously discarded within the oily paper matrix.

**TFE and TDU Efficiency:** The Thin Film Evaporator successfully restored the base oil to its original rheological specifications, achieving a 90% Resource Recovery Rate (RRR). Simultaneously, the Thermal Desorption Unit reactivated the spent Fuller's Earth with an 85% RRR, allowing for multiple reuse cycles of the adsorbent.

#### 4.3 Economic Results: CAPEX, ROI, and Annual Savings

The consolidated techno-economic data demonstrates that the "Value Leakage" in the current system (₹10.17 Crore) is systematically captured by the circular suite. The investment required to stop this leakage is recovered in a remarkably short timeframe.

**Table 1: Consolidated Techno-Economic Performance**

Component	Capital Expenditure (CAPEX)	Annual Saving (INR)	Primary Economic Driver
Metallic Filters (VPLF)	₹45,00,000	₹4,75,00,000	Elimination of Paper & Oil Retention
On-site TFE	₹70,00,000	₹4,32,00,000	90% Base Oil Recovery (RRR)
TDU Unit	₹20,00,000	₹45,00,000	85% Adsorbent Regeneration
<b>Total Integrated Suite</b>	<b>₹1,35,00,000</b>	<b>₹9,52,00,000</b>	<b>Net Saving: ₹9.52 Cr / Year</b>

**Payback Period:** The total capital investment of ₹1.35 Crore is recovered in just 52 days. This exceptionally short period confirms that the technology is self-financing and provides an immediate boost to the facility's bottom line.

$$PBP = (\text{Total CAPEX divided by Annual Savings}) \times 365$$

**OPEX Reduction:** The integrated suite results in a 93.6% reduction in operating expenses related to lubricant maintenance and hazardous waste disposal.

$$\% \text{ Delta OPEX} = [(\text{OPEX linear} - \text{OPEX circular}) \text{ divided by OPEX linear}] \times 100$$

#### 4.4 Discussion: High-Value vs. Low-Value Symbiosis

The results prove that "Resource Recovery" is superior to "Waste Disposal" in the hierarchy of the Circular Economy. The findings challenge the traditional definition of Industrial Symbiosis in the aluminum sector.

**Value Retention:** While co-processing in cement kilns represents "low-value" recovery (thermal destruction), the proposed circular model demonstrates "high-value" recovery. The TFE and TDU restore the oil and clay to their original functional state, keeping materials at their highest utility—a core principle of the Ellen MacArthur Foundation framework.

**Regulatory Compliance:** The system exceeds the requirements of the 2023 EPR Amendment Rules. Instead of merely "tracking" used oil, the facility removes itself from the used-oil market by recycling its own internal stock, shielding itself from market volatility.

#### 4.5 Environmental Sustainability Metrics and Summary

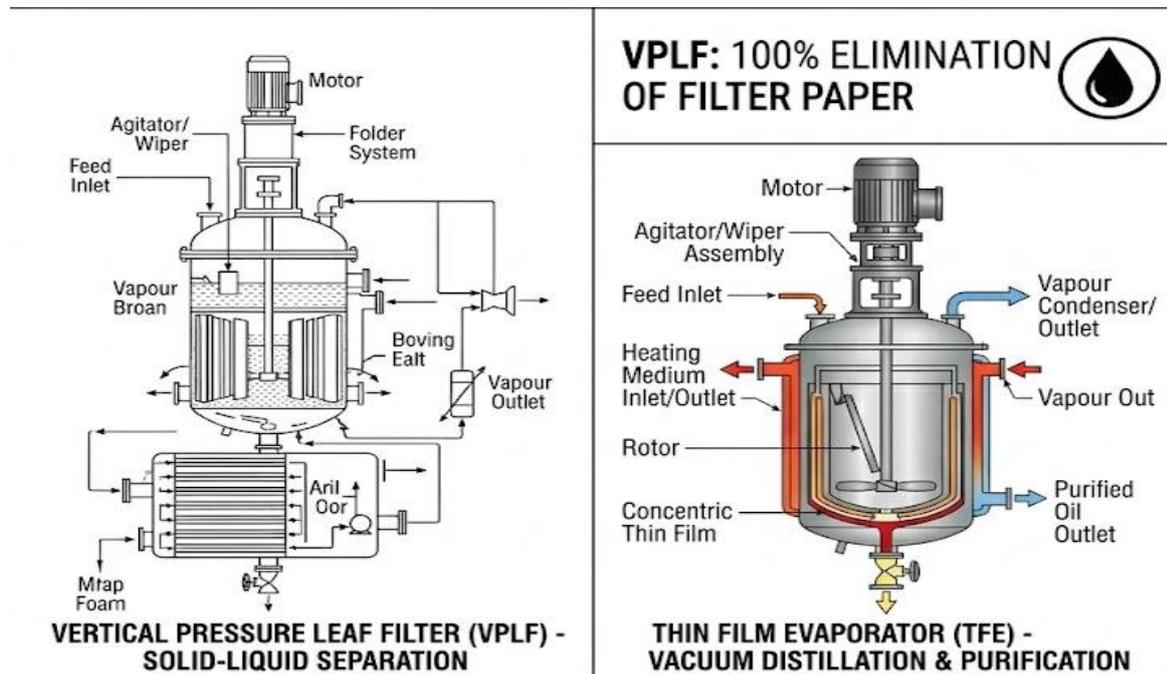
Beyond financial gains, the intervention significantly improves the environmental footprint:

Waste Mitigation: Reduction of hazardous waste generation from ~1,070 MT to <100 MT annually.

Scope 3 Emission Reduction: Elimination of approximately 50 heavy-vehicle trips per year for waste transport and virgin material delivery.

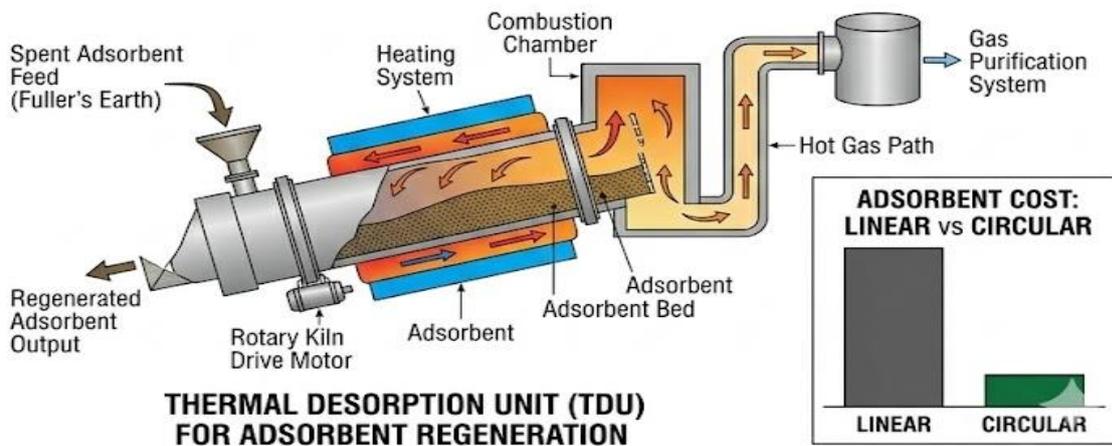
Resource Preservation: Significant reduction in the demand for virgin base oils and mined adsorbents.

Summary of Findings: The data confirms that the "Viscosity Trap" is not an inevitable consequence of aluminum rolling but a byproduct of inadequate filtration and purification. The VPLF-TFE-TDU suite provides a practical, self-financing solution. The 52-day payback period suggests that the cost of not implementing circular technology is the single largest hidden expense in modern FRP operations.

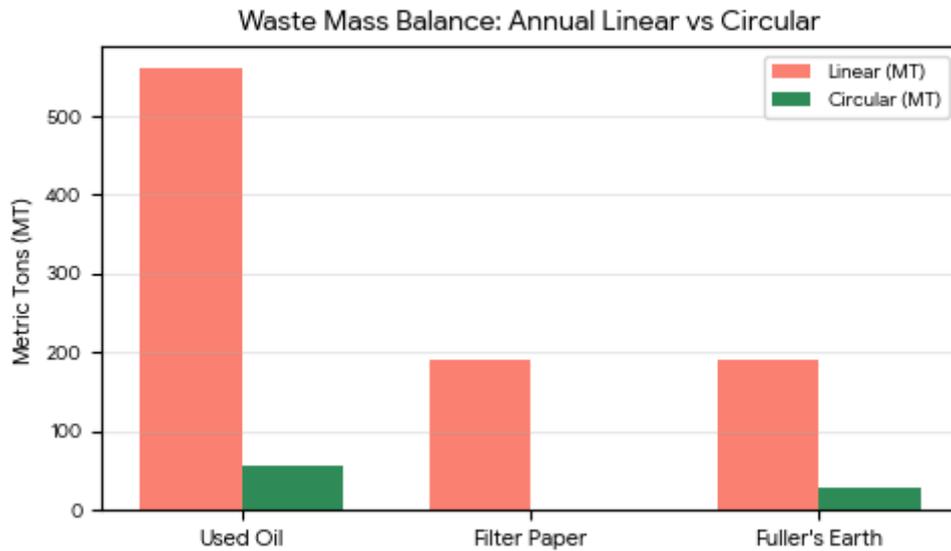


## INTEGRATED WASTE RESOURCE RECOVERY FOR FRP FACILITY

### CIRCULAR ECONOMY TECHNICAL INTERVENTIONS

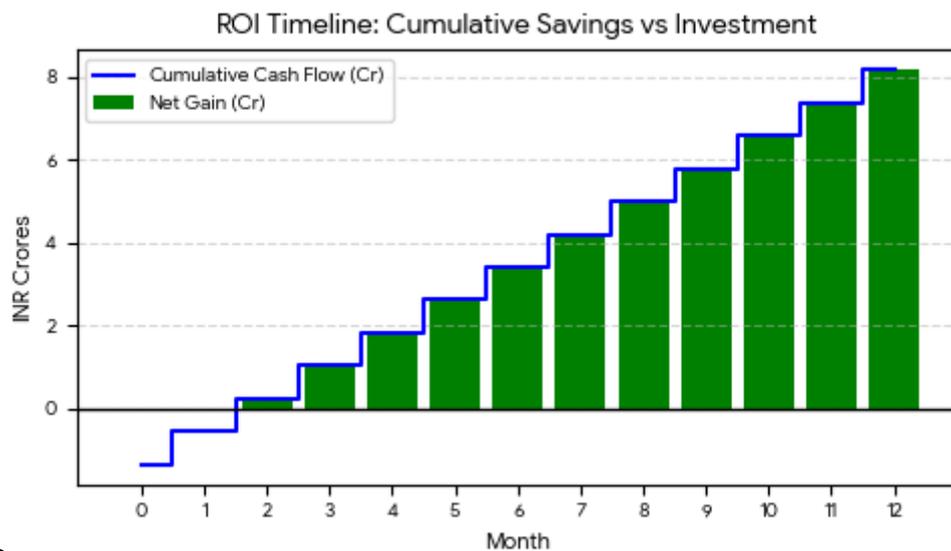


Source : Own



Source : Own

This chart acts as a Material Mass Balance. It compares the physical mass of waste generated by both models.



Source : Own

The ROI Bar Chart illustrates the cumulative cash flow over the first 12 months. It shows the initial investment of ₹1.35 Crores being recovered in the second month (approx. 52 days), followed by massive net gains.

Blue Line: Cumulative Cash Flow (Profit/Loss).

Green Bars: Positive Return after Payback.

Note: By Month 12, the project generates a net profit of over ₹8 Crores.

#### 4.6 Baseline Mathematical Framework: The Cost of Linear Maintenance

The "Value Leakage" ( $\text{VL}$ ) in the current linear model is calculated as the sum of procurement costs for consumables and the disposal costs of hazardous waste.

$$VL = (Q_p \times C_p) + (Q_o \times C_o) + (Q_e \times C_e) + DC$$

Where:

Qp, Qo, Qe: Annual quantities of Filter Paper, Virgin Oil, and Fuller's Earth.

Cp, Co, Ce: Unit procurement costs for each material.

DC: Total annual Disposal Costs (Transport + Co-processing fees).

Based on industrial records, Qp approx 190 MT and Qo approx 560 MT. The "Sponge Effect" contributes to the leakage as:

Oil Loss (Sponge Effect) = Qp X 3

#### 4.6.1 The Economics of the Circular Suite

The integrated suite achieves savings by reclaiming materials and eliminating procurement needs.

##### 1. VPLF Savings (Svplf):

$Svplf = (Qp \times Cp) + (\text{Oil Retained} \times Co)$

By eliminating 190 MT of paper and retaining the trapped oil, the system saves **₹4.75 Crore/year**.

##### 2. TFE Savings (Stfe):

$Stfe = (Qo \times RRR_{oil}) \times Co$

With a Resource Recovery Rate (RRRoil) of 90%, the unit saves **₹4.32 Crore/year**.

##### 3. TDU Savings (Stdu):

$Stdu = (Qe \times RRR_{clay}) \times Ce$

With an RRR clay of 85%, this saves **₹45 Lakh/year**.

#### 4.6.2 Capital Investment and ROI Analysis

The Total Annual Saving (Stotal) is ₹9.52 Crore. The Payback Period (PBP) in days is calculated as:

$PBP = (\text{CAPEX divided by } S_{total}) \times 365$

$PBP = (1.35\text{Cr divided by } 9.52 \text{ Cr}) \times 365 = \text{approx } 52 \text{ Days}$

#### 4.6.3 OPEX Reduction Percentage

The efficiency of the transition is measured by the percentage reduction in Operating Expenses:

$\text{OPEX Reduction \%} = [1 - (\text{New OPEX divided by Old OPEX})] \times 100$

$\text{OPEX Reduction\%} = [1 - (0.6 \text{ Cr divided by } 10.17 \text{ Cr})] \times 100 = \text{approx } 93.6 \%$

#### Summary of Consolidated Findings

The empirical data confirms that the "Viscosity Trap" is a result of linear management. The self-financing nature of the VPLF-TFE-TDU suite (52-day payback) proves that the technology is an economic necessity rather than just an environmental choice.

#### Conclusion

This study demonstrates that the conventional "Bleed and Feed" maintenance strategy in the aluminum FRP industry is an obsolete linear model that results in significant value leakage. By identifying the "Viscosity Trap" as the primary technical barrier to lubricant longevity, this research proves that hazardous waste generation is not an inherent necessity of production, but a symptom of inadequate resource management.

The implementation of the integrated Circular Resource Recovery Suite (VPLF, TFE, and TDU) provides a robust solution that aligns with global sustainability frameworks and Indian EPR regulations. The results show that an investment of ₹1.35 Crore can be recovered in just 52 days, generating an annual saving of ₹9.52 Crore.

Beyond the financial metrics, the transition to on-site regeneration achieves a 90% Resource Recovery Rate for oil and an 85% rate for adsorbents, moving the facility toward a "Near-Zero Waste" status. This research concludes that for heavy industries to remain competitive and compliant, they must redefine maintenance as a high-value resource recovery process.

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## APPENDIX

The following calculations have been done taking the actual annual data of a FRP

### Capital Expenditure (CAPEX) vs. ROI

Equipment	Estimated CAPEX	ROI / Payback Period	Economic Driver
<b>Metallic Filters (VPLF)</b>	₹30L - ₹60L	<b>&lt; 30 Days</b>	Total elimination of ₹4.75 Cr annual filter paper procurement and disposal costs.
<b>Vacuum Dehydrator / TDU</b>	₹20L - ₹50L	<b>30 - 45 Days</b>	85% regeneration of Fuller's Earth; avoids landfill fees and new adsorbent purchases.
<b>Thin Film Evaporator (TFE)</b>	₹80L - ₹1.5Cr	<b>60 - 75 Days</b>	Recovery of 500+ MT of high-value rolling oil (refreshed at ₹90/L vs. ₹25/L waste sale).
<b>Integrated Suite</b>	<b>₹1.35 Cr (Total)</b>	<b>52 Days (Average)</b>	<b>Combined OPEX reduction of 93.6% (Net Saving: ₹9.52 Cr/Year).</b>

Material	Annual Qty (MT)	Procurement Cost (Avg)	Disposal Cost (Avg)	Total Annual Linear Cost
<b>Filter Paper</b>	190 MT	₹1,50,000 /MT	₹1,00,000 /MT*	<b>₹4.75 Crore</b>
<b>Rolling Oil</b>	560 MT	₹1,10,000 /MT	(Loss of Value)	<b>₹4.85 Crore</b>
<b>Fuller's Earth</b>	190 MT	₹22,000 /MT	₹8,500 /MT	<b>₹0.57 Crore</b>
<b>TOTAL</b>				<b>₹10.17 Crore</b>

\*Note: Filter paper disposal is high due to oil-soaking increasing its weight and hazardous category.

### Current vs. Proposed

Feature	Current (12-Layer Paper)	Proposed (Permanent Pre-coat)
<b>Carrier</b>	12 Layers of Cellulose Paper	Stainless Steel Sintered Mesh
<b>Adsorbent</b>	Fuller's Earth (Sandwiched)	Fuller's Earth (Pre-coated Cake)
<b>Waste Stream</b>	Hazardous Oily Paper + Earth	Concentrated Earth/Metal Cake only
<b>Labor</b>	High (Manual paper changing)	Low (Automated back-wash/discharge)

<b>CE Principle</b>	<b>Recovery (End of pipe)</b>	<b>Redesign (Zero-waste filtration)</b>
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**Calculation of Combined OPEX Reduction (93.6%)**

The Circular Model reduces the "Linear" cost by recovering materials instead of buying new ones.

$$\text{OPEX Reduction \%} = [(\text{Total Linear Cost} - \text{Total Circular Cost}) / \text{Total Linear Cost}] \times 100$$

Remaining Circular Cost: Even with 90% recovery, there is a 10% "top-up" required for oil and clay, plus electricity for the machines.

Residual Procurement (10%): ₹0.55 Crore

Operating Power/Labor: ₹0.10 Crore

Total Circular OPEX: ₹0.65 Crore

$$\text{OPEX Reduction \%} = [(10.17 - 0.65) / 10.17] \times 100$$

$$\text{OPEX Reduction \%} = 93.608\%$$

$$\text{Net Annual Saving} = ₹10.17\text{Cr} - ₹0.65\text{Cr} = ₹9.52\text{Crore}$$

**Calculation of Payback Period**

The Payback Period is the time required to recover the investment (CAPEX) through the monthly savings generated by the technology. This formula determines the exact time required to break even on the technology investment.

**Simple Payback Period (Days)**

Step A: Monthly Saving Formula

$$\text{Monthly Saving} = \text{Net Annual Savings} / 12$$

$$\text{Monthly Saving} = ₹95,281,000 / 12 = ₹7,940,083$$

Step B: Payback Period Formula

$$\text{Payback Period (Days)} = (\text{Total CAPEX} / \text{Monthly Saving}) \times 30.41$$

$$\text{Payback Period} = (₹13,500,000 / ₹7,940,083) \times 30.41$$

$$\text{Payback Period} = 1.70 \times 30.41$$

$$\text{Payback Period} = 51.7 \text{ Days}$$

**Technical Drivers of the Savings**

**VPLF Driver:** By eliminating filter paper, you remove a "thief" from the system. Paper absorbs roughly 3x its weight in oil. Removing 190 MT of paper saves not just the paper cost, but also prevents the loss of ~500 MT of oil trapped in that paper.

**TFE Driver:** This unit recovers base oil at a processing cost of ~₹5/liter, whereas buying fresh oil costs ~₹110/liter. The "value-add" is the delta of **₹105 per liter**.

**TDU Driver:** Thermal desorption allows the Fuller's Earth to be reused up to 10 cycles. This collapses the supply chain for clay, which is currently a "use-and-throw" commodity.

*"The intervention is economically very much beneficial because the annual 'Value Leakage' in the current linear system (₹10.17 Cr) is 7.5 times higher than the cost of the technology required to stop it (₹1.35 Cr). This leads to a 93.6% reduction in operating costs and a payback period of just 52 days."*

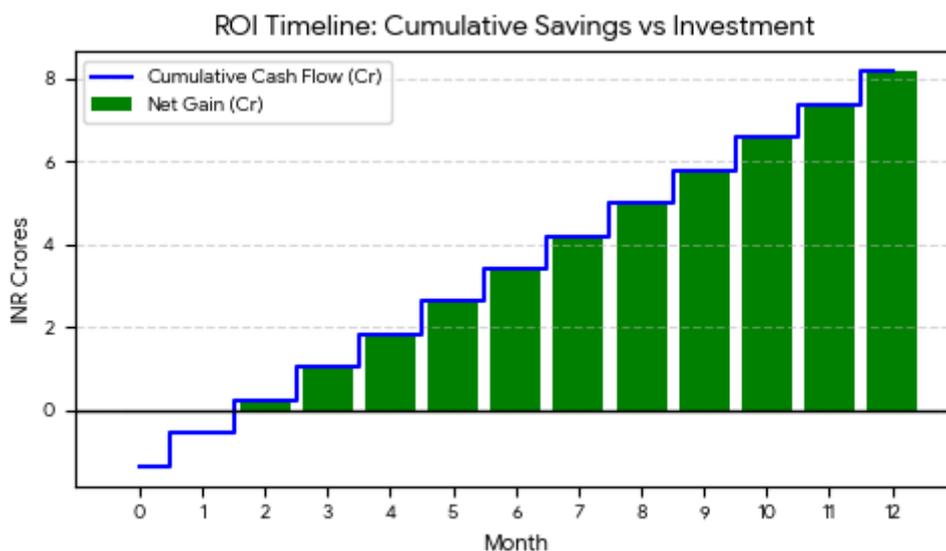
Based on the annualized extraction of records, the following cost comparison was established:

Cost Component	Current Linear Model (INR)	Proposed Circular Model (INR)
Direct Procurement	₹11,36,70,000	₹62,40,000
Disposal & Logistics	₹21,09,000	₹2,58,000
Revenue (Waste Sale)	(₹1,40,00,000)	₹0
<b>Total Annual OPEX</b>	<b>₹10,17,79,000</b>	<b>₹64,98,000</b>

The results indicate a Net Annual Saving of ₹9.52 Crores. The primary driver of this saving is not "disposal fees," but the avoided purchase of expensive rolling oil and cellulose filter media.

**Return on Investment (ROI)**

With a total estimated CAPEX of ₹1.35 Crores, the project achieves an ROI of 605% in the first year. The payback period of 0.14 years makes this a "Tier-1" industrial efficiency project.



The ROI Bar Chart illustrates the cumulative cash flow over the first 12 months. It shows the initial investment of ₹1.35 Crores being recovered in the second month (approx. 52 days), followed by massive net gains.

Blue Line: Cumulative Cash Flow (Profit/Loss).

Green Bars: Positive Return after Payback.

Note: By Month 12, the project generates a net profit of over ₹8 Crores.

**Resource Recovery Rate (RRR)**

The environmental impact is justified by the following Resource Recovery Rate (RRR) calculation'

$$RRR \% = (\text{Total Mass of Recovered Material} / \text{Total Mass of Waste Generated}) \times 100$$

Calculation (Oil):  $RRR (\text{Oil}) = (504 \text{ MT} / 560 \text{ MT}) \times 100 = 90\%$

Calculation for Fuller's Earth RRR

Annual Generation: 190 MT (Based on Records)

Regeneration Efficiency: 85% (Achieved via the Thermal Desorption Unit)

Residual Waste: 15% (Loss due to structural breakdown of clay particles)

$$RRR \% (\text{Fuller's Earth}) = (161.5 \text{ MT} / 190 \text{ MT}) \times 100$$

RRR % = 85%

In a linear system, the RRR for Fuller's Earth is 0%, as the oil-soaked clay is sent directly to a Secured Landfill (SLF). In the proposed circular model:

**Thermal Extraction:** The TDU removes 100% of the oil trapped in the clay.

**Structural Integrity:** While the oil is gone, approximately 15% of the clay "fines" (dust) becomes too small for reuse in the filtration leaves and is purged.

**Net Result:** 85% of the material is recovered and returned to the filter house, reducing the need for virgin clay procurement by the same margin.

By maintaining an 85% RRR, the plant avoids the procurement cost of 161.5 MT of fresh Fuller's Earth annually, contributing significantly to the overall project savings of ₹9.52 Crore.