EVONIK SUSTAINABILITY CHALLENGE 2025

Recycling of PET Waste to High-Purity BHET via Glycolysis

10-Page Interim Report

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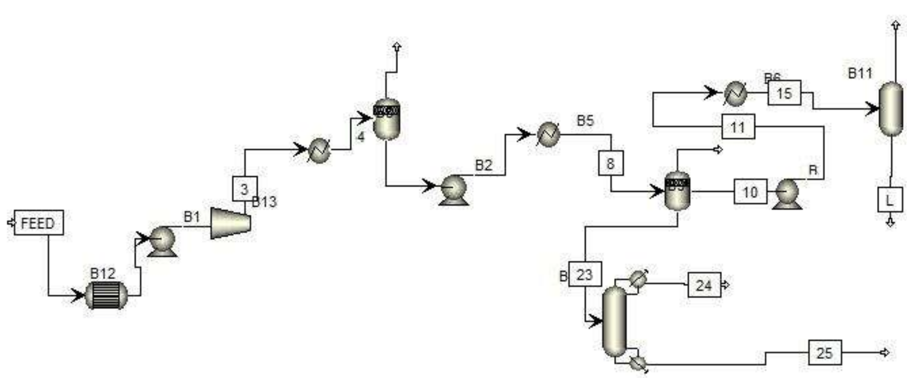
1. Executive Summary

This report presents our approach to designing a chemical recycling plant capable of processing post-consumer PET waste into high-purity Bis(2-hydroxyethyl) terephthalate (BHET) through glycolysis with sodium alkoxide as a catalyst. The plant is designed to produce 30,000 tons per annum (30 kta) of BHET, with a target purity of >99.5%.Our process features an optimized glycolysis reaction pathway, efficient separation and purification stages, and energy integration strategies that collectively enable economically viable production of BHET at costs below 75% of the prevailing PET market price. The plant is proposed to be located in Gujarat, India, taking advantage of robust infrastructure, proximity to waste sources, and favorable policy environment. Based on our techno-economic analysis, the project demonstrates promising financial metrics with an estimated payback period of 3.8 years and an internal rate of return (IRR) of 24.2%. The process achieves a carbon footprint reduction of approximately 40% compared to conventional PET production, aligning with sustainability objectives.

2. Process Overview and Chemistry

2.1 Block Flow Diagram



2.2 Feed Composition and Pre-Treatment

Feed Composition:

- PET waste (80-85% PET)
- Impurities (15-20%): Other polymers (PVC, PP, PE), inorganic contaminants, dyes, adhesives, and moisture

Pre-Treatment:

- **Sorting and Size Reduction:** Automated sorting using NIR technology, followed by shredding to 5-10 mm flakes
- **Washing:** Multi-stage washing with hot alkaline solution (1-2% NaOH) at 80°C to remove surface contaminants
- **Drying:** Centrifugal drying followed by thermal drying to reduce moisture content to <0.5 wt%
- **Melt Filtration:** Optional step for heavily contaminated streams to remove inorganic impurities through melt extrusion and filtration

The pre-treatment process is critical for achieving high reaction yields and product purities, as contaminants can inhibit catalyst activity and contaminate the final product.

2.3 Depolymerization via Glycolysis

Chemistry:

The glycolysis of PET is a transesterification reaction where ethylene glycol (EG) cleaves the ester bonds in PET to produce BHET monomers:

$$\textbf{PET + n(EG)} \rightarrow \textbf{n(BHET)}$$

The reaction is catalyzed by sodium alkoxide (typically sodium methoxide or sodium ethoxide), which provides significantly higher reaction rates and selectivity compared to traditional metal acetate catalysts.

Reaction Conditions:

- Temperature: 190-210°C (optimized at 200°C)
- Pressure: Slightly above atmospheric (1.2-1.5 bar)
- PET:EG ratio: 1:5 (mass ratio)
- Catalyst concentration: 0.5-1.0 wt% relative to PET
- Residence time: 3-4 hours
- Conversion: >98%
- BHET selectivity: >95%

Reactor Design:

The reactor is a jacketed stirred tank with a high-torque agitator designed to handle the highly viscous reaction mixture. The reactor is equipped with temperature control systems to maintain optimal reaction conditions and ensure uniform heating.

2.4 Separation and Purification

The separation and purification train consists of the following steps:

- **Filtration:** Removal of unreacted PET and insoluble impurities via pressure filtration at 180°C
- **Cooling Crystallization:** Controlled cooling of the filtrate to 80-100°C to precipitate BHET crystals
- **Solid-Liquid Separation:** Centrifugation to separate BHET crystals from the mother liquor
- **Purification:** Recrystallization from hot water (90-95°C) to achieve high purity
- **Drying:** Vacuum drying at 60-70°C to achieve moisture content <0.1%

This sequential purification approach ensures removal of oligomers, catalyst residues, and colored impurities to achieve the target product purity of >99.5%.

3. Process Simulation and Optimization

3.1 Simulation Methodology

The process was simulated using Aspen Plus V12. Due to the limited availability of built-in properties for BHET and PET in the Aspen database, the NRTL-HOC property method was used with custom parameters derived from experimental data for the glycolysis reaction and crystallization steps.

Key modeling approaches included:

Representation of PET as a custom pseudo-component

Modeling of the glycolysis reaction using RCSTR with kinetic parameters from literature

Calculation of crystallization yields using a custom separation block with temperature-dependent partition coefficients

3.2 Simulation Results

The simulation results are summarized below:

Material Balance (Base Case: 30 kta BHET):

- PET waste feed: 35,000 tons/year (82% PET content)
- Ethylene glycol consumption: 22,500 tons/year (including recycle)
- Fresh ethylene glycol makeup: 3,800 tons/year
- Sodium alkoxide catalyst: 230 tons/year
- BHET product: 30,000 tons/year (>99.5% purity)
- Process waste: 5,300 tons/year (including unreacted PET and impurities)

Energy Requirements:

- Heating duty: 12.5 MW
- Cooling duty: 10.8 MW

- Electricity consumption: 3.2 MW
- Specific energy consumption: 3.8 GJ/ton BHET

3.3 Process Optimization

Sensitivity analyses were conducted to optimize key process parameters:

Optimized Parameters:

- **EG:PET Ratio**: Reduced from traditional 8:1 to 5:1, resulting in 15% lower energy consumption in distillation with minimal impact on conversion
- **Reaction Temperature:** Optimized at 200°C, balancing reaction rate with unwanted side reactions
- **Crystallization Profile:** Two-step cooling crystallization (180°C → 120°C → 85°C) yielding 8% higher product recovery compared to single-stage crystallization
- **Energy Integration:** Implementation of heat integration between the reactor effluent and feed streams, reducing external heating requirements by 22%

4. Equipment Selection and Sizing

4.1 Key Equipment Specifications

Equipment	Specification	Design Capacity	Material of Construction	Notes
PET Feed System	Pneumatic conveying	5 tons/hr	Carbon steel	Includes metal detectors and NIR sorting
Washing System	Counter-current spray	6 tons/hr	SS316	3-stage washing with water recirculation
Glycolysis Reactor	Jacketed CSTR	30 m^3	SS316 with glass lining	High-torque agitator, 200°C design temp
Filtration Unit	Pressure filter	35 m^2	SS316	Operating temperature: 180°C
Crystallizer	Forced circulation	25 m^3	SS316	Cooling rate: 2°C/min
Centrifuge	Horizontal peeler	2.5 tons/hr	SS316	G-force: 1200g
Dryer	Vacuum rotary	3 tons/hr	SS316	Operating temperature: 70°C
EG Recovery Column	Packed column	2.5 tons/hr	SS304	20 theoretical stages

4.2 Alternative Equipment Evaluation

For the crystallization step, three technologies were evaluated:

Technology	Advantages	Disadvantages	Capital Cost	Operating Cost
Cooling Crystallizer (selected)	High purity, Energy efficient	Longer batch time	Medium	Low

Antisolvent Crystallization	Higher yield, Lower temperature	Solvent costs, Recovery needed	Medium	High
Melt Crystallization	Very high purity	High energy consumption, Fouling issues	High	Medium

The cooling crystallizer was selected based on its balance of product purity, energy efficiency, and operational simplicity.

5. Upstream Considerations: Collection and Sorting

5.1 PET Waste Supply Chain in India

India generates approximately 3.4 million tons of plastic waste annually, of which 14% (approximately 480,000 tons) is PET. Key sources include:

- Post-consumer bottles (65%)
- Industrial waste and rejected products (20%)
- Polyester textiles and fibers (15%)

The informal waste sector collects approximately 80% of PET bottles in urban areas, but collection rates in rural areas remain below 40%.

5.2 Collection Strategy

To ensure a stable supply of 35,000 tons/year of PET waste (approximately 7% of India's annual PET waste), we propose:

- **Direct Partnerships:** Establishing collection agreements with major bottling companies (Coca-Cola, PepsiCo) under Extended Producer Responsibility (EPR) frameworks
- **Waste Aggregator Network:** Creating a network of 50-100 waste aggregators across Gujarat and neighboring states
- **Material Recovery Facilities (MRFs):** Investing in 3-5 strategically located MRFs for preliminary sorting and densification
- **Digital Traceability:** Implementing a blockchain-based traceability system to track waste from collection to processing

5.3 Economic Aspects of Collection and Sorting

Activity	Cost (INR/kg)	Annual Cost (INR Million)	Percentage of Total
Collection from informal sector	8-12	350	52%
Transportation to MRFs	2-3	87.5	13%
Sorting and pre-processing	3-5	140	21%
Transportation to main plant	2-3	87.5	13%
Total	15-23	665	100%

The average cost of sourcing and preparing PET waste is estimated at INR 19/kg, which represents approximately 30% of the total BHET production cost.

6. Economic Viability and Profitability Analysis

6.1 Capital Expenditure (CAPEX)

The total fixed capital investment for the 30 kta BHET plant is estimated at INR 212 crore (approximately USD 25.5 million), broken down as follows:

Cost Component	Amount (INR Crore)	Percentage of Total
Equipment Purchase Cost	82	38.7%
Installation & Piping	41	19.3%
Instrumentation & Controls	16.4	7.7%
Electrical Systems	8.2	3.9%
Buildings & Structures	24.6	11.6%
Land Acquisition	15	7.1%
Engineering & Supervision	16.4	7.7%
Contingency	8.4	4.0%
Total Fixed Capital	212	100%

Working capital is estimated at INR 35 crore, bringing the total capital investment to INR 247 crore.

6.2 Operating Expenditure (OPEX)

The annual operating costs for the plant are estimated at INR 153.2 crore:

Cost Component	Amount (INR Crore/year)	Percentage of Total
Raw Materials	66.5	43.4%
Utilities	24.8	16.2%
Labor	15.5	10.1%
Maintenance	10.6	6.9%
Overheads	14.8	9.7%
Depreciation	21	13.7%
Total OPEX	153.2	100%

The breakdown of raw material costs is as follows:

- PET waste: INR 66.5 crore/year (INR 19/kg)
- Ethylene glycol: INR 34.2 crore/year (INR 90/kg)
- Sodium alkoxide catalyst: INR 9.2 crore/year (INR 400/kg)
- Other chemicals: INR 5 crore/year

6.3 Revenue Projection

Based on current market prices, the revenue is estimated as follows:

Product	Quantity (tons/year)	Price (INR/kg)	Revenue (INR Crore/year)
BHET (primary)	30,000	75	225
Recovered EG (by-product)	18,700	90	16.8
Total Revenue			241.8

6.4 Profitability Analysis

Financial Metric	Value
Annual Revenue	INR 241.8 crore
Annual Operating Cost	INR 153.2 crore
Annual Gross Profit	INR 88.6 crore
Profit Margin	36.6%
Payback Period	3.8 years
Internal Rate of Return (IRR)	24.2%
Net Present Value (10% discount rate)	INR 151.3 crore

The production cost of BHET is approximately INR 51/kg, which is 68% of the current PET sales price (INR 75/kg), meeting the economic viability criterion of ≤70-80%.

7. Plant Location Analysis

7.1 Location Criteria and Weightage

Criterion	Weightage	Rationale
Raw Material Availability	25%	Proximity to PET waste sources is critical for reducing transportation costs
Infrastructure	20%	Utilities, transportation networks, and industrial support services
Policy Support	15%	Government incentives for recycling and circular economy initiatives
Skilled Labor Availability	15%	Access to technical and engineering talent
Market Access	15%	Proximity to potential BHET consumers (PET manufacturers)
Environmental Considerations	10%	Regulatory compliance and community acceptance

7.2 Location Analysis for Indian States

State	Score (1-5 scale)	Key Advantages	Key Disadvantages
Gujarat (selected)	4.6	Strong industrial infrastructure, petrochemical hub, port access	Higher land costs
Maharashtra	4.3	Large waste generation, proximity to markets	Congested industrial zones, higher costs
Tamil Nadu	4.1	Good infrastructure, textile industry	Distance from northern markets
Uttar Pradesh	3.8	Lower costs, large population	Less developed infrastructure
Telangana	3.7	Growing industrial base	Water scarcity issues

7.3 Proposed Location: Dahej, Gujarat

The proposed plant location is the Dahej Special Economic Zone (SEZ) in Gujarat, offering:

Strategic Advantages:

- Located within Gujarat's petrochemical corridor

- Proximity to major PET manufacturers
- Access to Dahej port for equipment imports and potential exports
- Well-established industrial ecosystem with reliable utilities

Infrastructure:

- Dedicated industrial water supply
- Reliable power grid with backup options
- Excellent road and rail connectivity
- Hazardous waste treatment facilities

Economic Benefits:

- SEZ tax incentives (100% income tax exemption for first 5 years)
- Single-window clearance for regulatory approvals
- Lower import duties on specialized equipment

8. Process Sustainability Analysis

8.1 Environmental Impact

Impact Category	Value	Comparison to Virgin PET
Carbon Footprint	2.1 kg CO_2e/kg BHET	40% reduction
Water Consumption	18 L/kg BHET	25% reduction
Energy Consumption	3.8 GJ/ton BHET	35% reduction
Waste Generation	0.18 kg/kg BHET	-

8.2 Sustainability Improvements

Energy Integration:

- Waste heat recovery from the reactor effluent to preheat feed streams
- Variable frequency drives on major motors
- Solar PV installation for auxiliary power needs

Water Management:

- Closed-loop cooling water system reducing freshwater consumption by 40%
- Wastewater treatment and recycling from washing operations
- Rainwater harvesting system for process water makeup

Emissions Control:

- Thermal oxidizer for VOC emissions from drying operations
- Dust collection systems for handling of PET flakes
- Low-NOx burners for process heating

9 Risk Assessment and Mitigation :

Risk Category	Specific Risk	Probability	Impact	Mitigation Strategy

Feedstock	Inconsistent PET waste quality	High	Medium	Robust pre-treatment, supplier certification program
Feedstock	Supply shortages	Medium	High	Long-term supply contracts, multiple sourcing regions
Technical	Catalyst deactivation	Medium	Medium	Optimize processing conditions, inventory management
Technical	Product quality issues	Medium	High	Advanced online analytics, quality control lab
Market	BHET price volatility	High	High	Long-term offtake agreements, financial hedging
Regulatory	Policy changes affecting EPR	Medium	Medium	Engagement with regulatory bodies, industry associations
Operational	Equipment failure	Low	High	Preventive maintenance, critical spares inventory
Financial	Capital cost overruns	Medium	High	Detailed engineering before final investment, contingency budget

10. Conclusions and Path Forward

10.1 Key Findings

- The proposed PET glycolysis process is technically viable, achieving >98% conversion of PET waste to BHET with >99.5% product purity.
- The production cost of BHET is estimated at INR 51/kg, which is 68% of the current PET sales price, meeting the economic viability criterion.
- The process demonstrates robust economics with an IRR of 24.2% and a payback period of 3.8 years.
- Dahej, Gujarat is identified as the optimal location based on infrastructure, raw material availability, and policy support.
- The process achieves significant environmental benefits compared to virgin PET production, including a 40% reduction in carbon footprint.

10.2 Path Forward

Activities planned for the final project phase:

Process Refinement:

- Detailed heat integration analysis
- Equipment vendor consultations for final sizing
- Piping and instrumentation diagram (P&ID) development

Detailed Economic Analysis:

- Vendor quotations for key equipment

- Sensitivity analysis for key economic variables
- Scenario planning for varying market conditions

Implementation Planning:

- Preliminary project schedule
- Construction and commissioning strategy
- Staffing and recruitment plan

The team believes that this process represents a commercially viable and environmentally beneficial approach to chemical recycling of PET waste, contributing to the circular economy for plastics in India.

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