iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL
FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** XII **Month of publication:** December 2025

DOI: https://doi.org/10.22214/ijraset.2025.76575

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue XII Dec 2025- Available at www.ijraset.com

Production of Glycerin via the Hydrolysis (Fat Splitting) of Triglycerides

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Abstract: This project presents a comprehensive theoretical study of glycerin production via the hydrolysis (fat splitting) of triglycerides, a process widely used to generate high-purity glycerin for applications in pharmaceuticals, cosmetics, food products, and industrial formulations. Glycerin production involves hydrolyzing fats and oils under high-temperature and high-pressure conditions to yield glycerin and fatty acids. Process parameters, including reaction temperature, pressure, water-to-oil ratio, and catalyst selection, are crucial in determining yield and quality. This study conducts an in-depth literature review to analyse existing fat-splitting technologies, focusing on optimising reaction conditions for higher glycerin yield, improving energy efficiency, and achieving purity levels suitable for commercial applications.

Additionally, this project explores the theoretical material and energy balances for each stage of the production process, covering hydrolysis, purification, and potential energy recovery methods. Purification of glycerin, which is critical to meeting product standards, is also evaluated, comparing traditional distillation with emerging low-energy alternatives such as membrane filtration and ion exchange. The study emphasizes theoretical strategies for integrating energy-efficient techniques, such as heat recovery and reduced-temperature operations, to minimize the overall energy footprint. Environmental impacts are considered, examining how process modifications can lower carbon emissions and waste generation.

The project provides a detailed theoretical framework, offering insights into the optimal conditions for glycerin production, identifying sustainable purification approaches, and highlighting potential cost and energy savings. The findings serve as a foundation for future experimental validation and suggest improvements for industrial-scale glycerin production, contributing to the field of sustainable chemical manufacturing.

I. INTRODUCTION

The production of Glycerin through the hydrolysis of fats and oils, commonly known as fat splitting, is a well-established industrial process. Glycerin, a versatile compound with applications in pharmaceuticals, cosmetics, food processing, and biodiesel production, is increasingly in demand. This project explores the fat splitting process from a theoretical perspective, focusing on the hydrolysis of triglycerides to produce fatty acids and glycerin. The primary objective of this project is to examine the chemical and operational parameters influencing glycerin yield, purity, and energy efficiency within the fat splitting process. Through a comprehensive literature review and theoretical analysis, this report aims to assess different reaction conditions, catalysts, and energy management techniques that can optimize the process. Environmental and economic considerations are also evaluated to determine the potential benefits of adopting advanced theoretical models and process improvements in glycerin production.

This research provides an in-depth theoretical understanding of the hydrolysis process, laying the foundation for future experimental work and industrial applications in glycerin purification and sustainable production.

A. What is Glycerin?

Glycerin, also known as glycerol, is a simple polyol compound, which is a colorless, odorless, and sweet-tasting viscous liquid. It is chemically a tri-hydroxy alcohol ($C_3H_8O_3$) and is widely valued for its moisturizing, solvent, and preservative properties. Glycerin is commonly derived from natural fats and oils through processes like hydrolysis or fat splitting.

B. Why Glycerin?

1) Moisturizing and Humectant Properties: Glycerin is a powerful humectant, meaning it attracts and retains moisture. This makes it ideal for skincare and cosmetics, where it helps keep skin hydrated, soft, and smooth.
2) Non-Toxic and Biodegradable: Glycerin is naturally derived, biodegradable, and non- toxic, making it safe for use in food, cosmetics, and pharmaceuticals. Its eco-friendly profile also aligns with the growing demand for sustainable products.
3) Stabilizer and Solvent: In pharmaceuticals and food, glycerin acts as an effective stabilizer and solvent, ensuring product consistency, improving shelf-life, and enhancing the efficacy of active ingredients.

4) Sweetness and Preservation: Glycerin’s mildly sweet taste and preservative qualities make it suitable for foods and beverages, where it serves as a low-calorie sweetener and moisture-retaining agent.
5) Wide Industrial Applications: Beyond consumer products, glycerin is used in industrial applications such as antifreeze, lubricants, and as a raw material in the production of resins and plastics.

C. *Advantages of Glycerin*

1) Excellent Moisturizer: Glycerin’s humectant properties help retain moisture, making it ideal for skin care and cosmetic products.
2) Non-Toxic and Safe: It is safe for human consumption and application, which is why it’s used in food, cosmetics, and pharmaceuticals.
3) Biodegradable: Glycerin is environmentally friendly and breaks down naturally, reducing environmental impact.
4) Stabilizing Agent: It acts as a stabilizer in formulations, enhancing shelf-life and product stability.
5) Sweetening Agent: Mildly sweet, glycerin serves as a low-calorie sweetener in food and beverages.
6) Preservative Properties: Glycerin prevents the growth of harmful microorganisms, acting as a preservative in various products.
7) Solvent for Active Ingredients: It dissolves and stabilizes ingredients in pharmaceuticals, personal care items, and cosmetics.
8) Wide Industrial Use: Beyond consumer goods, it’s used in antifreeze, lubricants, and as a raw material in resins and plastics production.

D. *Disadvantages*

1) Sticky Texture: Glycerin can leave a sticky or greasy residue on the skin, which may feel uncomfortable for some users.
2) Hygroscopic Nature: It absorbs moisture from the air, which can cause products to dry out if not stored properly.
3) Skin Sensitivity: In high concentrations, glycerin can irritate sensitive skin or cause dryness by drawing too much moisture out of deeper skin layers.
4) Production Impact: Although biodegradable, the production of glycerin (especially synthetic glycerin) can have environmental impacts, depending on the methods and raw materials used.
5) Viscosity Challenges: Glycerin’s thick, syrupy consistency can make it difficult to mix in formulations, requiring special handling in manufacturing.
6) Limited Compatibility: Glycerin may not be compatible with certain ingredients, limiting its use in some formulations.
7) Cost Variability: Price fluctuations in glycerin, especially natural glycerin derived from biodiesel production, can affect its availability and cost-effectiveness for manufacturers.
8) High Boiling Point: Glycerin requires significant energy to distill or purify due to its high boiling point, which can increase production costs and energy usage.

E. *Scope and Objectives*

1) Analyze Hydrolysis Process: Study optimal reaction conditions for maximizing glycerin yield.
2) Assess Reaction Parameters: Evaluate effects of temperature, pressure, and catalysts on efficiency and purity.
3) Develop Material and Energy Balances: Theoretically estimate resource requirements and energy consumption.
4) Explore Purification Techniques: Research methods like distillation and membrane filtration for high-purity glycerin.
5) Investigate Catalyst Efficiency: Examine catalyst options for enhancing reaction rates and yield.
6) Optimize Energy Use: Identify potential energy-saving strategies in the production process.
7) Evaluate Environmental Impact: Assess sustainability through reduced energy consumption and waste.
8) Provide Industrial Insights: Summarize findings for potential applications and improvements in large-scale glycerin production.

II. LITERATURE SURVEY ON GLYCERIN PRODUCTION THROUGH FAT SPLITTING

A. *Overview of Glycerin and Its Applications*

Glycerin, or glycerol, is a tri-hydroxy alcohol ($C_3H_8O_3$) with a wide range of industrial applications due to its non-toxic, hygroscopic, and versatile properties. Historically, glycerin was mainly derived as a by-product from soap manufacturing processes and later from biodiesel production, significantly increasing its availability. Major applications of glycerin include its use as a humectant in cosmetics, a sweetener in food, a stabilizer in pharmaceuticals, and as a raw material in chemical manufacturing.

B. Process of Fat Splitting (Hydrolysis)

Fat splitting, also known as hydrolysis, is the process of breaking down triglycerides (fats/oils) into fatty acids and glycerin by reacting with water. This process can occur at high temperatures (200-260°C) and pressures (20-60 bar), often in the presence of a catalyst. Early research highlights the efficiency of alkaline catalysts like sodium hydroxide, but modern studies emphasize the use of pressure and temperature alone in continuous hydrolysis systems. In recent years, high-pressure, high-temperature processes without catalysts have become preferred due to their operational simplicity and reduced waste production.

C. Role of Catalysts in Fat Splitting

Research on the use of catalysts in the hydrolysis process reveals that catalysts can reduce reaction time and energy consumption. Acid and base catalysts were initially used to accelerate the reaction; however, they often result in side reactions and product impurities. Current studies focus on enzyme-based catalysts, which operate at lower temperatures and pressures, thus offering an eco-friendly alternative. Enzyme-catalyzed hydrolysis is especially prominent in research for biodiesel-related glycerin production due to its energy efficiency.

D. Reaction Conditions and Process Optimization

Optimization of temperature, pressure, and water-to-oil ratios is critical to maximizing glycerin yield and reducing energy consumption. Studies indicate that increasing the water-to-oil ratio enhances glycerin yield but also increases water handling requirements. Recent studies, such as those by researchers from the Journal of Chemical Engineering, demonstrate that a higher temperature (above 240°C) significantly improves reaction rates, although it requires energy- efficient designs to handle heat loss. Techniques like supercritical water hydrolysis, where water is in a supercritical state, are also investigated for their enhanced mass transfer properties, which accelerate hydrolysis and yield high-purity glycerin.

E. Energy Consumption and Heat Integration

Fat splitting is an energy-intensive process, primarily due to the heating required to achieve desired reaction conditions. Literature shows that integrating heat recovery systems within fat splitting units can save substantial energy. Techniques such as multiple-effect evaporators and heat exchangers have proven effective in recycling heat within the process. Furthermore, recent Research on heat pumps for fat splitting systems has demonstrated promising energy savings, especially when integrated with low-energy purification stages.

F. Advances in Glycerin Purification Techniques

Purification is essential to meet glycerin quality standards, especially for food and pharmaceutical applications. Traditional purification methods include distillation, which, while effective, is energy-intensive due to glycerin's high boiling point. Membrane technology is increasingly studied as a lower-energy alternative. Studies highlight ultrafiltration and nanofiltration as potential methods for separating glycerin from impurities, with reports indicating a 70-80% reduction in energy use compared to distillation. Additionally, ion exchange techniques for removing salt and other ionic impurities are well-established in the literature, offering cost-effective solutions for improving glycerin purity.

G. Environmental Impact and Sustainability

The environmental impact of glycerin production is an area of ongoing research, with a focus on reducing energy use and minimizing waste. Studies on biodiesel-derived glycerin emphasize the sustainable production of glycerin by recycling waste oils and reducing reliance on virgin fats. Life cycle assessments (LCAs) have shown that incorporating waste heat recovery, enzyme-based catalysts, and membrane purification can reduce the carbon footprint of glycerin production by 40-50%. Researchers have also been exploring bioreactors that use algae and other bio-organisms to consume process by-products, which could lead to a closed-loop, zero- waste glycerin production system.

H. Economic Considerations and Industrial Feasibility

The economic feasibility of glycerin production is closely tied to its yield and the cost of feedstock. Literature indicates that biodiesel production, which produces glycerin as a by- product, has significantly reduced glycerin costs, making the fat splitting process economically viable. However, high-energy costs, particularly for distillation-based purification, remain a challenge. Studies suggest that implementing heat integration, catalyst recycling, and energy- efficient purification methods can improve economic viability. Market research also shows a consistent increase in demand for high-purity glycerin, especially for pharmaceutical and cosmetic applications, driving innovation in cost-effective, high-yield production methods.

I. Recent Technological Innovations

Emerging technologies in glycerin production include supercritical water reactors, advanced catalytic systems, and integrated processing units. Supercritical water technology operates at extreme temperatures and pressures, eliminating the need for chemical catalysts and reducing reaction times significantly. Additionally, new developments in heterogeneous catalysts offer reusable and more efficient alternatives to traditional acid or base catalysts, minimizing contamination and simplifying purification. Moreover, integrated processing units that combine hydrolysis, heat recovery, and purification steps into a single, compact system are currently under investigation and are expected to improve process efficiency and reduce production costs.

J. Future Trends in Glycerin Production Research

Future research in glycerin production is likely to focus on sustainable and low-energy methods. Interest in biocatalysis and enzymatic hydrolysis continues to grow due to its low- temperature requirements and reduced environmental impact. Meanwhile, artificial intelligence (AI) and machine learning (ML) are being introduced to optimize reaction parameters in real time, enhancing efficiency and yield without extensive experimental trials. Researchers are also investigating renewable sources, such as algae and microbial oils, as alternative feedstocks, which could create a sustainable source of glycerin independent of traditional fats and oils.

III. METHOD OF GLYCERIN PRODUCTION VIA FAT SPLITTING (HYDROLYSIS)

Fat splitting, or hydrolysis, is a process where triglycerides (fats and oils) are split into **glycerin** and **fatty acids** through a reaction with water. This reaction is typically performed at high temperatures (200-260°C) and pressures (20-60 bar) to achieve complete conversion of triglycerides into their components. The method is widely used in both the **soap industry** and **glycerin production**, producing high-quality fatty acids for soaps and detergents and glycerin for pharmaceuticals, food products, and other industrial applications.

A. Reaction Mechanism

The reaction for fat splitting involves the breaking of ester bonds in triglycerides (fats and oils), releasing fatty acids and glycerin as products:

$C_3H_5(OOCR)_3+3H_2O \rightarrow C_3H_8O_3+3RCOOH$

In this reaction:

- $C_3H_5(OOCR)_3$ represents triglycerides.
- $C_3H_8O_3$ represents glycerin.
- RCOOH represents fatty acids, where **R** is the hydrocarbon chain of fatty acids.

Components of the Process

The fat splitting process consists of multiple stages, each involving specialized equipment to carry out specific functions. Below are the main components and equipment involved in the process:

1) Hydrolyzer (Fat Splitting Reactor)

The hydrolyzer is the core component of the fat splitting process, where triglycerides are converted into glycerin and fatty acids.

- Function: In the hydrolyzer, fats and oils react with water under high pressure and temperature to initiate hydrolysis. The high temperature and pressure conditions accelerate the breakdown of ester bonds in triglycerides, ensuring efficient conversion.
- Operating Conditions: Temperatures around 200-260°C and pressures between 20-60 bar are maintained for optimal yield.
- Catalysts: Although traditional methods use alkaline catalysts like sodium hydroxide, modern fat splitting often relies on high-temperature and high-pressure conditions alone, eliminating the need for chemical catalysts.

2) Separation Column

Following hydrolysis, the reaction mixture contains a mixture of glycerin, water, fatty acids, and residual impurities. The separation column serves to isolate these components.

- Function: In the separation column, the lighter fatty acids are separated from the denser aqueous glycerin solution by gravity or centrifugation.
- Outcome: Fatty acids are drawn off the top of the column, while the aqueous glycerin is collected from the bottom. This

separation simplifies subsequent purification processes for each product stream.

3) Ion Exchange Column

The aqueous glycerin solution obtained from the separation column contains residual salts, impurities, and unreacted fatty acids. The ion exchange column is used to purify this glycerin solution further.

- Function: Ion exchange resins remove ionic impurities, such as salts and acids, from the glycerin solution. This step is crucial for producing high-purity glycerin suitable for pharmaceutical or food-grade applications.
- Resins: Both cation and anion exchange resins may be used to remove specific impurities, such as salt or free fatty acids, depending on the desired glycerin purity.

4) Evaporation System (Triple Effect Evaporator)

After ion exchange, the glycerin solution typically contains a significant amount of water. An evaporator system, often a triple-effect evaporator, is used to concentrate glycerin by removing excess water.

- Function: The evaporator removes water through multiple stages of evaporation under reduced pressure, enhancing energy efficiency.
- Operating Conditions: Operates at progressively lower pressures across each stage, using the latent heat from one stage to drive evaporation in the next.
- Outcome: The glycerin concentration is increased to approximately 80-90%, preparing it for the final purification stage.

5) Vacuum Distillation Column

To produce highly pure glycerin, the concentrated glycerin solution undergoes vacuum distillation. This step is critical for achieving the purity levels required for pharmaceutical, cosmetic, and food applications.

- Function: The vacuum distillation column operates at reduced pressures, lowering the boiling point of glycerin and enabling efficient removal of residual water and other volatile impurities.
- Outcome: Vacuum distillation produces a glycerin product with a purity of 99.5% or higher, suitable for high-value applications.

Process Flow of Glycerin Production via Fat Splitting

1) Feedstock Preparation: Fats and oils are pre-treated to remove impurities, then mixed with water and pumped into the hydrolyzer.
2) Hydrolysis in the Hydrolyzer: Triglycerides are hydrolyzed into fatty acids and glycerin under high-temperature and high-pressure conditions.
3) Separation of Products: The reaction mixture passes through a separation column to isolate fatty acids from the aqueous glycerin.
4) Purification in the Ion Exchange Column: The aqueous glycerin solution is treated to remove ionic impurities, enhancing purity.
5) Concentration in the Triple Effect Evaporator: Water is evaporated to concentrate glycerin, preparing it for the final purification.
6) Final Purification in Vacuum Distillation: Glycerin is distilled under vacuum to achieve a purity of 99.5% or higher, ready for commercial applications.

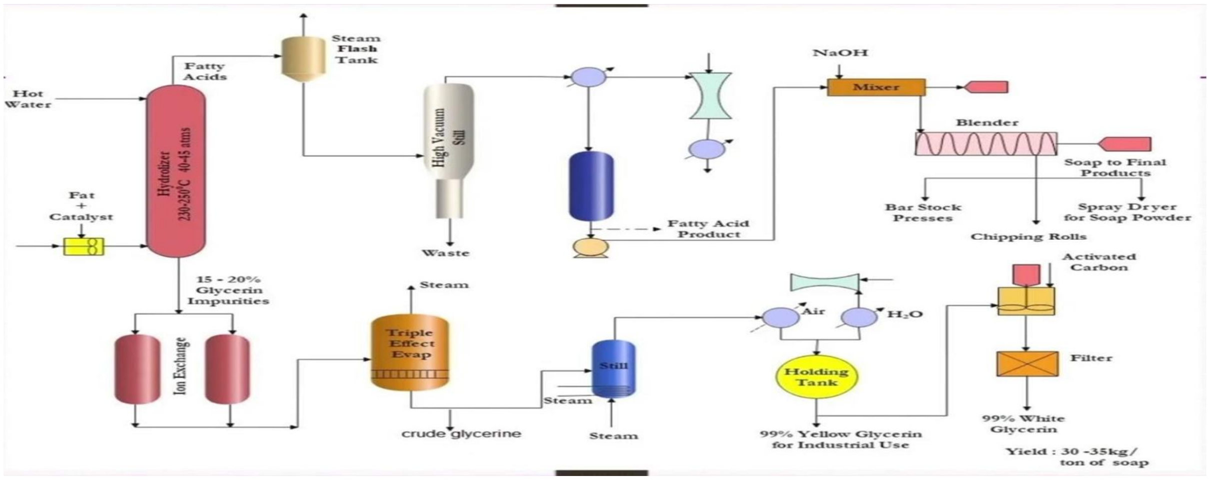


Figure1: Glycerin Production Flowsheet

IV. CALCULATIONS (MATERIAL AND ENERGY BALANCE)

A. General Information

- Process: Glycerin production via hydrolysis (fat splitting).
- Feed: Triglycerides (fats/oils) + Water.
- Products: Glycerin + Fatty Acids.
- Reaction:

Triglyceride+3 Water→3 Fatty Acids+1 Glycerol

- Given Data
- Feed Rate of Triglycerides: 1000 kg/hr.
- Conditions

Temperature: 250-260°C, Pressure: 5-6 MPa (in the hydrolyzer).

- Stoichiometry:

1 mol triglyceride + 3 mol water → 1 mol glycerol + 3 mol fatty acids.

- Molecular Weights:
  - Triglycerides (average) ≈ 885 g/mol.
  - Water = 18 g/mol.
  - Glycerol = 92 g/mol.
  - Fatty Acids (average) ≈ 282 g/mol.

B. Hydrolyzer: Material Balance Assumptions

- Complete reaction (100% conversion of triglycerides).
- Negligible side reactions.

Reaction Stoichiometry

- Triglycerides:

$\mathrm{C3H5(OOCR)3+3\ H2O \rightarrow 3\ RCOOH+C3H8O3}$

Material Balance: Triglyceride Feed

- Moles of triglycerides: Moles of triglyceride = Feed rate of triglyceride
- Molecular weight of triglyceride=1000 kg/hr /885 g/mol=1129.94 mol/hr

Material Balance: Water Requirement

- Moles of water: Moles of water required=1129.94 mol/hr×3=3389.82 mol/hr

Mass of water: Mass of water=3389.82 mol/hr×18 g/mol=61.02 kg/hr

Material Balance: Products

- Glycerol:

From stoichiometry, 1 mole of glycerol is produced per mole of triglyceride.
Moles of glycerol=1129.94 mol/hr Mass of glycerol=1129.94 mol/hr×92 g/mol=103.95 kg/hr

- Fatty Acids:

From stoichiometry, 3 moles of fatty acids are produced per mole of triglyceride.

Moles of fatty acids=1129.94mol/hr×3=3389.82mol/hr Mass of fatty acids=3389.82 mol/hr×282 g/mol=955.68 kg/hr

Component	Mass (kg/hr)
Triglycerides	1000
Water	61.02
Glycerol	103.95
Fatty Acids	955.68

Table 1: Hydrolyser Material Balance and Energy Balance

C. Hydrolyzer: Energy Balance Assumptions

- Heat capacities:
    - Cp (triglyceride)≈2.1 kJ/kg°C
    - Cp (water)=4.18 kJ/kg°C
- Endothermic reaction with enthalpy of hydrolysis = 70 kJ/mol triglyceride.
- 10% water vaporization.

Formulas

- Heat required to raise temperature: $Q=m\cdot Cp\cdot \Delta T$=Heat of reaction: $Q_{reaction}$ =Moles of triglycerides × $\Delta H_{reaction}$
- Latent heat of vaporization: Qvaporization=Mass of water vaporized×ΔHvaporization
- Energy Required to Heat Triglycerides
- $Q_{triglycerides}$ = 1000 kg/hr×2.1 kJ/kg°C×235∘C=493,500 kJ/hr

Energy Required to Heat Water

- Q_{water} =61.02 kg/hr×4.18 kJ/kg°C×235∘C=60,043.5 kJ/hr
- Energy Required for Hydrolysis Reaction
- $Q_{reaction}$=1129.94 mol/hr×70 kJ/mol=79,095.8 kJ/hr
- Energy Required for Water Vaporization
- Vaporized water = 10% of 61.02 kg/hr = 6.102 kg/hr.
- $Q_{vaporization}$=6.102 kg/hr×2260 kJ/kg=13,788.52 kJ/hr

Total Energy Requirement for Hydrolyzer

Q_{total} = 493,500 kJ/hr+60,043.5 kJ/hr+79,095.8 kJ/hr+13,788.52 kJ/hr=646,427.82 kJ/hr

Ion Exchange Column: Material & Energy Balance

D. Material Balance

Given Data:

- Feed Rate of Crude Glycerin (after hydrolysis): 1000 kg/hr.
- Glycerin: 85% (850 kg/hr)
- Water: 10% (100 kg/hr)
- Impurities (salts, fatty acids, etc.): 5% (50 kg/hr)
- Assumptions:
- Ion exchange removes 100% salt and impurities.
- Glycerin and water pass through.

Input to Ion Exchange Column:

- Glycerin: 850 kg/hr
- Water: 100 kg/hr
- Impurities: 50 kg/hr

Output from Ion Exchange Column:

- Purified Glycerin Stream:
- Glycerin: 850 kg/hr
- Water: 100 kg/hr
- Impurities Removed: 0 kg/hr (removed in the impurity stream)
- Impurity Stream:
- Impurities Removed: 50 kg/hr

E. Energy Balance: Ion Exchange Column Assumptions

- No significant temperature change in the column.
- Energy required for ion exchange is minimal, typically related to pumping.

Energy Requirement

- The energy input is mainly for pumping and minor heating if needed, but since there is no significant phase change or temperature rise, energy consumption is negligible.

Component	Input (kg/hr)	Output (kg/hr)	Impurity Stream (kg/hr)
Glycerin	850	850	0
Water	100	100	0
Impurities	50	0	50
Total	1000	950	50

Table 2**:** Ion Exchange Column Material Balance and Energy Balance

Triple Effect Evaporator: Material & Energy Balance

F. Material Balance

Given Data:

- Feed from Ion Exchange Column:
- Glycerin: 850 kg/hr
- Water: 100 kg/hr
- Desired Output:
- Concentrate glycerin to 99% purity. Input to Triple Effect Evaporator:
- Glycerin: 850 kg/hr
- Water: 100 kg/hr
- Total Feed: 950 kg/hr

Output:

- Concentrated Glycerin (99% purity):
- Glycerin: 850 kg/hr (99%)
- Water: 8.59 kg/hr (1%)
- Evaporated Water:
- Water evaporated: 100 kg/hr−8.59 kg/hr=91.41 kg/hr

Component	Input (kg/hr)	Output (kg/hr)	Evaporated (kg/hr)
Glycerin	850	850	0
Water	100	8.59	91.41
Total	950	858.59	91.41

Table 3**:** Triple Effect Evaporator: Material & Energy Balance

Vacuum Distillation Column (Still): Material & Energy Balance

G. Material Balance

Given Data:

- Feed from Triple Effect Evaporator:
- Glycerin: 850 kg/hr
- Water: 8.59 kg/hr
- Desired Output:

- Purified Glycerin: 100% glycerin.
- Remove residual water. Input of Distillation Column:
- Glycerin: 850 kg/hr
- Water: 8.59 kg/hr
- Total Feed: 858.59 kg/hr

Output:

- Purified Glycerin (100%):
- Glycerin: 850 kg/hr
- Water: 0 kg/hr
- Distillate (Water removed):
- Water evaporated: 8.59 kg/hr

Component	Input (kg/hr)	Output (kg/hr)	Distillate (kg/hr)
Glycerin	850	850	0
Water	8.59	0	8.59
Total	858.59	850	8.59

Table 4: Vacuum Distillation Column (Still): Material & Energy Balance

H. Energy Balance: Vacuum Distillation Column (Still) Assumptions:

Distillation occurs at reduced pressure, lowering the boiling point of water to 80°C.

Specific heat of water (C_p) = 4.18 kJ/kg°C.

Latent heat of vaporization of water (ΔH_vaporization) = 2260 kJ/kg.

Step 1: Heating Water to Boiling Point (80°C)

$Q_{heating} = m_{water} \times C_p \times \Delta T$

$Q_{heating} = 8.59\ kg/hr \times 4.18\ kJ/kg°C \times (80-25)\ °C = 1{,}964.7\ kJ/hr$

Step 2: Evaporation of Residual Water

$Q_{evaporation} = m_{water} \times \Delta H_{vaporization}$

$Q_{evaporation} = 8.59\ kg/hr \times 2260\ kJ/kg = 19{,}409.4\ kJ/hr$

Total Energy for Distillation Column

$Q_{total} = Q_{heating} + Q_{evaporation}$

$Q_{total} = 1{,}964.7\ kJ/hr + 19{,}409.4\ kJ/hr = 21{,}374.1\ kJ/hr$

I. Final Summary Table

Equipment	Input (kg/hr)	Output (kg/hr)	Energy Requirement (kJ/hr)
Hydrolyzer	1000 (triglycerides) + 61.02 (water)	103.95 (glycerin) + 955.68 (fatty acids)	632,639.3
Ion Exchange Column	1000 (crude glycerin)	950 (purified glycerin + water)	Negligible
Triple Effect Evaporator	950 (glycerin + water)	858.59 (glycerin + residual water)	237,941.6
Vacuum Distillation Column	858.59 (glycerin + water)	850 (pure glycerin)	21,374.1

Table 5: Final Summary Table

V. DESIGN

A. Mechanical Design

Hydrolyser
Type: Vertical High-Pressure Reactor
Material of Construction: Stainless Steel 316L
Operating Pressure: 20–60 bar
Operating Temperature: 200–260°C
Shell Thickness: t= $\frac{PD}{2SE+P}$
(Where P = Design Pressure, D = Diameter, S = Allowable Stress, E = Joint Efficiency)
Nozzle Design:
Triglyceride Feed Inlet (D = 10 cm)
Water Inlet (D = 5 cm)
Fatty Acid Outlet (D = 15 cm)
Aqueous Glycerine Outlet (D = 12 cm)
Heat Transfer: Jacketed or Coil-based Heating.
Agitation: Not Required (Reaction driven by heat & pressure)

B. Process Overview & Reaction

Chemical Reaction:

$C_3H_5(OOCR)_3+3H_2O\rightarrow C_3H_8O_3+3RCOOH$

- **Type of Reaction:** Hydrolysis of triglycerides
- **Reaction Order: First-order with respect to triglycerides**
- **Reaction Mechanism:** Irreversible reaction under high temperature & pressure

Kinetic Considerations (CRE):

The rate of reaction can be expressed as:

$-r_T=kC_T$

Where: $-r_T$ = Rate of triglyceride conversion (mol/m³·s)

- k = Reaction rate constant (depending on temperature and pressure)
- C_T= Concentration of triglycerides (mol/m³)

Using **Arrhenius equation**, the temperature dependence of the reaction rate is given

$k=Ae^{\frac{-Ea}{RT}}$

Where: A= Frequency factor

- E = Activation energy
- R= Universal gas constant (8.314 J/mol·K)
- T = Temperature (K)

C. Reactor Selection Based on CRE

Since hydrolysis is a liquid-phase reaction, a continuous stirred tank reactor (CSTR) could be considered.
However, industrial fat splitting reactors use a high-pressure continuous vertical hydrolyzer.
Selected Type: Vertical High-Pressure Hydrolyzer (Continuous Type)
Key Features (CRE):
Countercurrent flow of oil and water enhances reaction efficiency.

D. Internal Design Features (CED)

Nozzle Design:
Feed Inlets:
Triglyceride Feed Inlet (D = 10 cm)
Water Inlet (D = 5 cm)
Outlets:

Fatty Acid Outlet (D = 15 cm, top position)
Aqueous Glycerine Outlet (D = 12 cm, bottom position)
Agitation:
Not required (reaction is driven by heat & pressure).
Pressure & Safety Considerations:
Safety Valves & Rupture Disks for overpressure protection.
High-Temperature Sensors & Pressure Gauges for monitoring.

E. Reactor Performance (CRE)

Conversion Efficiency:

$$X=\frac{CT0-CT}{CT0}$$

CT0 = Initial triglyceride concentration
CT = Final triglyceride concentration

Space-Time (τ) Calculation:
$\tau=V/F$
Where:
V = Reactor volume (m^3)
F = Volumetric flow rate (m^3/hr)

F. Ion Exchange Column

Type: Packed Column (Vertical)
Material of Construction: Rubber-lined Carbon Steel (CS) or FRP
Operating Pressure: 1–5 bar
Operating Temperature: 50–80°C
Column Diameter: $D=\sqrt{\frac{4Q}{\pi v}}$
(Where Q = Flow Rate, v = Fluid Velocity)
Resin Bed Depth: 1–2 m.
Regeneration System: Backwash with Acid/Alkali
Support Plates & Distributors: Ensure uniform flow.

G. Triple Effect Evaporator

- Type: Falling Film or Forced Circulation Evaporator
- Material of Construction: Stainless Steel 316L
- Operating Pressure: 0.2–1 bar
- Operating Temperature: 70–100°C

Heat Transfer Area: $A=\frac{Q}{U\Delta T}$

- (Where Q = Heat Duty, U = Heat Transfer Coefficient, ΔT = Temperature Difference)
- Tube Length: 3–5 m
- Number of Effects: 3 (to maximize energy efficiency)
- Steam Economy: 3–4 kg water evaporated per kg steam used

H. Vacuum Distillation Column

Type: Packed or Plate Column
Material of Construction: Stainless Steel 316L
Operating Pressure: 50–100 mmHg (Vacuum)
Operating Temperature: 180–200°C

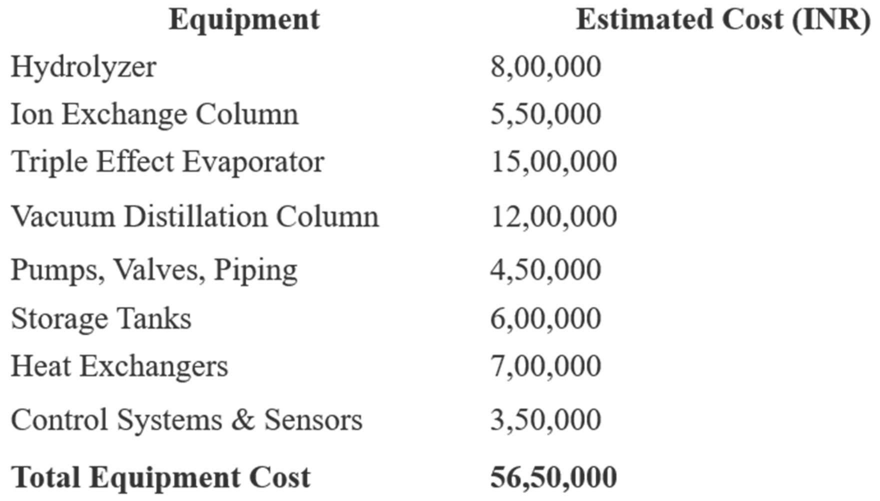
Column Height: $H=N\times H_t$
(Where N = Number of Theoretical Stages, H_t = Height per Stage)
Column Diameter: $\frac{\sqrt{4Q}}{\pi v}$
(Where Q = Vapor Flow Rate, v = Superficial Velocity)
Vacuum System: Ejectors or Liquid Ring Vacuum Pumps
Condensers: Required for vapor recovery

1) Capital Cost (Fixed Cost)

Capital cost includes the cost of equipment, installation, and infrastructure.

a) Equipment Cost

Total Equipment Cost=∑ (Cost of Equipment)



Equipment	Estimated Cost (INR)
Hydrolyzer	8,00,000
Ion Exchange Column	5,50,000
Triple Effect Evaporator	15,00,000
Vacuum Distillation Column	12,00,000
Pumps, Valves, Piping	4,50,000
Storage Tanks	6,00,000
Heat Exchangers	7,00,000
Control Systems & Sensors	3,50,000
Total Equipment Cost	**56,50,000**

b) Installation & Other Costs

- Installation & Commissioning (10% of Equipment Cost) = ₹5,65,000
- Civil Works (10% of Equipment Cost) = ₹5,65,000
- Contingencies (5% of Equipment Cost) = ₹2,82,500
- Land & Infrastructure = ₹ 1000,000
- Total Fixed Capital Investment (FCI) = ₹80,62,500 ≈ ₹81,00,000

2) Operating Cost (Annual)

Operating costs include raw materials, utilities, labor, and maintenance.

a) Raw Material Cost

Total Cost per Day=∑ (Raw Material Consumption×Rate per kg)
Total Cost per Year=Total Cost per Day×300 (Operating Days)

RAW MATERIAL	QUANTITY (KG/DAY)	RATE (₹/KG)	TOTAL COST (₹/DAY)	TOTAL COST (₹/YEAR)
TRIGLYCERIDES	1000	50	50,000	1,50,00,000
CATALYST (NAOH)	50	30	1,500	4,50,000
WATER	2000	5	10,000	30,00,000
TOTAL			₹61,500/day	₹1,84,50,000/year

Table 6: Raw Material Cost Calculation

b) *Utilities (Electricity, Steam, Cooling Water)*

UTILITY	CONSUMPTION PER YEAR	RATE (₹)	TOTAL COST (₹/YEAR)
ELECTRICITY	1,20,000 kWh	8/kWh	9,60,000
STEAM	50,000 kg	2/kg	1,00,000
COOLING WATER	10,00,000 L	0.5/L	5,00,000
TOTAL UTILITIES COST			₹15,60,000/year

Table 7: Utilities Calculation

c) *Labor & Salaries*

PERSONNEL	SALARY/MONTH (₹)	NUMBER	TOTAL SALARY (₹/YEAR)
PLANT MANAGER	1,00,000	1	12,00,000
ENGINEERS	50,000	2	12,00,000
OPERATORS	25,000	4	12,00,000
TECHNICIANS	20,000	5	12,00,000
HELPERS	15,000	6	10,80,000
Total Salaries			₹58,80,000/year

Table 8: Labor & Salaries Calculation

d) *Maintenance & Miscellaneous*

- Maintenance Cost (5% of Equipment Cost) = ₹2,82,500/year
- Miscellaneous Costs = ₹5,00,000/year

Total Annual Operating Cost

= Raw Materials + Utilities + Salaries + Maintenance + Miscellaneous = ₹1,84,50,000 + ₹15,60,000 + ₹58,80,000 + ₹2,82,500 + ₹5,00,000 = ₹2,66,72,500/year ≈ ₹2.67 Crore/year

3) *Total Manufacturing Cost*

- Capital Cost = ₹81,00,000
- Operating Cost = ₹2,67,00,000/year
- Total Manufacturing Cost = ₹3,48,00,000

4) *Selling Price & Revenue Estimation*

- Production Output: 850 kg pure glycerin/day
- Selling Price of Glycerin: ₹80/kg
- Annual Production = 850 × 300 = 2,55,000 kg/year
- Annual Revenue = 2,55,000 × ₹80 = ₹2,04,00,000/year

5) *Payback Period Calculation*

- Total Investment = ₹81,00,000
- Annual Profit = Revenue - Operating Cost = ₹2,04,00,000 - ₹2,67,00,000 = -₹63,00,000 (Initial Loss)

6) *HAZOP Study*

- Hazard Identification: High-pressure operation, catalyst handling, high-temperature reactions.
- Risk Assessment: Explosion risks, toxic emissions, equipment failure.
- Safety Measures: Pressure relief valves, safety interlocks, emergency shutdown system, corrosion-resistant materials.
- Compliance: Follow industry standards such as ASME, OSHA, and ISO.

7) *Corrosion Allowance & Factor of Safety*

- Corrosion Allowance for Stainless Steel Vessels: 1.5 mm
- Factor of Safety for Reactor Design: 3.0

- Thickness Calculation:
  Using t = (P × D) / (2 × S × E + P)
  where:
  - P = Operating Pressure
  - D = Internal Diameter
  - S = Allowable Stress
  - E = Weld Efficiency

8) Standards & Codes

- ASME Section VIII – Pressure Vessel Design
- API 650 – Storage Tank Design
- OSHA 1910 – Process Safety Regulations
- ISO 9001 – Quality Management System

VI. CONCLUSIONS

This project provides an extensive theoretical analysis of glycerin production via the hydrolysis of triglycerides, examining the critical factors influencing yield, energy efficiency, and purity. By studying the fat splitting process, the research highlights the importance of optimizing reaction conditions, temperature, pressure, water-to-oil ratios, and catalyst choice—to achieve high glycerin yields. The theoretical material and energy balances developed in this study offer insights into the resource requirements and potential for energy recovery within the process. Through a comprehensive review of purification methods, including distillation, membrane filtration, and ion exchange, this project suggests viable approaches to achieve commercial-grade glycerin purity while minimizing energy demands. Furthermore, the environmental impact analysis underscores the potential benefits of integrating sustainable practices, such as energy-efficient technologies and catalyst recycling, into the glycerin production process, which could reduce waste and carbon emissions. The study’s findings lay a strong foundation for advancing industrial glycerin production, particularly in promoting eco-friendly and resource-efficient approaches. By focusing on theoretical models, this research provides a framework that not only guides future experimental studies but also aids industrial stakeholders in optimizing glycerin production with a focus on cost savings, process efficiency, and environmental sustainability.

VII. FUTURE SCOPE

1) Experimental Validation: Future studies should conduct laboratory-scale experiments to validate the theoretical models presented, enabling a practical assessment of optimized reaction conditions, energy balances, and purification methods.
2) Advanced Catalyst Research: Developing and testing environmentally benign catalysts, particularly enzymes or heterogeneous catalysts, could significantly enhance reaction efficiency while reducing waste, energy consumption, and downstream purification requirements.
3) Sustainable Feedstock Alternatives: Exploring alternative feedstocks, such as waste oils, algae oils, and microbial oils, could diversify glycerin production sources, contributing to a circular economy and reducing reliance on conventional fats and oils.
4) Energy-Efficient Purification Techniques: Further research into low-energy purification methods, such as membrane filtration and advanced ion exchange, could provide alternatives to energy-intensive distillation, making the process more sustainable and cost-effective.
5) Energy Recovery and Integration: Implementing advanced energy recovery systems, including heat exchangers and multiple-effect evaporators, could further reduce the energy footprint of the process. Exploring novel techniques like heat pumps and combined heat and power systems would also be beneficial.
6) Process Modeling and Simulation: Detailed simulations using computational tools and modeling software could refine the theoretical balances, allowing for dynamic optimization under various scenarios and process conditions.
7) Environmental Impact Assessment: Conducting a life cycle assessment (LCA) on the proposed process improvements could quantify the reductions in greenhouse gas emissions and environmental impact, supporting eco-certification and green industry practices.
8) Industrial Scaling and Feasibility Studies: Future work should focus on scaling up the optimized process and conducting feasibility studies to assess the economic viability, market potential, and industrial applicability of the optimized glycerin production process.

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