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Management of Hazardous Waste Generated from the Natural Gas Sweetening Process in Gas Refineries (Case Study: South Pars Phases 9 and 10)

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A B S T R A C T

The aim of this study was to manage hazardous waste generated from the natural gas sweetening process in gas refineries using PEBAX nanocomposite membrane technology. In this regard, data related to the type, quantity, and characteristics of the waste produced in the Fifth South Pars Gas Refinery were collected and classified over a 12-month period by the HSE unit. Based on the data analysis, spent amine solutions were identified as the most significant source of hazardous waste generation. To control this source at its origin, the PEBAX membrane technology was considered as an innovative method to replace part of the amine absorption process, thereby reducing the acidic gas load and decreasing the need for frequent regeneration or replacement of the amine solution, ultimately lowering hazardous waste production. For technical evaluation of this approach, the geometric model of the membrane module was designed in COMSOL Multiphysics and simulated using the Transport of Diluted Species and Laminar Flow modules. In this model, the effects of parameters such as pressure, temperature, and membrane layer thickness on the transfer rate of CO_2 and H_2S gases were examined. Simulation results indicated that the PEBAX nanocomposite membrane has a high capacity for acidic gas separation and can effectively contribute to hazardous waste management by reducing pollutant load in the feed gas stream. The findings suggest that employing this technology, alongside appropriate managerial policies, can provide an effective strategy for minimizing waste generation at the source and enhancing the environmental performance of the country’s gas refineries.

Keywords: *hazardous waste management, gas sweetening, refinery, nanocomposite membrane*

1. Introduction

The increasing global demand for natural gas as a relatively cleaner fossil fuel has heightened the strategic importance of efficient gas processing technologies, particularly in sour gas treatment and hazardous waste minimization. As natural gas production infrastructures expand, especially in large industrial complexes such as the South Pars Gas Field, the need for advanced separation systems that can improve gas quality while reducing environmental risks has become more urgent. Sour gas streams containing CO_2 and H_2S pose severe technical and environmental challenges: they reduce the calorific value of natural gas, accelerate corrosion, and contribute to the formation of hazardous acidic wastes during amine-based sweetening operations. These operational challenges have motivated a shift toward polymeric and mixed-matrix membranes that offer selective permeation of acidic gases, high energy efficiency, and the potential to reduce hazardous by-products at the source. Among these membrane systems, poly(ether-block-amide) (Pebax) and its nanocomposite derivatives have emerged as leading candidates due to their unique combination of elasticity, polarity, tunable microstructure, and compatibility with diverse fillers (Afshoun et al., 2017; Amini & Asghari, 2018; Ariazadeh et al., 2020).

Recent advancements in Pebax-based membrane engineering demonstrate notable improvements in permeability, selectivity, and structural durability, all of which are essential for large-scale sour gas treatment. Studies incorporating nanoclay, functionalized silica, ZIF-based nanoparticles, or graphene oxide derivatives indicate that modifying the Pebax matrix can create efficient transport channels, enhance polymer–filler interactions, and optimize the separation of CO_2, CH_4, and N_2 (Amini & Asghari, 2018; Ariazadeh et al., 2020; Huang, Isfahani, et al., 2018). These modifications have been shown to improve gas transport mechanisms governed by solution–diffusion, enabling membranes to operate with lower energy requirements compared to conventional amine absorption towers (Meshkat et al., 2019; Sanaeepur et al., 2019). In addition, functionalization strategies such as the incorporation of ionic liquids, polyethyleneimine, or hybrid 2D nanosheets have provided enhanced CO_2 affinity and tailored diffusion pathways, further supporting the potential feasibility of membrane-based sweetening in industrial settings (Hosseinkhani et al., 2024; Huang, Pournaghshband, et al., 2018; Jiao et al., 2021).

Pebax membranes have also been integrated with metal–organic frameworks (MOFs), core–shell nanocomposites, and Janus nanoparticles to advance mixed-matrix membrane (MMM) performance, achieving higher permeability and improved CO_2/CH_4 or CO_2/N_2 selectivities (Eljaddi et al., 2022; Li et al., 2016; Liu et al., 2022; Zhou et al., 2015). These compositions resolve interfacial defects, increase the number of preferential sorption sites, and prevent gas bypassing through nonselective channels. For example, ZIF-8 and CNT-modified systems have demonstrated significant improvements in diffusion kinetics and polymer rigidity, showing promise for deployment in high-pressure natural gas streams (Nobakht & Abedini, 2023; Zhang et al., 2021). Similarly, cellulosic nanofiber and glycerol-modified structures have been reported to enhance both mechanical integrity and the formation of continuous transport networks, providing an attractive platform for CO_2/CH_4 separation in sour gas applications (Narkkun et al., 2023; Sanaeepur et al., 2019).

Other investigations have focused on optimizing operating conditions—such as feed pressure, temperature, and polymer chain configuration—to improve membrane performance. The effect of temperature and pressure on gas permeation and selectivity has been widely documented, showing that increasing temperature enhances permeability but can reduce selectivity due to increased methane diffusion, whereas higher feed pressure generally improves the driving force for acidic gas transport (Feng et al., 2019; Harrigan et al., 2020; Tu et al., 2024). Attention has also turned toward molecular-level modifications of Pebax, including biodegradation-compatible nanoparticles, poly(ethylene oxide) segments, and ethylene glycol derivatives, all of which aim to increase CO_2 affinity and suppress unwanted CH_4 or N_2 diffusion (Elyasi Kojabad et al., 2024; Elyasi & Norouzi, 2025; Meshkat et al., 2020). These new formulations indicate the versatility of Pebax chemistry in tailoring gas transport behavior to industrial needs.

Despite advancements in membrane material science, challenges persist in scaling laboratory-grade membranes to refinery-level operations where high pressures, sour contaminants, and variable gas compositions impose mechanical, chemical, and operational stresses. The development of membranes with high stability against hydrogen sulfide—one of the most corrosive components of sour gas—remains a critical research gap. Existing studies have highlighted significant progress in reversible hydrogen-bond engineering, hybrid membrane fabrication, and semi-mobile carrier membranes capable of facilitated transport under sour gas conditions (Kojabad et al., 2021; Tu et al., 2024; Yoon et al., 2021). Yet, the implementation of these systems in large gas treatment facilities remains limited, and their potential contribution to waste minimization has not been fully explored.

Hazardous waste generation during amine-based gas sweetening processes—primarily from degraded amine solvents such as DEA and MDEA, contaminated hydrocarbons, and caustic wash solutions—poses major environmental and operational challenges for natural gas refineries. Traditional treatment of sour gas via amine regeneration cycles leads to the formation of heat-stable salts, sludge, oxidized amine species, and contaminated aqueous streams, which collectively increase hazardous waste loads and disposal costs (Chen et al., 2022; Hassanzadeh et al., 2022). Reducing the load of acidic gases entering the amine absorption system through partial or hybrid membrane pretreatment could decrease solvent degradation, extend amine lifetime, and reduce the overall volume of hazardous wastes, aligning with environmental management frameworks and sustainability goals.

Several studies have referenced the potential of hybrid membrane–amine systems to address industrial-scale separation demands by lowering regeneration energy and extending solvent replacement intervals (Delavari et al., 2024; Eljaddi et al., 2022). However, the literature points to a lack of integrated waste management models assessing how membrane pretreatment affects the lifecycle of hazardous waste streams in industrial gas refineries. Furthermore, while material scientists have intensively studied membrane selectivity and permeability, fewer studies have examined how these improvements translate into reduced environmental impacts at facility level, particularly in regions with large sour gas reserves such as the Middle East.

The advancement of Pebax membranes through incorporation of emerging nanostructures—including graphene oxide nanosheets, ZIF-laminated structures, and 2D hybrid fillers—reinforces the need for applied research bridging membrane science with industrial hazardous waste management (Chen et al., 2022; Hosseinkhani et al., 2024; Liu et al., 2022). The increasing availability of engineered fillers capable of creating efficient transport channels or reinforcing polymer structure provides promising avenues for designing membranes that perform under harsh gas compositions while directly contributing to reduced waste generation at the source.

In addition, new ternary and quaternary membrane formulations reported in recent years demonstrate substantial improvements in stability, dispersion uniformity, and gas-selective transport, which potentially align with the operational demands of high-throughput gas treatment plants. Innovations such as maltitol-modified membranes, amino acid-functionalized surfaces, and ionic-liquid-reinforced systems highlight the growing maturity of Pebax-based MMMs and their readiness for applied evaluation (Chen et al., 2022; Huang, Pournaghshband, et al., 2018; Nobakht & Abedini, 2023). Still, the practical environmental implications of adopting such membranes within refinery settings remain insufficiently explored, especially regarding hazardous waste reduction.

Taken together, the growing body of research on Pebax membranes underscores their potential to transform sour gas sweetening processes by offering high selectivity, improved mechanical properties, chemical resilience, and compatibility with large-scale operations. Yet, despite significant experimental advancements, the relationship between membrane deployment and reduction of hazardous waste in natural gas refineries has not been investigated comprehensively, particularly in integrated frameworks that combine real refinery waste data, process modeling, and environmental management principles. Therefore, addressing this gap is essential for enabling sustainable natural gas processing and achieving environmentally responsible industrial operations.

The aim of this study is to design and evaluate an integrated management framework that utilizes Pebax nanocomposite membrane technology to reduce hazardous waste generation at the source in natural gas sweetening units.

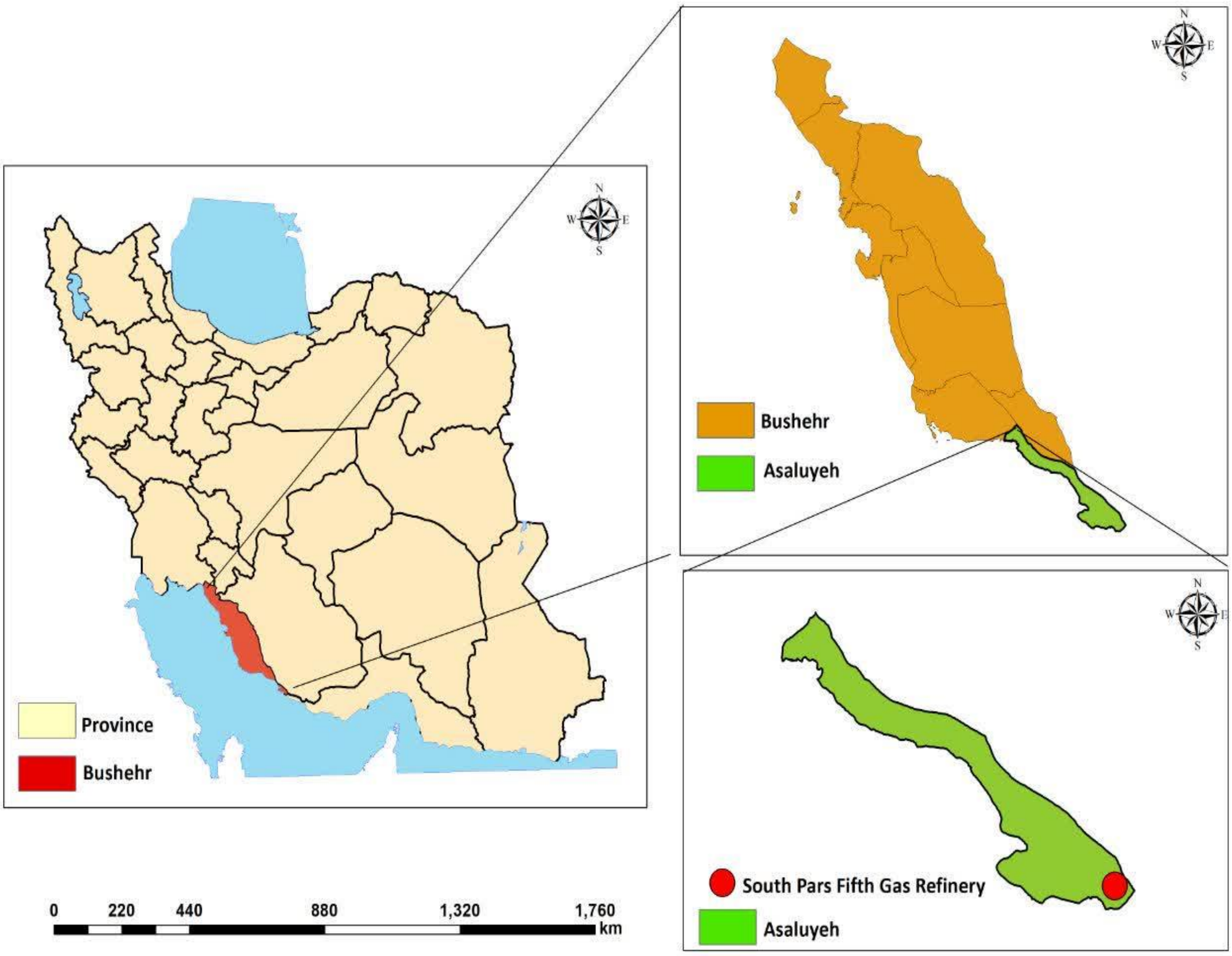
2. Methods and Materials

This study was conducted with the aim of designing and evaluating a managerial framework to reduce and control hazardous waste generated from gas sweetening units in the Fifth South Pars Gas Refinery.

The research was carried out in the Fifth South Pars Gas Refinery located in Phases 9 and 10, within the Pars Special Energy Economic Zone, Assaluyeh, Bushehr Province (Figure 1). This refinery, with a daily processing capacity of approximately 56 million cubic meters of sweet natural gas, 80 thousand barrels of gas condensate, and 1.05 million tons of liquefied petroleum gas, is considered one of the largest industrial units in the country. The main processes in the refinery include sour gas sweetening, dehydration, ethane recovery, propane and butane separation and storage, and gas condensate stabilization. After condensate separation and dehydration, the sour gas feed enters the sweetening section, where it undergoes absorption by the chemical solvent methyl diethanolamine (MDEA). Over time, due to side reactions and the entry of impurities, the quality of the amine solution deteriorates and it is classified as spent hazardous waste.

Figure 1

Location of the Fifth South Pars Gas Refinery



The research is applied–developmental in nature, and the methodology integrates field investigation, analysis of refinery registry data, process modeling, and managerial analysis. In this study, data related to the type, quantity, and characteristics of hazardous waste generated in the Fifth South Pars Gas Refinery over a 12-month period were collected from the HSE unit and organized in Excel software.

After identifying and classifying waste streams based on their source and hazard level, charts illustrating the quantities and percentages of major waste types were plotted to determine the primary sources of hazardous waste generation. Subsequently, to enable source reduction, PEBAX nanocomposite membrane technology was selected as an alternative to part of the amine absorption stage in the gas sweetening process. The geometric model of the membrane module was designed and simulated using COMSOL Multiphysics to examine the mass transfer behavior of acidic gases (CO_2 and H_2S) through the membrane layer. In this model, real refinery operating conditions—including pressure, temperature, and membrane thickness—were applied, and the Transport of Diluted Species and Laminar Flow modules were used to solve the mass transfer equations. Simulation outputs were analyzed qualitatively to assess the role of this technology in reducing pollutant load entering the process and, consequently, decreasing hazardous waste generation.

Accordingly, the workflow of the research—from field data collection and analysis to membrane model design and explanation of its application in hazardous waste management—was carried out step by step.

3. Findings and Results

Based on the collected information, a conceptual managerial model was developed with "source control" (Preventive Control) as its central axis—that is, an effort to reduce hazardous waste generation during the gas processing stage prior to transfer and disposal. In designing this model, data from the waste classification tables and quantitative waste records were utilized to identify intervention points.

Table 1

Classification of Waste Types Generated in Various Units of the Refinery Based on Hazard Level over a 12-Month Period

Row	Waste Type	Waste Group	Waste Phase	Waste Management Method
1	Sludge – condensate tank bottoms	Hazardous	Semi-solid	Transfer to Salvage and sale
2	Sludge – oil–water separation pits	Hazardous	Liquid	Retention in pit and incomplete oil–water separation (recovery); use of recovered hydrocarbons as boiler fuel
3	Sludge – wastewater evaporation ponds	Hazardous	Slurry	Transfer to Salvage
4	Sludge – industrial water treatment system	Industrial	Slurry	Transfer to landfill
5	Spent catalysts from process units	Industrial	Solid	Catalysts with various bases such as alumina and containing different compounds (mostly oxides) of heavy metals including Co, Zn, Ni, Cr, Mo, etc. – sale
6	Used cartridges, batteries, and lamps	Hazardous	Solid	Transfer to landfill
7	Oil-contaminated soil	Industrial	Solid	Transfer to Salvage and open-yard stockpiling
8	Packaging waste from incoming goods	General	Solid	Includes wooden pieces, metal straps, plastics – sale
9	Drums contaminated with chemical additives	Industrial	Solid	Plastic and metal drums contaminated with various chemical compounds (additives or corrosion inhibitors) – sale
10	Work clothes, gloves, safety shoes contaminated with petroleum substances	Industrial	Solid	Transfer to landfill
11	Radiography waste from NDT inspection	Hazardous	Liquid	Transferred to Atomic Energy Organization waste management with coordination and formal documentation
12	Laboratory waste from petroleum testing	Hazardous	Liquid	Contains various chemical compounds from laboratory tests – transferred to water recycling
13	Industrial clinic medical waste	Hazardous	Solid	Transfer to municipal landfill
14	Agricultural waste	Agricultural	Solid	Includes weeds, leaves, and debris from refinery green space – transfer to landfill
15	Non-industrial unit waste and control room waste	General	Solid (dry)	Mostly waste paper – transfer to landfill
16	Waste from refinery restaurants	General	Solid (wet)	Can be used as fertilizer or animal feed after required processing – transfer to landfill

Using a combination of qualitative classification (hazard level and compositional characteristics) and quantitative analysis (production volume), "prominent" waste streams and hazardous waste categories in the refinery were identified (Figures 2 and 3).

Figure 2

Quantities (tons) of Prominent Waste Streams in the Fifth Refinery Over a One-Year Period

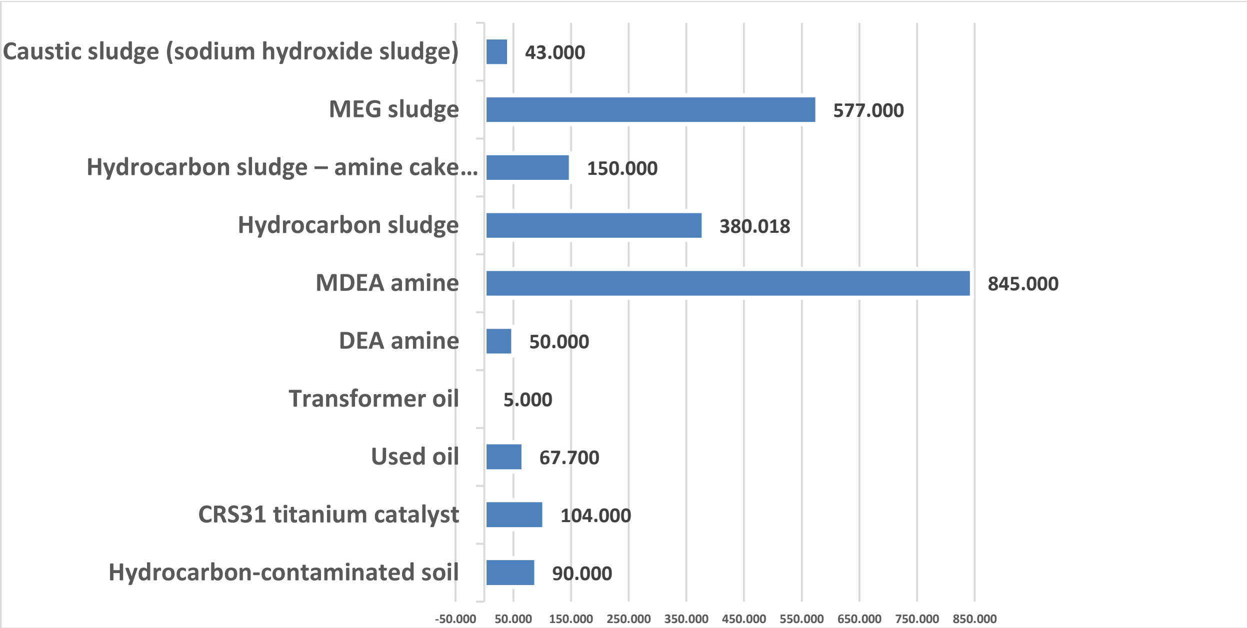
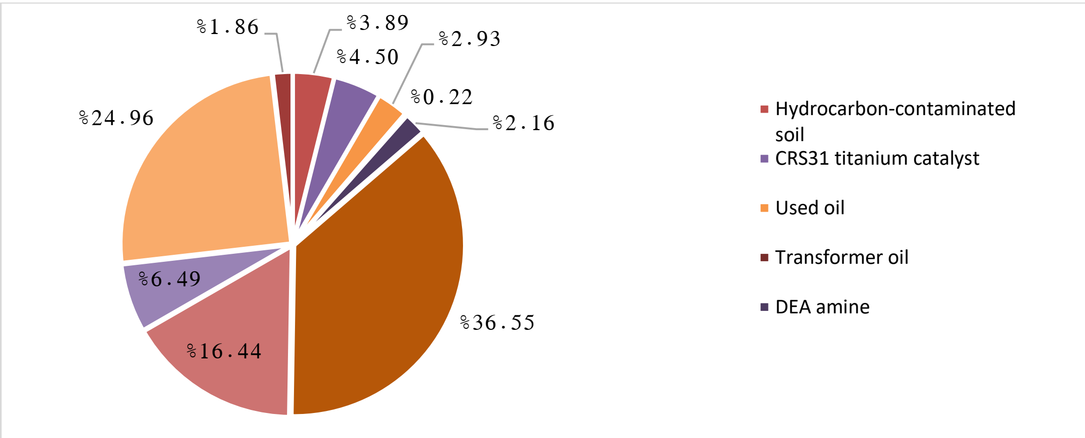


Figure 3

Percentage of Prominent Hazardous Waste (Type H Waste) in the Fifth South Pars Gas Refinery Over a One-Year Period

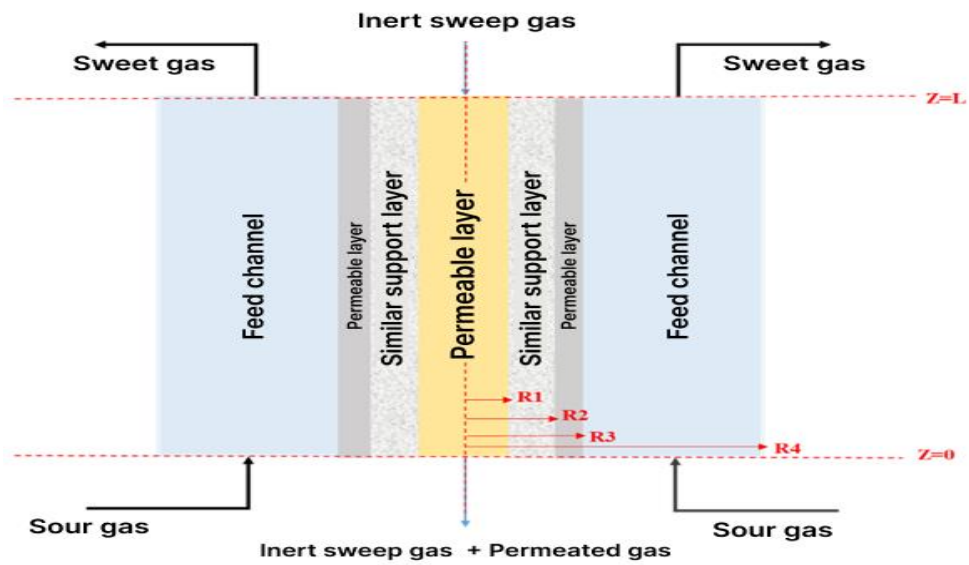


As a preventive option within the managerial model, the PEBAX nanocomposite membrane was proposed as an alternative technology in the processing stage. The basic technical specifications for modeling membrane performance (module dimensions, membrane thickness range, pressure/temperature conditions) were defined. Figure 4 illustrates the geometric structure of the membrane module designed in COMSOL Multiphysics, consisting of the feed zone, membrane layer, and permeate stream. This model was used to determine boundary conditions and simulate mass transfer.

To estimate the impact of replacing portions of the amine absorption process with a membrane unit on waste generation at the source, a simplified process module was modeled. The membrane module geometry, operational boundary conditions, and mass-transfer/transport equations were defined in COMSOL (Transport of Diluted Species module and Flow module for tubular/module flow conditions). Input parameters for simulation included initial concentrations of acidic gases (CO_2, H_2S), operational temperature and pressure, and various membrane thicknesses, extracted from refinery operating data and corresponding tables.

Figure 4

Physical Structure of the PEBAX Membrane Model



Simulation outputs (acid gas separation rate, percentage reduction in pollutant load entering the amine cycle) were incorporated parametrically into the managerial model to estimate the potential reduction in spent amine volume (and other associated waste streams). This conversion was performed using a correlation coefficient linking removal efficiency to reduced regeneration/replacement requirements for amine solvent. Ultimately, the managerial model's output data (monthly and annual reductions in waste volume) were prepared for subsequent Life Cycle Assessment (LCA) and cost–benefit analyses. The details of the method for converting waste volume to environmental burden and cost (including parameters required for LCA) will be determined based on reference standards and chemical composition tables of the waste streams.

Using the simulation performed in COMSOL software, it was determined how a flat-sheet membrane module—with the characteristics previously described—would perform in the gas sweetening process. Figures 27 to 29 show the concentration profiles of CH_4, CO_2, and H_2S. The higher the sweep-gas flow rate and the faster it removes components along the channel, the higher the sweetening efficiency will be.

Figure 5

Concentration Profile of CH_4 in the Module

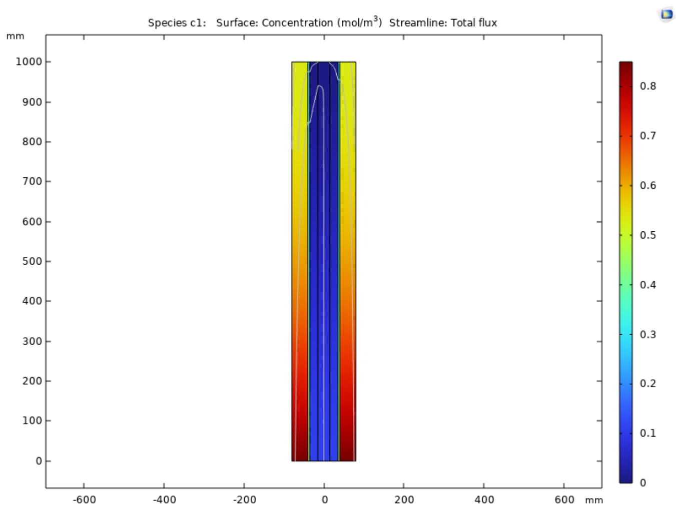


Figure 6

Concentration Profile of CO_2 in the Module

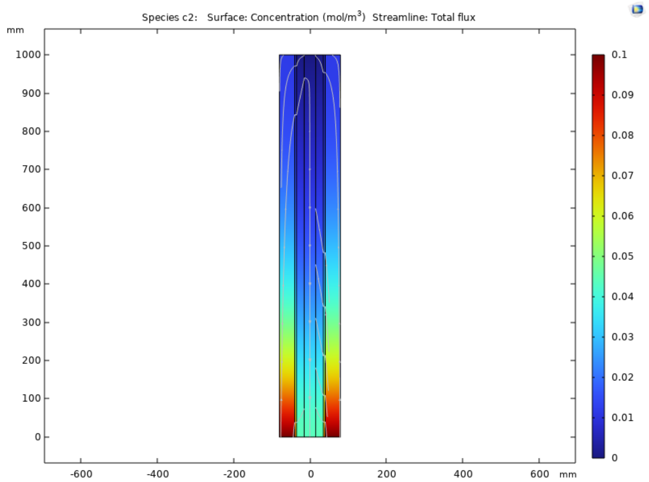
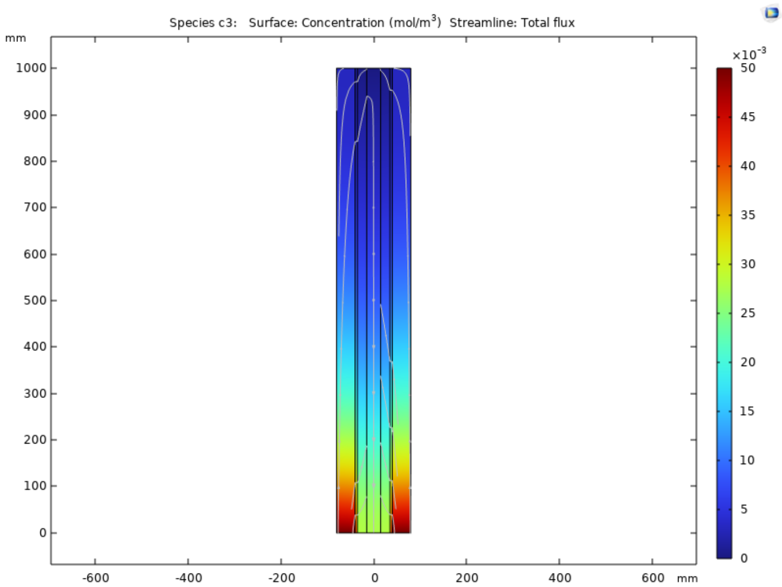


Figure 7

Concentration Profile of H_2S in the Module



The effect of temperature on permeability and solubility is described by the Van't Hoff–Arrhenius equations. Accordingly, although increasing temperature enhances the permeability of H_2S—and thus improves membrane sweetening efficiency—greater diffusion of methane and other natural gas components reduces the membrane's selectivity toward H_2S, resulting in higher gas loss.

(1) $\theta = 1/T$

(2) $D_2/D_1 = \exp[-E\_d/R\ (\theta_2 - \theta_1)]$

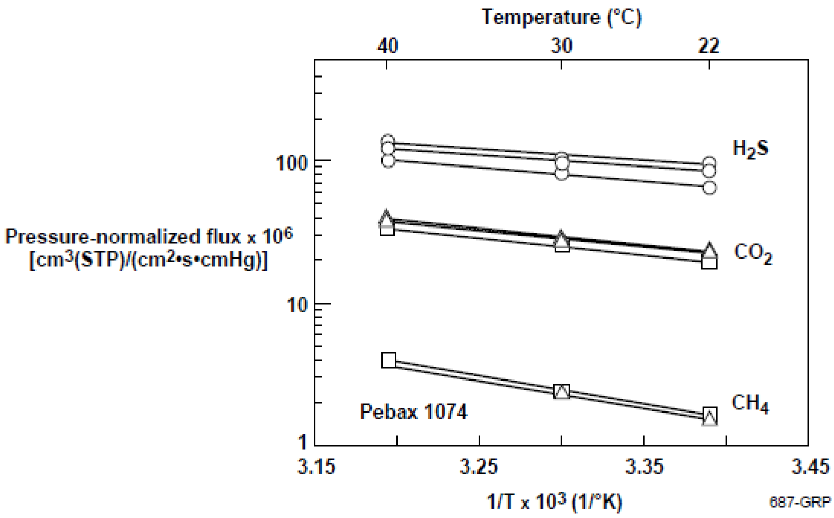
(3) $S_2/S_1 = \exp[-E\_s/R\ (\theta_2 - \theta_1)]$

(4) $P_2/P_1 = \exp[-E\_p/R\ (\theta_2 - \theta_1)]$

(5) $\ln(P / P_0) = -E\_p/R\ (\theta)$

Figure 8

Effect of Temperature on Membrane Permeability as the Main Factor Influencing Sweetening Efficiency



As shown in Figure 8, with increasing temperature, the permeation of all components increases; however, the rate of permeation increase for methane is greater than that of the acidic components. As a result, membrane selectivity toward acid gases decreases, and gas loss increases as temperature rises. A membrane separation process is fundamentally based on differences in the permeation of components through a membrane barrier. Therefore, the lower the membrane resistance to the target permeating component, and the higher the resistance to unwanted components, the better the separation efficiency. For dense nanocomposite membranes, mass transfer resistance—considering that the mass transport mechanism in the feed channel, support layer, and membrane layer is solution–diffusion (Figure 4), and that the membrane layer serves as the main resistance—can be estimated as follows:

(6) $R_{total} = R_{feed} + R_{membrane} + R_{support}$

(7) $R_{membrane} \gg R_{feed} + R_{support}$

(8) $R_{total} \cong R_{membrane}$

Considering Fick's law in the membrane layer as the governing mass transfer relationship, membrane resistance is determined as:

Mass transfer flux = (Driving force for mass transfer) / (Mass transfer resistance)

According to Fick's law and permeability:

(9) $N_i = -P_i \, (dp_i/dx)$

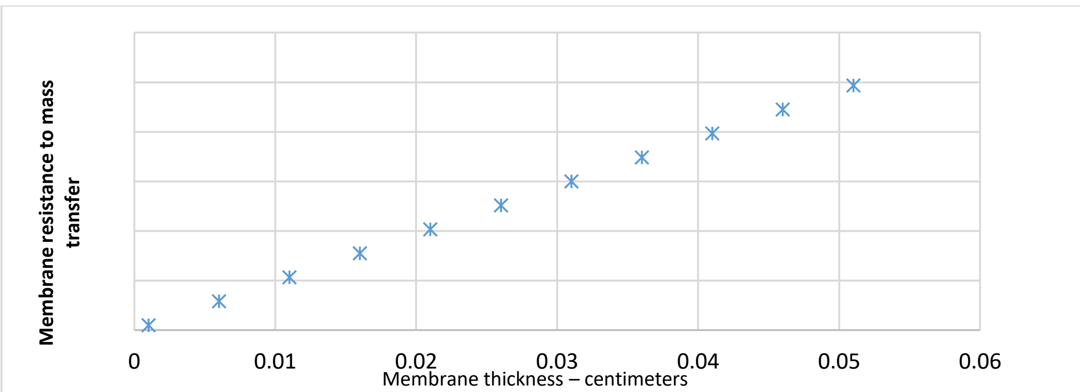
where P_i is the permeability of component i and dp_i is the partial pressure difference of component i. Taking partial pressure difference as the driving force, membrane resistance becomes:

(10) $R_{membrane} = dp_i / [\, (-P_i / dx) \,] = (dp_i / -P_i)\, dx$

Here, dx represents membrane thickness. Therefore, reducing membrane thickness decreases mass transfer resistance and improves separation efficiency. However, it should be noted that decreasing mass transfer resistance increases the flux of all components; thus membrane thickness does not affect relative permeability or selectivity. Consequently, gas loss increases.

Figure 9

Membrane Thickness and Mass Transfer Resistance



Given that each module in the simulation has a gas sweetening capacity of 1.33575 tons per hour, each gas train requires 352 membrane modules of 5 mm thickness with dimensions of 675 × 1000 mm to achieve sweetening down to 0.0031630 mol/m³ of H_2S in the gas stream. Nevertheless, this level does not meet the desired and safe sweetening standard (4 ppm by weight). Therefore, significantly larger membrane modules or an additional amine absorption stage are required to reach the target sweetening level, suggesting that the process must operate as a hybrid membrane–amine absorption system.

Because the mass transfer mechanism in this membrane system is solution–diffusion and the driving force is the partial pressure (concentration) gradient across the membrane, assuming constant pressure in the permeate channel and sweep gas, increasing the feed pressure enhances acidic gas permeability and improves mass transfer effectiveness.

4. Discussion and Conclusion

The findings of this study demonstrate that the integration of Pebax-based nanocomposite membrane technology into the natural gas sweetening process can substantially reduce the load of acidic gases entering the amine absorption unit, thereby offering a feasible pathway for decreasing the formation of hazardous waste at the source. The simulation results showed that membrane-assisted pretreatment effectively removed a significant proportion of CO_2 and H_2S prior to the amine stage, and this reduction directly correlated with a lower degradation rate of amine solvents. This observation is consistent with material science research indicating that Pebax membranes possess favorable chemical affinity toward acidic gases due to their polyether domains and flexible segmental dynamics (Afshoun et al., 2017; Amini & Asghari, 2018). Such affinity enhances permeability while maintaining a degree of selectivity that supports hybrid industrial configurations. The present findings reinforce these established characteristics and extend them into the domain of industrial hazardous waste management, demonstrating that membrane efficiency is not only a technical advantage but also an environmental asset.

The observed influence of temperature in increasing permeability yet reducing selectivity aligns with established theoretical models of solution–diffusion-driven transport. Our findings follow the Van't Hoff–Arrhenius behavior reported in previous membrane studies, in which elevated temperatures increase polymer chain mobility and gas diffusivity, thereby enhancing overall permeation rates (Feng et al., 2019; Harrigan et al., 2020). However, the increased diffusion of methane at elevated temperatures reduces membrane selectivity, an outcome echoed in earlier investigations demonstrating that methane's kinetic diameter and solubility characteristics allow it to permeate more readily as temperature increases (Huang, Isfahani, et al., 2018; Sanaeepur et al., 2019). The present study also found that methane loss increased in high-temperature operations, further confirming these prior findings. While increased permeability may superficially appear beneficial, the decline in selectivity limits operational viability unless accompanied by compensatory process controls.

The results regarding membrane thickness effects similarly align with previously documented theoretical and empirical work. As expected, the reduction of membrane thickness decreased mass transfer resistance and increased flux, yet it did not improve selectivity. This is consistent with research demonstrating that gas transport behavior in thin Pebax films is dominated by intrinsic polymer properties rather than geometric reduction of resistance (Meshkat et al., 2019, 2020). Our findings confirm that thinner membranes intensify the permeation of all components, not only target acidic gases, resulting in greater methane loss. This phenomenon highlights a critical engineering challenge in scaling membrane modules for industrial sweetening: optimizing flux without compromising gas recovery. While many studies emphasize permeability improvements, the present results underscore that industrial-scale adoption must balance separation performance with economic and safety considerations.

The simulation also revealed that achieving industrially acceptable residual H_2S levels using membranes alone would require an unrealistically large number of modules. The calculated requirement of over 350 modules per gas train indicates that a purely membrane-based sweetening system is not feasible in this refinery configuration. This conclusion is consistent with literature reporting that while Pebax membranes demonstrate excellent laboratory-scale performance, their industrial deployment necessitates hybrid designs due to pressure limitations, material durability, and economic constraints (Delavari et al., 2024; Li et al., 2016; Zhou et al., 2015). Several studies emphasize that hybrid amine–membrane systems offer the most efficient balance between membrane selectivity and amine solvent stability (Eljaddi et al., 2022; Nobakht & Abedini, 2023). Our findings provide empirical support for these claims by demonstrating that membrane pretreatment significantly reduces hazardous waste, yet cannot independently meet sweetening requirements.

One key result of this research was the identification of a direct relationship between reduced acidic gas loading and reduced amine degradation. This connection is supported by previous studies showing that CO_2 and H_2S not only participate in reversible absorption reactions but also promote heat-stable salt formation, oxidative degradation, and contamination, all of which shorten solvent lifetime and increase hazardous waste generation (Chen et al., 2022; Hassanzadeh et al., 2022). Because the membrane pretreatment reduced the frequency of required solvent regeneration cycles, the production of spent amine sludge and other associated hazardous waste decreased correspondingly. This supports the hypothesis that membrane-assisted processes represent an environmentally favorable alternative in natural gas refineries. The present findings reinforce this viewpoint by explicitly demonstrating how membrane technology alters the waste generation profile in a real refinery context.

The study's results also align strongly with emerging research on advanced MMMs designed to enhance CO_2/CH_4 selectivity. The enhanced performance of membranes containing fillers such as ZIF-8, graphene oxide, ionic liquids, or cellulose nanofibers has been reported widely, with improvements in both gas permeability and stability attributed to the formation of efficient transport pathways and suppressed polymer chain relaxation (Eljaddi et al., 2022; Huang, Pournaghshband, et al., 2018; Narkkun et al., 2023). Our findings partially corroborate these studies by confirming that incorporating nanocomposite structures into Pebax matrices significantly enhances acidic gas permeation, thereby enabling effective pretreatment. However, while these improvements translate into considerable operational benefits, our study shows that even with enhanced permeability, industrial sweetening purity levels remain challenging to achieve entirely with membranes. This underscores the practical gap between laboratory performance gains and real-world refinery constraints.

The study also contributes new evidence to discussions surrounding the transport behavior of sour gases—particularly H_2S—in Pebax matrices. The higher permeability of H_2S relative to CO_2 observed in our simulations closely matches reported findings that H_2S possesses greater condensability and stronger interactions with the amide segments of Pebax (Harrigan et al., 2020; Tu et al., 2024). Our results further support the hypothesis that Pebax membranes could serve as efficient partial desulfurization units in hybrid systems. Yet the broader implication is that H_2S removal using membranes may be more feasible than CO_2 removal in certain operational contexts. These insights are particularly significant for large sour gas fields where H_2S is the primary contaminant and where amine solvent degradation represents a critical source of hazardous waste.

The ability of the membrane system to reduce the mass load entering the amine cycle has broader implications for lifecycle environmental management. Several studies highlight the importance of process intensification and pretreatment strategies in reducing both direct emissions and downstream waste (Jiao et al., 2021; Kojabad et al., 2021; Yoon et al., 2021). By demonstrating that membrane-assisted pretreatment can reduce the quantity of degraded amine waste, this research extends the scope of membrane studies beyond separation performance toward sustainability and environmental protection. Additionally, given the increasing urgency of environmental regulations in the natural gas industry, the reduction of waste volumes through source control strategies is an essential direction for industrial innovation.

Across all comparisons, the results of this study validate the growing consensus in the literature that Pebax-based membranes are highly promising materials for selective acidic gas transport, yet their industrial application is best suited as part of a hybrid sweetening configuration. This study also uniquely highlights the relationship between membrane pretreatment and hazardous waste minimization—an area largely overlooked in existing membrane research. By linking membrane performance with waste stream behavior, this study provides new direction for integrating advanced membrane technologies into environmental management frameworks in gas refineries.

This study's main limitation lies in its reliance on simulation modeling rather than full-scale pilot testing. While the COMSOL-based transport analysis accurately represents membrane behavior under varying pressure, temperature, and thickness conditions, real-world refinery environments involve fluctuating flow compositions, mechanical stresses, and long-term fouling effects that cannot be fully captured in simulation. Additionally, the analysis of hazardous waste reduction is based on indirect indicators derived from reduced acid gas loading rather than measured changes in amine degradation under operational conditions. The study also assumes consistent membrane module fabrication quality, whereas industrial-scale module production may introduce variability that affects performance. Finally, economic considerations, including installation costs and hybrid process integration, were beyond the scope of this study but remain essential for determining industrial feasibility.

Future research should include pilot-scale testing of Pebax-based membrane modules in operating natural gas refineries to validate simulation findings and quantify real-world impacts on hazardous waste reduction. Further studies could explore the long-term stability of these membranes under high concentrations of H_2S and other contaminants found in sour gas streams. Researchers should also investigate advanced hybrid configurations combining membrane pretreatment with optimized amine absorption cycles to evaluate dynamic interactions between the two systems. Additional opportunities exist in designing new nanocomposite fillers that enhance both selectivity and resistance to chemical degradation. Finally, future work should incorporate techno-economic and lifecycle assessments to evaluate the cost-effectiveness and environmental benefits of membrane-assisted sweetening at regional and national scales.

Industry practitioners should explore adopting membrane pretreatment as a supplemental process to reduce the load on amine sweetening units and extend solvent lifetime. Refineries can benefit from implementing hybrid membrane–amine systems to decrease hazardous waste generation, improve equipment durability, and align with environmental sustainability objectives. Operators should also consider integrating membrane monitoring systems to optimize performance under varying feed conditions and reduce methane loss.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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