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FINE-TUNING DEA AMINE CONDITIONS FOR EFFICIENT CO_2 REMOVAL IN NATURAL GAS PROCESSING: A SIMULATION-BASED APPROACH

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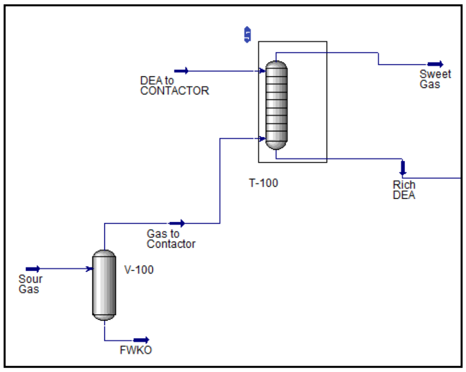
Graphical abstract



Abstract

Efficient CO_2 removal from natural gas is essential for meeting pipeline specifications and minimizing corrosion risks. This study investigates the influence of temperature, pressure, and Diethanolamine (DEA) concentration on CO_2 absorption efficiency in the gas sweetening process, using simulations conducted with Aspen HYSYS V.10. Through a comprehensive sensitivity analysis, we explore the interaction between these parameters, revealing that temperature is a primary driver in optimizing DEA's CO_2 capture capability. Results indicate that elevated temperatures (60–80°C) significantly enhance CO_2 absorption, stabilize performance, and reduce CO_2 composition to near-zero levels, especially at DEA concentrations between 0.4–0.6 mol/mol. While pressure contributes to absorption efficiency, its impact is most pronounced at lower temperatures and diminishes as temperature increases. A critical concentration threshold of 0.4–0.5 mol/mol is identified, beyond which CO_2 removal efficiency markedly improves, particularly at 40°C and higher. The findings suggest that optimal conditions for industrial gas sweetening applications include a temperature of 60–80°C, a DEA concentration of 0.4–0.6 mol/mol, and adjusted pressures to maintain stability without excessive dependency. These conditions enable maximum CO_2 removal, ensure compliance with gas quality standards, enhance operational efficiency, and reduce energy consumption. This study provides actionable insights for the gas processing industry, offers a roadmap for optimizing CO_2 absorption processes through precise parameter control, and supports the development of more sustainable and cost-effective gas sweetening technologies, with implications for improved environmental compliance and enhanced profitability in gas treatment operations.

Keywords: Amine DEA, Absorption, CO_2 Composition, Diethanolamine

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Abstrak

Penyingkiran CO_2 yang berkesan dari gas asli adalah penting untuk memenuhi spesifikasi saluran paip dan meminimumkan risiko kakisan. Kajian ini menyiasat pengaruh suhu, tekanan, dan kepekatan Diethanolamine (DEA) terhadap kecekapan penyerapan CO_2 dalam proses pemurnian gas, menggunakan simulasi yang dijalankan dengan Aspen HYSYS V.10. Melalui analisis sensitiviti yang komprehensif, kami meneroka interaksi antara parameter-parameter ini, yang menunjukkan bahawa suhu merupakan faktor utama dalam mengoptimumkan keupayaan DEA untuk menangkap CO_2. Hasil kajian menunjukkan bahawa suhu tinggi (60–80°C) secara signifikan meningkatkan penyerapan CO_2, menstabilkan prestasi dan mengurangkan komposisi CO_2 ke tahap hampir sifar, terutamanya pada kepekatan DEA antara 0.4-0.6 mol/mol. Walaupun tekanan menyumbang kepada kecekapan penyerapan, impaknya paling ketara pada suhu rendah dan berkurang apabila suhu meningkat. Satu ambang kepekatan kritikal pada 0.4–0.5 mol/mol telah dikenal pasti, di mana kecekapan penyingkiran CO_2 bertambah baik dengan ketara, terutamanya pada 40°C dan ke atas. Penemuan ini mencadangkan bahawa keadaan optimum untuk aplikasi pemurnian gas industri termasuk suhu 60–80°C, kepekatan DEA antara 0.4–0.6 mol/mol, dan tekanan yang disesuaikan untuk mengekalkan kestabilan tanpa terlalu bergantung padanya. Keadaan ini membolehkan penyingkiran CO_2 yang maksimum, memastikan pematuhan dengan piawaian kualiti gas sambil meningkatkan kecekapan operasi dan mengurangkan penggunaan tenaga. Kajian ini menyediakan panduan praktikal untuk industri pemprosesan gas, menawarkan peta jalan untuk mengoptimumkan proses penyerapan CO_2 melalui kawalan parameter yang tepat. Dengan meningkatkan pemahaman mengenai tingkah laku DEA dalam penangkapan CO_2, penyelidikan ini menyokong pembangunan teknologi pemurnian gas yang lebih mampan dan menjimatkan kos, dengan implikasi untuk pematuhan alam sekitar yang lebih baik dan peningkatan keuntungan dalam operasi rawatan gas

Kata kunci: Amine DEA, Absorpsi, Komposisi CO_2, Diethanolamine

1.0 INTRODUCTION

Globally, natural gas stands as the largest natural resource after coal and oil, playing a pivotal role in meeting the world's energy demands [1]. The crucial energy resource, consists of hydrocarbon (CnH_2n+_2) and non-hydrocarbon components [2]. In 2024, demand for natural gas is projected to increase by 2.5%, largely driven by rapid growth in Asian markets [3]. Its potential has positioned natural gas as a prime candidate for strategic energy reserves. In Indonesia, the government has implemented comprehensive regulations to support the governance of natural gas across both upstream and downstream sectors, including Law No. 22 of 2001 on Oil and Gas, Law No. 20 of 2007 on Energy, Government Regulation No. 79 of 2014 on National Energy Policy, and various additional regulations from the Ministry of Energy and Mineral Resources [4].

Recently, Indonesian oil and gas company EMP Bentu Limited discovered an estimated 126 billion cubic feet of gas in one of its wells during drilling activities in 2024. This discovery will be followed up with the drilling of several development wells, construction of gas pipelines, and additional production facilities [5]. The composition of natural gas varies due to differences in well types, and it can be classified as either associated gas or non-associated gas. Despite differences in well sources, natural gas, predominantly composed of methane, remains the most commonly used fuel. As a fossil fuel, natural gas is made up of the shortest and lightest hydrocarbon molecules, primarily methane (CH_4)[6]. However, natural gas often contains various contaminants that can disrupt production and utilization processes, such as H_2S and CO_2 [7]. Acid gases, particularly hydrogen sulfide (H_2S) and carbon dioxide (CO_2), can form acids in aqueous environments, leading to corrosion—a problem influenced by factors such as acidity or pH, the phases of water, gas, or oil, produced water chemistry, temperature, chlorides, flow rates, and the composition and condition of metals used [8].

Thus, before it can be utilized, produced oil and gas must undergo a series of treatment processes to make it safe for distribution to consumers. For natural gas to be commercially viable, it must undergo treatment to remove CO_2, water, and H_2S. In gas sweetening process, distinctions are made based on the type and amount of acidic gas contaminants removed, which may involve the selective removal of CO_2, H_2S, or both [9]. Various CO_2 separation technologies are available, including physical absorption, chemical absorption, and membrane technology.

Amines are categorized by their structure—primary, secondary, or tertiary—based on the number of organic groups attached to the nitrogen atom [10]. Among the various amine compounds discussed, Diethanolamine (DEA) is the most commonly used. This is because Diethanolamine (DEA) absorbs CO_2 more rapidly than Methyl Diethanolamine (MDEA). Furthermore, Diethanolamine (DEA) has better capacity and is less corrosive than Monoethanolamine (MEA). Although DEA systems may not be as efficient as some other chemical solvents, they are more affordable to implement and operate. Additionally, DEA systems are easier to maintain and are generally more familiar in the field. CO_2 removal and demonstrated that CO_2 absorption using DEA is a promising technology for CO_2 capture due to its cost-effectiveness and its ability to handle large volumes of acidic gases [11]. Diethanolamine (DEA) is a preferred solvent in CO_2 capture processes due to its favorable balance of reactivity, efficiency, and lower corrosivity compared to Monoethanolamine (MEA). As a secondary amine, DEA provides lower vapor pressure and a reduced heat of reaction, making it both cost-effective and easier to regenerate, while also offering strong performance in capturing acid gases like CO_2, COS, and CS_2 [12]. This regeneration capacity allows for repeated use, lowering operational costs over time.

Typically, sweet gas contains less than 4 ppmv of H_2S, and pipeline-quality gas must meet strict specifications, allowing between 0.25 and 1.0 grains of H_2S per 100 scf (6 to 24 mg/Sm³, or 4 to 16 ppmv) [13]. O_2, another critical contaminant, should be kept below 2% for pipeline compatibility [14]. Acidic and corrosive in the presence of water vapor, CO_2 can damage pipelines and equipment, especially as it freezes at -78°C—significantly higher than methane's freezing point of -182°C—posing a risk of blockages in heat exchangers operating at temperatures as low as -150°C. The removal of CO_2 and H_2S is therefore essential for the petrochemical, oil, and natural gas industries to ensure safe and efficient transportation and utilization of natural gas [15].

In gas production, extensive processing equipment is essential to purify the output by removing contaminants like hydrogen sulfide (H_2S) and carbon dioxide (CO_2), collectively known as sour gases. The process of "sweetening" these gases not only improves their quality but also prevents operational issues. Reducing CO_2 and water content is crucial for two main reasons: economically, it minimizes the transport of unwanted components, and technically, it enhances the heating value of biogas or natural gas, making it more efficient as a fuel source [16].

Various methods are available for gas sweetening, including absorption, cryogenic separation, adsorption, and membrane filtration. Acid gases like CO_2 and H_2S are particularly corrosive when combined with water, necessitating their removal to protect pipelines and equipment from damage [16]. In the petrochemical, oil, and natural gas industries, CO_2 absorption is a critical process for ensuring the reliability and safety of gas infrastructure, as the presence of acid gases can lead to severe corrosion issues that compromise operational integrity [17].

To separate CO_2 from natural gas, techniques such as physical and chemical absorption, adsorption, cryogenic processing, membrane technology, and even biological methods like algae or microbial systems are employed [18]. Among these, chemical absorption—specifically using Diethanolamine (DEA)—is one of the most economical and widely applied methods, proven effective in large-scale applications. DEA-based absorption systems excel at capturing acidic components, particularly H_2S and CO_2, making them suitable for hydrocarbon streams with high sour gas content [19].

The main objective of the industrial absorption process is to isolate unwanted components from gas mixtures or to create valuable reaction products. In chemical absorption, specialized solvents and reactants interact with dissolved gas components to achieve efficient separation [20]. Research in CO_2 absorption has shown that both the heat of absorption and CO_2 solubility must be considered to select the optimal absorbent, as these factors directly impact the efficiency and cost-effectiveness of the capture process [21].

The selection of temperature, pressure, and DEA concentration as the primary variables in this study was based on their dominant role in determining the thermodynamic and kinetic behavior of the CO_2 absorption process. Temperature directly influences the reaction kinetics and solubility of CO_2 in the DEA solution, while pressure affects the partial pressure of CO_2, thereby altering mass transfer rates. DEA concentration determines the availability of reactive amine molecules for CO_2 capture. Although other operational variables such as gas flow rate and solvent circulation rate also influence absorption efficiency, they are generally considered secondary and are often optimized after establishing the fundamental absorption conditions. Furthermore, maintaining constant flow and circulation parameters allows clearer analysis of the core interactions between temperature, pressure, and solvent concentration without introducing confounding variables.

The novelty of this study lies in its comprehensive simulation-based sensitivity analysis using Aspen HYSYS V.10 to systematically fine-tune the DEA amine operating parameters—specifically temperature, pressure, and concentration—for efficient CO_2 removal in natural gas processing. Unlike previous works that examine these parameters in isolation or rely solely on experimental data, this study integrates them within a dynamic simulation environment to identify critical operational thresholds and interdependencies. The main findings reveal that DEA concentrations between 0.4–0.6 mol/mol combined with temperatures of 60–80°C significantly reduce CO_2 levels in sweet gas to near-zero values, while higher pressures only improve performance at lower temperature ranges. These insights provide an optimized and energy-efficient operational window, contributing valuable guidance for improving industrial gas sweetening processes and supporting the transition toward more cost-effective and environmentally compliant CO_2 capture strategies.

2.0 METHODOLOGY

In this study, Diethanolamine (DEA), a secondary alkanolamine, was selected due to its favorable balance between reactivity, regeneration efficiency, and lower corrosivity. Alkanolamines such as DEA, MEA, and MDEA are commonly used in CO_2 capture simulations within Aspen HYSYS due to their defined chemical behavior and established kinetic models. The "Acid Gas – Chemical Solvent" thermodynamic package was applied to simulate the chemical absorption of CO_2 accurately [22, 23, 24].

A sophisticated simulation tool widely utilized for complex gas processing, oil refining, and optimization across the oil and gas sector, making it exceptionally suited for CO_2 absorption modeling [25]. Aspen HYSYS V.10 provides a comprehensive platform for simulating gas absorption dynamics, with Diethanolamine (DEA) selected as the absorbent due to its proven efficiency in capturing acidic gases like CO_2. The simulation follows a structured design approach: initially, essential components—feed gas, solvent, and product—are defined. Next, a thermodynamic model is selected to capture the interactions accurately; The simulation utilizes the 'Acid Gas - Chemical Solvent' property package, specifically designed for systems involving acid gas absorption using chemical solvents such as amines.

Following model selection, the software requires precise operating conditions, including pressure, temperature, and concentration, which are input to reflect industrial parameters. Finally, the simulation is executed, running iterative calculations until it reaches a 'converged' status, indicating that the system has stabilized. This process not only confirms the reliability of the results but also provides an insightful, realistic framework for enhancing CO_2 removal operations within the gas industry. The detailed simulation outputs serve as a valuable foundation for optimizing industrial gas sweetening processes and refining operational efficiency [26].

This study employs chemical absorption, simulating the sweetening process under varying pressure, temperature, and DEA Amine concentration scenarios to determine optimal natural gas conditions. Absorption, or gas sweetening through chemical solvents, is a well-studied technology, with findings demonstrating that this method is one of the most efficient options for CO_2 separation

This research utilized secondary data to meet the dataset requirements for studying gas sweetening processes. A simulation-based research method was applied, beginning with the development of a base case model using Aspen HYSYS V.10. Once the base case was established, multiple scenarios were simulated by varying pressure, temperature, and Diethanolamine (DEA) concentration to observe their effects on CO_2 composition in the sweetened gas. The following section detailed the data used in this research:

Table 1. Composition of sour natural gas feed to the DEA amine sweetening simulated case [27]

Component	Mole Fraction
C1	0.8692
C2	0.0393
C3	0.0093
i-C4	0.0026
n-C4	0.0029
i-C5	0.0014
n-C5	0.0012
n-C6	0.0018
N_2	0.0016
H_2S	0.0172
CO_2	0.0413
H_2O	0.0122
DEA	0.0000

Table 2 Operating conditions [27]

Item	Value
Number of stage	20
Top Stage Pressure	6850 Kpa
Bottom Stage Pressure	6900 Kpa
Estimate for Top Stage Temperature	40 °C
Estimate fo Bottom Stage Temperature	70 °C
Number of Stage	18
Condenser Pressure	190 Kpa
Reboiler Pressure	220 Kpa
Condenser Pressure Drop	15 Kpa
Reboiler Pressure Drop	10 Kpa
Overhead Rate	1.5 MMSCFD
Reflux Ratio	1.5
Reboiler Temperature	125 °C

It is important to note that this study relied entirely on simulation using Aspen HYSYS V.10, and therefore certain assumptions and simplifications were made. The thermodynamic model selected—*Acid Gas–Chemical Solvent*—is widely adopted in gas processing simulations, but it may not fully capture non-ideal behavior observed in actual industrial systems. For instance, real plant conditions often involve variables such as DEA degradation, foaming, corrosion effects, and non-uniform flow profiles, which were not modeled in this study. Additionally, flow rate variations, equipment-specific pressure drops, and solvent losses were assumed constant or ideal.

The absence of validation using experimental or industrial operational data is acknowledged as a limitation. Although the simulation outcomes offer valuable trend insights and process optimization potential, further experimental studies or plant-scale validation are necessary to confirm their industrial applicability. Future work should address these limitations by incorporating empirical data, analyzing long-term solvent behavior (e.g., DEA degradation), and evaluating operational dynamics under non-ideal conditions.

3.0 RESULTS AND DISCUSSION

1) Simulation Result Process

After initial separation, the gas undergoes a sweetening process within the contactor to ensure compliance with pipeline specifications and optimize gas quality. This phase employs compounds such as amines, potassium carbonate, and physical solvents, which are effective for treating sour gas concentrations of up to 8%—typically with thresholds of 2% CO_2 and 4 ppm H_2S in the feed gas [27]. Table 3 reveals that the CO_2 content in the gas exiting the separator is still below the required standards, underscoring the need for further CO_2 reduction in the sweetening stage. Lowering CO_2 levels in the treated gas is crucial not only to prevent corrosion in pipelines but also to preserve the heating value of natural gas, ensuring both safety and efficiency in downstream applications. Therefore, this study is essential to develop effective strategies for minimizing CO_2 in acid gas to address operational challenges and optimize the commercial viability of natural gas.

Table 3 Composition Gas @ Separator Outlet

Gas Composition	Gas outlet separator
Methane	0.8794
Ethane	0.0398
Propane	0.0094
i-Butane	0.0026
n-Butane	0.0029
i-Pentane	0.0014
n-Pentane	0.0012
n-Hexane	0.0018
Nitrogen	0.0016
CO_2	0.0418
H_2S	0.0174
H_2O	0.0007

Figure 1 illustrates a simulation of the contactor, where the system operates across 20 stages. At the top stage, the pressure is set to 6850 kPa and the temperature to 40°C, while at the bottom stage, the pressure is slightly higher at 6900 kPa with a temperature of 70°C. This configuration provides a controlled environment for efficient gas sweetening, optimizing the conditions for CO_2 and H_2S absorption.

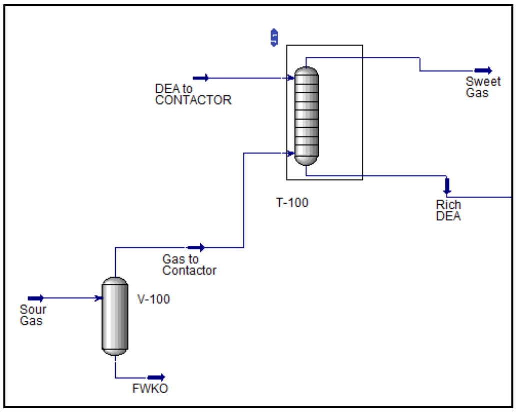

Figure 1 Sweetening Process Simulation [28]

In the gas sweetening process within this absorber, Intx (Intallox) type ceramic packing is utilized, designed with a height of 11 meters and an absorber diameter of 0.9 meters. This specific packing configuration enhances contact between the gas and the Diethanolamine (DEA) solution, optimizing the absorption of CO_2. Process parameters such as temperature, pressure, and lean amine concentration are precisely adjusted to reach the desired CO_2 levels in the treated sweet gas exiting the absorber. This setup ensures effective CO_2 removal, meeting gas quality specifications while maximizing the efficiency of the sweetening process.

2) Sensitivity Analysis

a) Sensitivity of Temperature on DEA Amine to CO_2 Composition

This study examined the effect of varying Diethanolamine (DEA) temperatures on its efficiency in absorbing CO_2, aiming to assess the temperature sensitivity in the gas sweetening process. Temperatures tested included 20°C, 40°C, 60°C, and 80°C. Simulation results indicated how changes in DEA temperature influenced the CO_2 composition in the sweetened gas, revealing valuable insights into the optimal thermal conditions for maximizing CO_2 absorption and enhancing process efficiency.

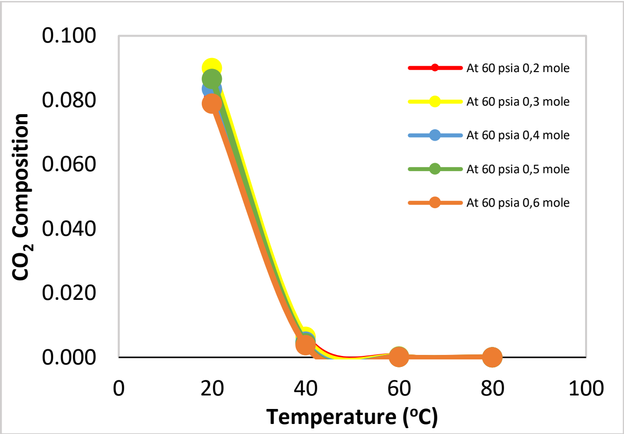

Figure 2 The Sensitivity Of DEA Amine Temperature To CO_2 Composition In Sweet Gas At a Pressure 60 Psia

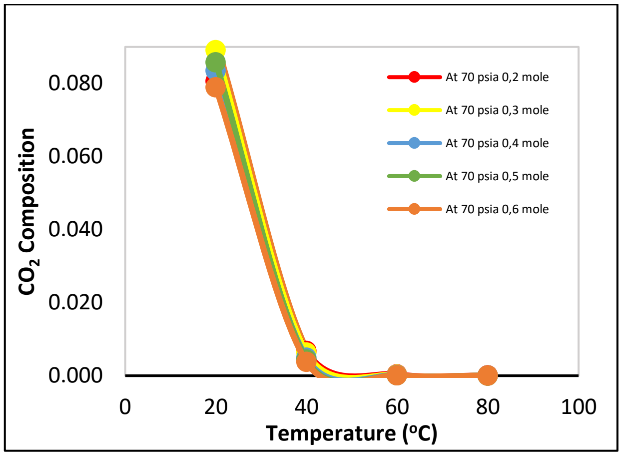

Figure 3 The Sensitivity Of Dea Amine Temperature To CO_2 Composition In Sweet Gas At a Pressure 70 Psia

Figures 2 to 6 show that across all tested pressures (60, 70, 80, 90, and 100 psia), the CO_2 composition in the sweet gas significantly decreases as temperature increases from 20°C to around 40°C. This trend is consistent in all graphs, demonstrating that increasing temperature enhances DEA's ability to absorb CO_2 effectively up to this threshold. Beyond 40°C, the CO_2 composition stabilizes near zero, indicating that further temperature increases (up to 80°C) offer no additional absorption benefits. This indicates that 40°C represents a threshold temperature, beyond which additional temperature offers marginal benefits for CO_2 absorption.

In each graph, lines representing various DEA concentrations (0.2 to 0.6 moles) follow a similar trend, with minimal variation. This consistency implies that, under the tested conditions, DEA concentration has a relatively minor impact on CO_2 absorption efficiency compared to temperature changes.

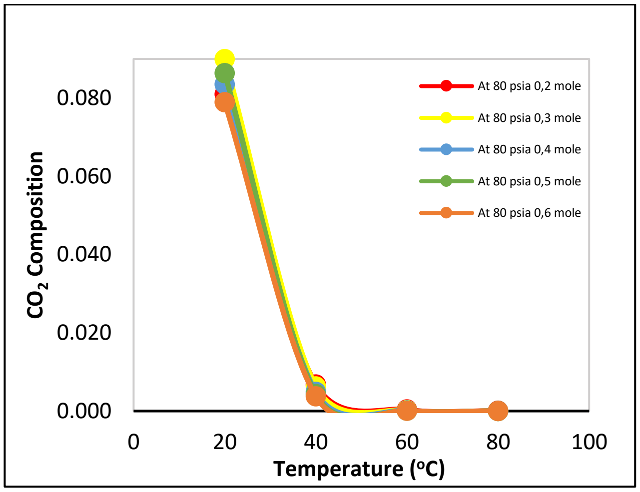

Figure 4 The Sensitivity Of Dea Amine Temperature To CO_2 Composition In Sweet Gas At a Pressure 80 Psia

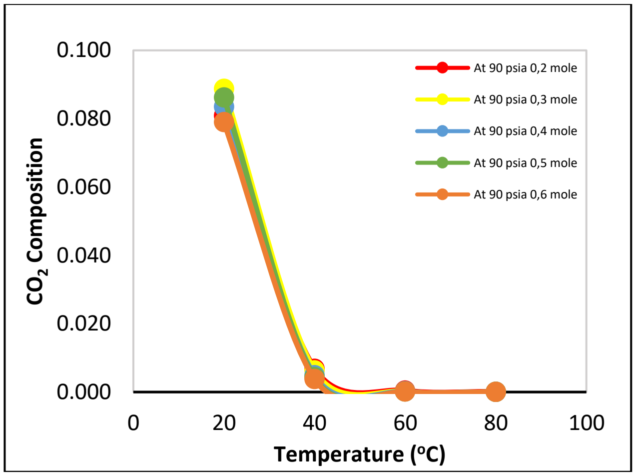

Figure 5 The Sensitivity Of Dea Amine Temperature To CO_2 Composition In Sweet Gas At a Pressure 90 Psia

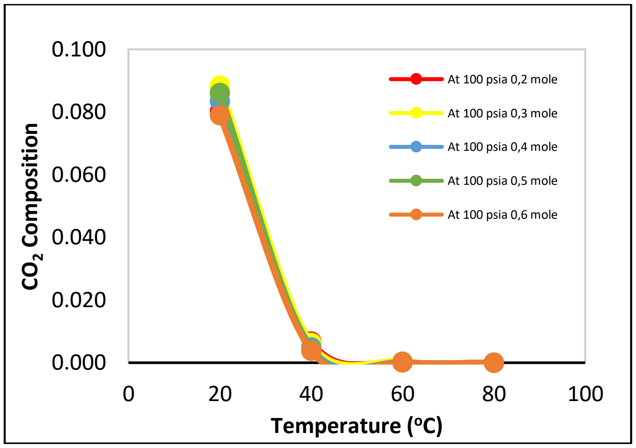

Figure 6 The Sensitivity of Dea Amine Temperature to CO_2 Composition in Sweet Gas at a Pressure 100 Psia

Despite variations in pressure (from 60 to 100 psia), the overall behavior of CO_2 composition relative to temperature remains largely unchanged. The trend of steep CO_2 reduction around 20–40°C is consistent across all pressures, indicating that pressure variations within this range do not significantly affect the temperature sensitivity of CO_2 absorption.

The combined data across pressures and DEA concentrations suggests that the most efficient CO_2 absorption occurs at temperatures around 40°C. Higher temperatures beyond this point do not improve absorption, while the impact of pressure and DEA concentration is less pronounced within the tested ranges. These results reveal that temperature is the primary factor influencing CO_2 absorption efficiency in the gas sweetening process using DEA, with 40°C identified as an optimal temperature for reducing CO_2 composition to near zero across various pressures and DEA concentrations.

Figures 2 to 6 illustrate a clear inverse relationship between temperature and CO_2 composition in sweet gas: as the temperature increases from 20°C to 80°C, the CO_2 composition decreases significantly. This trend suggests that higher temperatures enhance CO_2 absorption efficiency, likely due to faster absorption kinetics. At elevated temperatures, the DEA solvent reacts more effectively with CO_2, thereby reducing its concentration in the treated gas.

This alignment of temperature increase with improved CO_2 absorption efficiency underscores the importance of optimal temperature settings for DEA solutions. By adjusting the temperature appropriately, the absorption rate can be maximized, ensuring lower CO_2 levels in the purified gas. Therefore, precise temperature control in DEA-based gas sweetening processes is crucial to achieving effective CO_2 removal and enhancing the overall efficiency of the gas treatment operation.

As temperature increases, the reaction kinetics between DEA and CO_2 accelerate due to enhanced molecular collisions, promoting the faster formation of carbamate and bicarbonate species, which leads to improved CO_2 absorption efficiency [29]; [30]. Additionally, higher temperatures reduce the viscosity of the DEA solution, improving gas–liquid contact and mass transfer efficiency within the absorber. However, prolonged operation at elevated temperatures may promote thermal degradation of DEA, forming heat-stable salts and reducing solvent performance [31].

Despite the short-term performance benefits, operating at elevated temperatures can pose long-term challenges to DEA stability. Prolonged exposure to high temperatures can promote thermal degradation of DEA, resulting in the formation of degradation products such as oxazolidones, HEIA (Heat Stable Salts), and other heat-stable amine species. These byproducts can reduce solvent effectiveness, increase regeneration energy demand, and cause corrosion or fouling in the system. Therefore, while 60–80°C offers optimal performance in controlled simulations, actual industrial applications must carefully manage operating temperatures to balance absorption efficiency with solvent longevity and maintenance costs.

b) Sensitivity of DEA Amine Pressure to CO_2 Composition

These four graphs, Figures 7 through 10, illustrate the relationship between pressure and CO_2 composition in sweet gas at varying temperatures (20°C, 40°C, 60°C, and 80°C) across pressures ranging from 60 psia to 100 psia. The trends provide insights into how changes in pressure and temperature affect the efficiency of CO_2 absorption in the sweetening process when using DEA as the solvent:

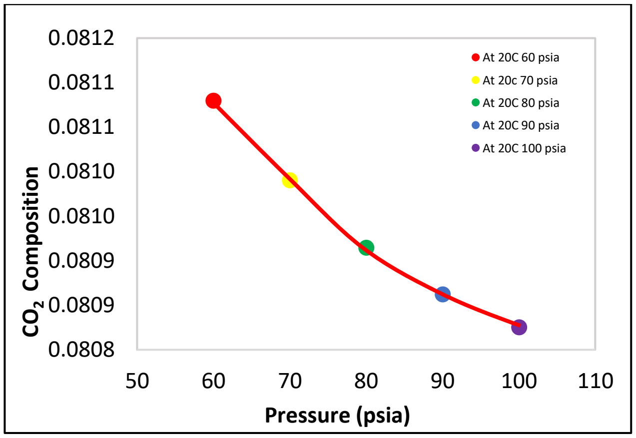

Figure 7. The Sensitivity of DEA Amine Pressure To CO_2 Composition In Sweet Gas At a Temperature 20°C

Figure 7 shows that at 20°C, as pressure increases from 60 psia to 100 psia, the CO_2 composition in the sweet gas decreases. This indicates that higher pressures at lower temperatures enhance the DEA's ability to absorb CO_2, resulting in a lower CO_2 concentration in the sweet gas. This downward trend shows that, at lower temperatures, increasing pressure is beneficial for CO_2 Absorption.

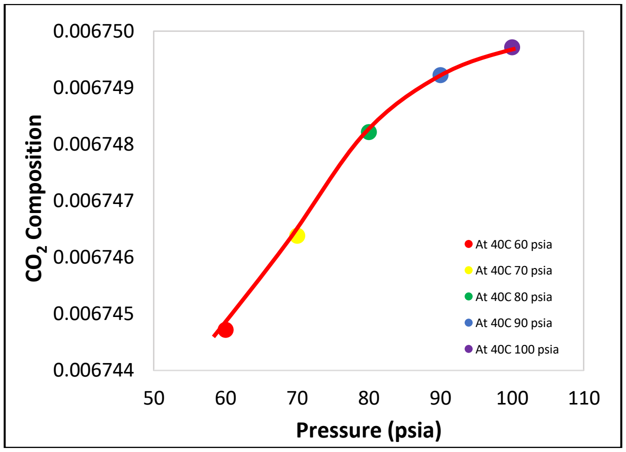

Figure 8 The Sensitivity of DEA Amine Pressure To CO_2 Composition In Sweet Gas At a Temperature 40°c

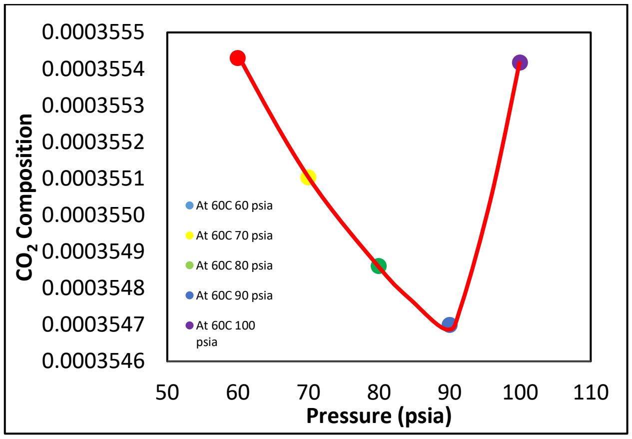

Figure 9 The Sensitivity of DEA Amine Pressure To CO_2 Composition In Sweet Gas At a Temperature 60°C

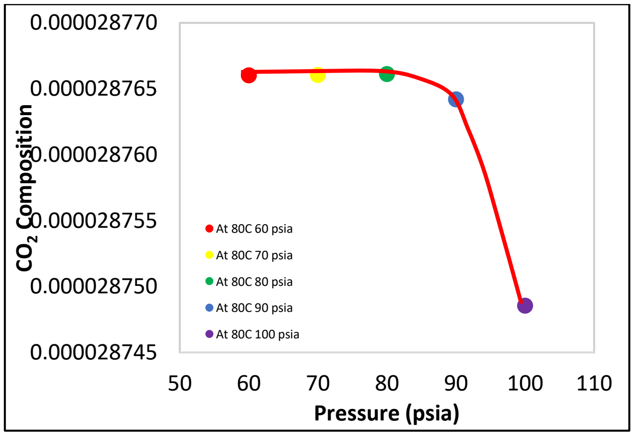

Figure 10 The Sensitivity of DEA Amine Pressure To CO_2 Composition In Sweet Gas At a Temperature 80°C

Figure 8 displays that at 40°C, the CO_2 composition exhibits an increasing trend with higher pressures. As pressure rises, the CO_2 concentration in the sweet gas slightly increases, indicating that higher pressures at this temperature slightly reduce absorption efficiency. This change in behavior compared to 20°C suggests that the effect of pressure on CO_2 absorption is sensitive to temperature, and there may be an optimal pressure range that maximizes absorption at each temperature.

Figure 9 shows that at 60°C, the relationship between pressure and CO_2 composition follows a U-shaped curve. The CO_2 concentration initially decreases as pressure rises from 60 psia to 80 psia, reaching a minimum, but then increases as pressure continues to increase up to 100 psia. This indicates that there is an optimal pressure (around 80 psia) at which CO_2 absorption is maximized at 60°C, while both lower and higher pressures at this temperature result in slightly reduced absorption.

Figure 10 illustrates that at 80°C, the CO_2 composition decreases as pressure increases from 60 psia to around 90–100 psia. The decline is more pronounced at higher pressures, with the CO_2 composition reaching its lowest point at 100 psia. This suggests that at higher temperatures (80°C), increasing pressure continues to enhance CO_2 absorption, with maximum efficiency achieved at the highest tested pressure.

All results indicate that the effect of pressure on CO_2 absorption efficiency is temperature-dependent. At lower temperatures (20°C), increasing pressure consistently enhances CO_2 absorption. However, as temperature rises to 40°C and 60°C, the influence of pressure becomes more complex, showing both increases and decreases in CO_2 composition, depending on the specific pressure range. At 80°C, higher pressures again support better CO_2 absorption, indicating a return to a more straightforward relationship.

The results suggest that there may be an optimal pressure for each temperature to achieve maximum CO_2 absorption. For instance, at 60°C, the optimal pressure appears to be around 80 psia, while at 80°C, higher pressures near 100 psia are more effective These findings highlight the importance of balancing temperature and pressure settings in DEA-based gas sweetening processes. Operators can adjust these parameters to optimize CO_2 removal efficiency, potentially leading to energy and cost savings by selecting the most efficient pressure and temperature combination for their specific operating conditions.

The CO_2 composition in sweet gas exhibits varied responses to pressure increases from 60 psia to 100 psia, highlighting the nuanced role of pressure in the CO_2 absorption process at different temperatures. In Figure 7, a consistent decrease in CO_2 composition with rising pressure indicates that higher pressures enhance CO_2 absorption efficiency at this temperature, likely due to increased solubility of CO_2 in the DEA solution. In contrast, Figure 8 shows an upward trend in CO_2 composition as pressure increases, suggesting that at this temperature, higher pressures may actually hinder absorption efficiency, potentially due to changes in reaction kinetics or solvent behavior under different thermal conditions.

Figure 9 presents a more complex pattern: CO_2 composition initially decreases with increasing pressure up to 90 psia, but rises sharply as pressure reaches 100 psia, suggesting an optimal pressure range around 60–90 psia for maximizing CO_2 absorption at this temperature. Similarly, Figure 10 demonstrates a stable CO_2 composition from 60 psia to 80 psia, followed by a marked decrease from 80 psia to 100 psia, indicating that higher pressures enhance absorption only beyond a certain threshold.

These observations underscore the critical role of pressure in optimizing CO_2 absorption. Properly maintaining pressure within optimal ranges is essential, as it directly influences the interaction between CO_2 and the DEA solution in the absorber, impacting overall sweetening efficiency. Fine-tuning pressure based on temperature conditions can thus lead to more effective CO_2 removal, improving both the performance and cost-efficiency of the gas sweetening process.

c) Sensitivity of DEA Amine Concentration to CO_2 Composition

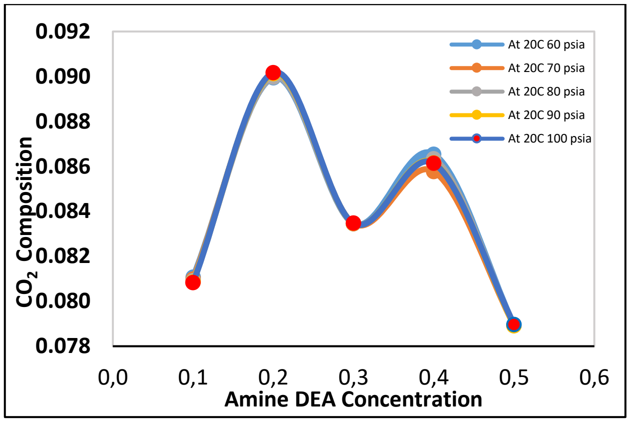

Figure 11 The Sensitivity of DEA Amine Concentration to CO_2 Composition in Sweet Gas At a Temperature 20°C’

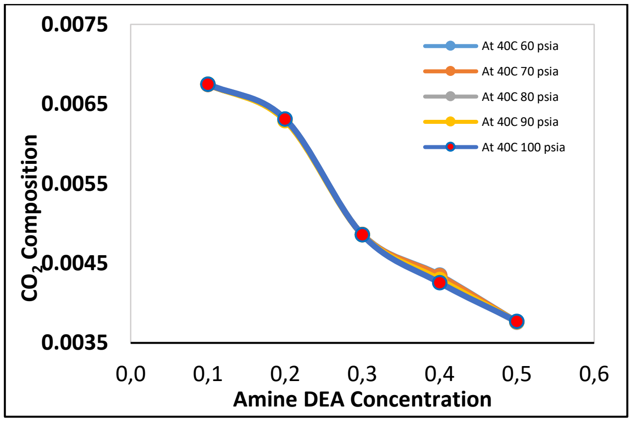

Figure 12 The Sensitivity of DEA Amine Concentration to CO_2 Composition in Sweet Gas At a Temperature 40°C

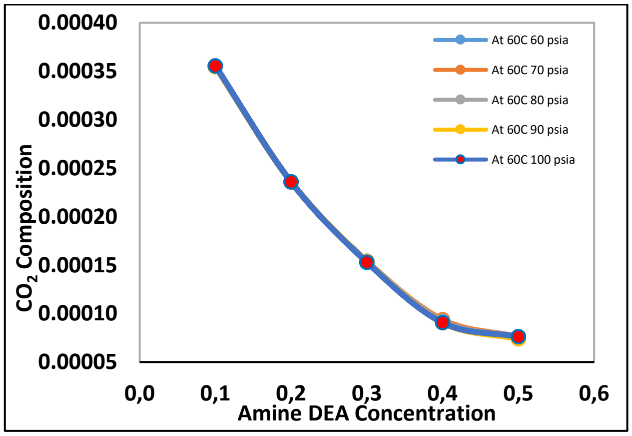

Figure 13 The Sensitivity of DEA Amine Concentration to CO_2 Composition in Sweet Gas At a Temperature 60°C

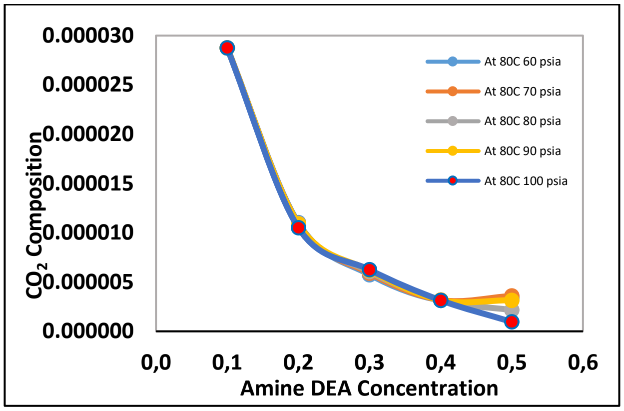

Figure 14 The Sensitivity of DEA Amine Concentration to CO_2 Composition in Sweet Gas At a Temperature 80°C

Figures 11 to 14 illustrate the relationship between DEA (Diethanolamine) concentration and CO_2 composition in sweet gas across different temperatures (20°C, 40°C, 60°C, and 80°C) and pressures (60–100 psia). Each graph represents a specific temperature, allowing us to observe how varying the DEA concentration influences CO_2 absorption at different thermal and pressure conditions. Across all graphs, increasing DEA concentration generally reduces CO_2 composition, but the effect is more pronounced at higher temperatures. At 20°C, the CO_2 absorption process is less stable, with fluctuations indicating inconsistent absorption efficiency. As the temperature rises to 40°C, 60°C, and 80°C, the effect of DEA concentration on reducing CO_2 becomes more stable and predictable.

Higher temperatures (60°C and 80°C) combined with increased DEA concentrations (0.4–0.5 moles) are the most effective conditions for CO_2 absorption. At these temperatures, the DEA solution shows strong and consistent CO_2 removal performance, achieving near-zero CO_2 composition in sweet gas at higher concentrations. While pressure plays a role in CO_2 absorption efficiency, its impact diminishes at higher DEA concentrations and temperatures. At 80°C, increasing DEA concentration alone is sufficient to reduce CO_2 levels, regardless of pressure variations.

These findings suggest that for optimal CO_2 removal in industrial applications, operating at elevated temperatures (60–80°C) with higher DEA concentrations (around 0.4–0.5 moles) is ideal. This setup not only enhances CO_2 absorption efficiency but also reduces dependency on pressure adjustments, potentially lowering operational costs. The figures reveal how CO_2 composition in sweet gas responds to increasing DEA concentrations (from 0.2 to 0.6 moles), with distinct absorption patterns emerging across different temperature conditions.

In Figure 11 (20°C), CO_2 composition exhibits erratic fluctuations as DEA concentration rises, indicating instability in absorption efficiency at lower temperatures, where the reaction kinetics may be too slow to sustain consistent CO_2 removal. This suggests that lower temperatures may hinder the solvent's performance, leading to unpredictable absorption behavior.

In Figure 12 (40°C), CO_2 composition decreases more predictably with higher DEA concentrations, yet there is a substantial drop between 0.3 and 0.4 mole concentrations. This pronounced gap suggests a critical concentration threshold at 40°C, beyond which DEA's CO_2 absorption capacity significantly improves, likely due to enhanced molecular interactions at this temperature.

Figures 13 and 14 (60°C and 80°C) show a stable and continuous decline in CO_2 composition as DEA concentration increases, with each increment yielding a more efficient reduction in CO_2 levels. The 80°C graph (Figure 14) demonstrates the most effective CO_2 absorption, with composition levels dropping sharply and consistently, underscoring the optimal synergy between high temperature and elevated DEA concentrations. Notably, CO_2 composition at 80°C is considerably lower than at 60°C across all concentration levels, highlighting the role of higher temperatures in maximizing CO_2 absorption efficiency.

These observations suggest that while increasing DEA concentration generally enhances CO_2 absorption, the process becomes markedly more efficient at higher temperatures, where both reaction kinetics and solvent capacity are optimized. For industrial applications, operating at temperatures of 60°C or higher with DEA concentrations around 0.4 to 0.6 moles can achieve superior CO_2 removal, offering a stable and predictable performance essential for effective gas sweetening operations.

This study offers a comprehensive analysis of CO_2 absorption efficiency in gas sweetening using Diethanolamine (DEA) under varying temperatures, pressures, and concentrations. The findings underscore the complex interplay between these parameters, revealing that each factor significantly impacts the DEA's ability to capture CO_2 and achieve target purity levels in sweet gas.

To strengthen the relevance of this study, the results obtained were compared with findings from previous studies and fundamental principles of chemical absorption. The observed trend that increasing DEA temperature up to 60–80°C significantly enhances CO_2 absorption is consistent with recent experimental results, who demonstrated that the reaction kinetics between CO_2 and secondary amines such as DEA increase with temperature due to improved molecular agitation and reduced solvent viscosity, enhancing mass transfer rates [32]. Similarly, the observed that an optimal temperature range of 60–70°C yielded the highest CO_2 loading capacity with minimal energy penalty during regeneration in a packed column absorber [33].

Moreover, our identification of a critical DEA concentration threshold (0.4–0.5 mol) aligns with work, who reported that beyond a certain amine concentration, the increase in CO_2 absorption rate becomes less pronounced, due to solvent saturation and limited CO_2 partial pressure [34]. This supports the simulation outcome where DEA concentrations beyond 0.5 mol did not substantially reduce CO_2 composition further.

Regarding pressure sensitivity, our findings indicate that pressure plays a secondary but complex role. This is in line with the principles outlined, who found that while pressure increases CO_2 solubility (in accordance with Henry's Law), its effect becomes less dominant when absorption kinetics are temperature-controlled and the solvent is near saturation [35].

Overall, the consistency between our simulation-based observations and recent experimental studies strengthens the validity of the proposed operational window. Furthermore, these findings support the thermodynamic theory that temperature influences the reaction enthalpy, while concentration drives equilibrium conversion, both critical to optimizing absorber performance [36]. Thus, this study contributes to the body of knowledge by providing a validated simulation-based approach for identifying optimal operating conditions for DEA-based CO_2 absorption systems.

4.0 CONCLUSION

The study highlighted temperature as a critical factor in CO_2 absorption efficiency. At lower temperatures (20°C), CO_2 absorption was inconsistent, likely due to slower reaction kinetics that reduced solvent effectiveness. However, as temperatures increased to 40°C, 60°C, and 80°C, DEA's performance in capturing CO_2 improved markedly, achieving near-complete removal at higher DEA concentrations. This trend reflected that elevated temperatures not only enhanced reaction rates but also stabilized the absorption process, allowing for consistent and predictable CO_2 reduction.

While pressure played a role in influencing CO_2 absorption, its impact varied depending on the temperature. At lower temperatures, higher pressures generally aided in CO_2 capture, but as temperature increased, the effect of pressure became less pronounced. Notably, at 80°C, CO_2 composition decreased steadily across all tested pressures, indicating that high temperatures could reduce dependency on pressure adjustments, thus simplifying operational requirements.

The study revealed that DEA concentration had a profound impact on CO_2 composition, with a critical threshold observed around 0.4 to 0.5 moles. At 40°C, a notable improvement in CO_2 absorption occurred between 0.3 and 0.4 mole concentrations, suggesting that this range represented a tipping point where DEA's capacity to absorb CO_2 significantly strengthened. At higher temperatures, increasing DEA concentration continued to yield lower CO_2 levels, reinforcing the synergy between concentration and temperature in maximizing absorption efficiency.

Based on the findings, the optimal conditions for effective CO_2 removal in industrial gas sweetening processes included a temperature of 60–80°C, a pressure range adjusted to maintain stability (with less dependency as temperature rose), and DEA concentrations between 0.4 and 0.6 moles. Under these conditions, DEA's CO_2 absorption capacity was maximized, ensuring minimal CO_2 composition in sweet gas and providing a stable, efficient, and cost-effective solution for gas treatment.

It is important to note that this study was conducted entirely through simulation using Aspen HYSYS V.10 and does not include direct experimental validation or benchmarking against real industrial datasets. While the simulation provides valuable insights and trends consistent with fundamental gas absorption principles, future work should focus on experimental validation under actual field conditions or pilot-scale units. Comparison with industrial data would further strengthen the findings and enhance the applicability of the recommended operating parameters. Collaborative studies with gas processing facilities are recommended to validate the model and improve its predictive accuracy for full-scale implementation. These insights can guide operational strategies for gas processing plants targeting high-efficiency CO_2 removal with minimal solvent loss and energy expenditure.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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