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Carbon-Dioxide Capture in Simulated Gas Stream

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Abstract: The solubility of CO_2 determined by an aqueous blend of (TSP+PZ+K-Lys) were experimentally investigated to obtained new data on CO_2 loading at total concentrations ranging from (1.0 to 3.0) mol.kg-1, temperature between (303.07 to 353.07) K and CO_2 partial pressure ranging from (10.08 to 20.08) kPa with the help of a bubbling absorber. The results were compared to data available in the literature, the (TSP+PZ+K-Lys) blend demonstrated higher CO_2 absorption capacity, indicating that this blend could serve as an efficient and promising absorbent for CO_2 capture applications.

Keywords: *CO_2 Solubility, Chemical Absorption, Sustainable CO_2 Capture, Solvent Utilization, Potassium Lysinate, TSP.*

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I. INTRODUCTION

Greenhouse gases (GHG) are the primary contributors to air pollution in the atmosphere, and their impacts are increasingly severe in recent years. Among these gases, carbon dioxide accounts for nearly 75%, while the remaining portion consists of other gases such as nitrous oxides (N_2O), methane (CH_4), Sulphur oxides (SO_2), hydrogen, and others. Carbon dioxide is the most dominant greenhouse gas occurred by man-made activity and between the period of 1970-2004, its annual emission grew up by 80% [1]. Generally, the major sources of CO_2 emission are from industrial processes, transportation, energy sector and combustion of fossil fuels etc. [2]. The dominant contribution of carbon dioxide makes it particularly harmful, leading to adverse effects on human health and causing significant environmental damage. As a result, global warming and climate change have emerged as critical issues.

Over the past three to four decades, several technologies have been introduced to overcome this problem. Basically, there are three major technologies for carbon capture like- pre-combustion, post-combustion and oxy-fuel combustion.[3] The Purpose of pre-combustion is to eliminate the carbon dioxide before combustion takes place. In this method of capture, fuels are firstly gasified with oxygen and steam and converting into synthesis gas mainly carbon monoxide (CO) and hydrogen (H_2) and then synthesis gas undergoes steam reforming process followed by water jet reaction that converts carbon monoxide into carbon dioxide and hydrogen, and H_2 is uses for hydrogen-based power generation [4]. Post-combustion capture is the process that focuses on removing carbon dioxide from flue gases after combustion of fossil fuels [4]. Several techniques are employed for this process- adsorption [5], chemical absorption [6], membrane separation [3], cryogenic separation [7], chemical looping [8], algae-based separation [9]. The oxy-Fuel combustion comprises of burning of fossil fuels in pure oxygen instead of air that producing flue gases mainly contains carbon dioxide (CO_2) and water vapour (H_2O), that can easily capture and stored.

Currently, chemical absorption is the most effective method for capturing carbon dioxide. For this process, a chemical solvent is used for capturing CO_2. Some of the commonly used chemical absorbents are Tri-Sodium Phosphate (TSP) [10], piperazine (PZ) [11], potassium lysinate (K-Lys)[12], monoethanolamine (MEA)[13], diethanolamine (DEA)[14], triethylamine (TEA)[15], N-methyl diethanolamine (MDEA)[16], 2-amino-2-methyl-1-propanol (AMP)[17], diisopropanolamine (DIPA)[18], diglycolamine (DGA)[19], ammonia [20], sodium hydroxide (NaOH) [21], Ca $(OH)_2$ [22]. Recently, new development emerged in carbon capture technology as uses of blended absorbents that provides faster absorption efficiency, lower energy requirements and enhanced absorption capacity.

In these experimental studies, a blended absorbent comprising of tri-sodium phosphate (TSP), piperazine (PZ) and potassium lysinate (K-Lys) was utilized. TSP is an inorganic compound that acts as a buffering and promoting agent, it enhancing the CO_2 absorption rate and improving overall stability of the solvent. PZ is an amine compound used as an activator in CO_2 absorption processes. It is recognized for its fast reaction rate and resistance to thermal and oxidative degradation [23]. It having high absorption rate and absorbing efficiency than other solvents like MEA, DEA. Potassium lysinate (k-Lys) is an amino acid-based salt that enhance the

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overall absorption rate and minimizes solvent degradation and considered as eco-friendly absorbent for CO_2 capture processes due to its low volatility and low toxicity and biodegradability. Therefore, to achieve high CO_2 absorption efficiency, a blend consisting of the amine piperazine (PZ) as a strong activator, the inorganic absorbent trisodium phosphate (TSP) as a promoting agent and amino acid-based salt potassium lysinate (K-Lys) as minimizing solvent degradation was used for experimental studies.

The present work is aimed to achieve a higher CO_2 absorption rate compared to previous findings and to identify an efficient absorbent for CO_2 capture. Experiments were conducted within a temperature range of (303.07 to 353.07) K, using total absorbent concentrations between (1.0-3.0) mol.kg^{-1} and CO_2 partial pressure ranging from (10.08 to 20.08) Kpa.

Table 1 Experimental Conditions Used in this Present Work

Sl. No.	Parameter	Data
01	CO_2 partial pressure in inlet (pCO_2)/kPa	10.133 – 20.265
02	Temperature of liquid (T)/k	303.14-353.14
03	Volume of the liquid /cm³	150
04	pH of the distilled water	6.95
05	Mole ratio of blend (TSP +PZ) (X1)	0.5-3
06	Total amine concentration (C_T)/mol.dm^{-3}	1.0-3.0

II. MATERIALS AND METHODS

➢ *Materials*

Various chemical and apparatus are used for the experimental studies. The absorbent included TSP (Sisco Research Laboratories Pvt. ltd., Mumbai) of minimum purity 98.5% and PZ (Sisco Research Laboratories Pvt. ltd., Mumbai) of minimum purity of 98% and Potassium lysinate (Tokyo Chemical Industry (India) Pvt. Ltd.), of minimum purity 97%. The constant temperature water bath (CE 404, Narang Scientific Works Pvt. Ltd., New Delhi, India) having a temperature range of 273-473 K and an accuracy of ±0.1 was utilized to maintain desired absorbents temperature during experiments. The other chemicals used in the experiments included sodium hydroxide (NaOH), hydrochloric acid (HCL), barium chloride ($BaCl_2$) each with a minimum purity of 99%. The distilled water is used in the experiment to prepare blend absorbent of (TSP+ K-Lys+ PZ) and other solutions preparation. The TSP having molecular weight of 163.94 g/mol and PZ having molecular weight of 86.14 g/mol and K-Lys having 185.29 g/mol. A gas cylinder having composition of 20% CO_2 with 80% N_2, along with another cylinder containing 99.99% pure nitrogen was used. The gases were mixed in mixing chamber to obtained the required initial CO_2 concentration in the gas stream.

➢ *Methods*

The absorption of CO_2 into the aqueous blend of (TSP+PZ+K-Lys) was carried out in a bubbling absorber. The bubbling absorber is made of borosilicate glass filled with an absorbent solution of (TSP+PZ+K-Lys) blend which was immersed in a constant temperature water bath, maintained at a uniform temperature through the experiment. The water bath temperature and liquid temperature were monitored by thermometer with a precision of 0.1 K. The schematic representation of the experimental setup was explained and labelled in Fig. 1, and the experimental conditions used in this present work are listed on table 1.

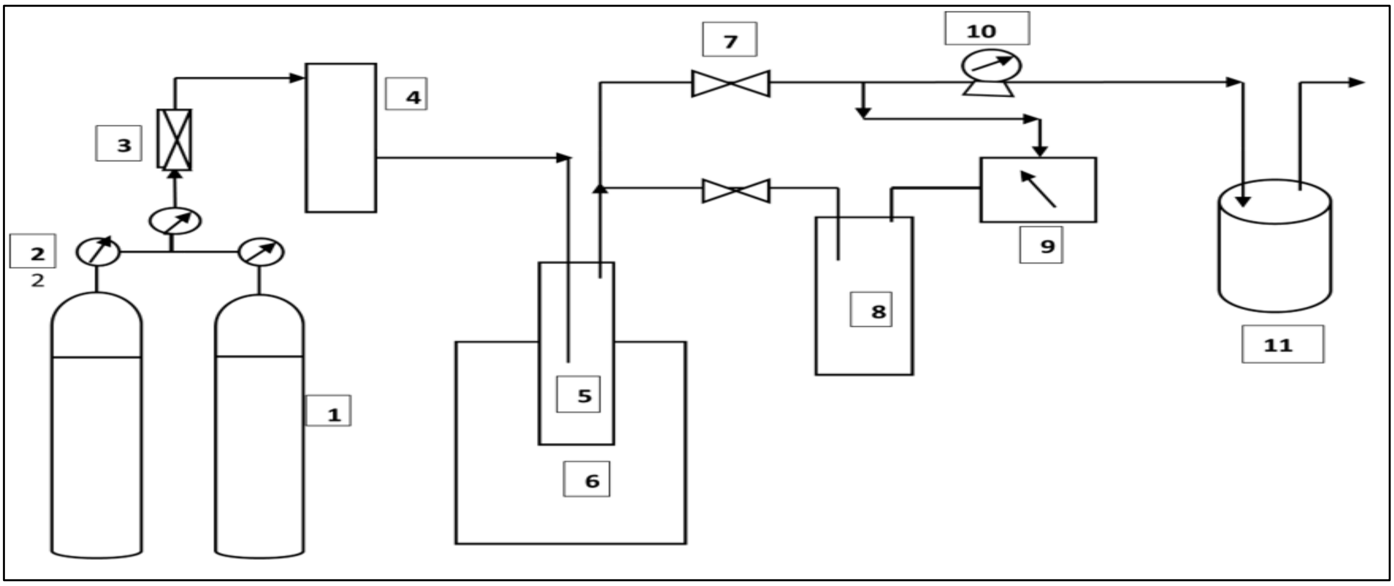

Fig 1 Experimental Set-up for Bubble Column: 1, Gas Cylinder (CO_2 and N_2); 2, Two-Stage S.S. Pressure Regulator; 3, Gas Rotameter; 4, Gas Mixing and Pressure Release Chamber; 5, Bubble Column; 6, Constant Temperature Water Bath; 7, S.S. Valve; 8, Moisture Trap Column; 9, CO_2 Analyzer; 10, Wet Gas Flow Meter; 11, Flask with Absorbing Solution

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The bubble column with a capacity of approximately 150 cm^3, was filled with an aqueous blend of (TSP+K-Lys+PZ) and placed in water bath to ensure a constant temperature was achieved. Then, the main gas stream is slowly turned on and maintained a minimum gas flow rate, allowing the CO_2- N_2 mixture to bubble through the liquid. After interval of 10 min, the CO_2 compositions in both inlet and outlet gas stream was measured using microprocessor-based CO_2 analyzer (UNIPHS). Once equilibrium was achieved in both streams, the solubility of CO_2 was measured by standard titration method with 0.1 N of HCL solution using phenolphthalein as indicator followed by methyl orange indicator, until the titration end point was achieved. Titration was carried out on two or more sample to check the reproducibility of data. Various experimental data of CO_2 capture in total aqueous blend was reported in table 2,3,4,5.

III. CO_2 SOLUBILITY MODEL

The chemical reaction equilibrium and gas-liquid phase equilibrium occurring simultaneously for the blend of (TSP+PZ+K-Lys+CO_2+H_2O), when CO_2 is absorbed into an aqueous solution of (TSP+PZ+K-Lys) with distilled water, the following reaction may occur.

Reaction of TSP (Na_3PO_4) with CO_2

$CO_2(g) + H_2O \leftrightarrow HCO_3^- + H^+$ [24]
$HCO_3^- \leftrightarrow CO_2^{3-} + H^+$ [25]
$CO_2(g) + Na_3PO_4 \cdot 12H_2O \leftrightarrow Na_2HPO_4 \cdot 7H_2O(s) + NaHCO_3(s) + 4H_2O$ [11]

Reaction of PZ with CO_2

$CO_2(g) + H_2O \leftrightarrow HCO_3^- + H^+$ [24]
$PZ + CO_2 + H_2O \leftrightarrow PZCOO^- + H_3O^+$ [26]
$CO_2 + PZCOO^- + H_2O \leftrightarrow PZ(COO)_2 + H_3O^+$ [26]
$PZCOO^- + H_3O+ \leftrightarrow H^+PZCOO^- + H_2O$ [26]

Reaction of K-Lys with CO_2

$CO_2(g) + H_2O \leftrightarrow HCO_3^- + H^+$ [24]
$HCO_3^- \leftrightarrow CO_2^{3-} + H^+$ [25]
$CO_2 + {}^+H_3N\text{-}R_2R_1CH\text{-}NH^2 + B \leftrightarrow {}^+H_3N\text{-}R_2R_1CH\text{-}NHCOO^- + BH^+$ [24]
${}^+H_3N\text{-}R_2R_1CH\text{-}NHCOO^- + H_2O \leftrightarrow {}^+H_3N\text{-}R_2R_1CH\text{-}NH_2 + HCO_3^-$ [25]

Reaction of TSP+ K-Lys+PZ with CO_2

$CO_2 + Na_3PO_4.12H_2O + PZ + K\text{-}Lys \leftrightarrow Na_2HPO_4.7H_2O(s) + PZCOO^- + ({}^+H_3N\text{-}Lys\text{-}NHCOO^-) + H_3O^+ + (Water)$

IV. RESULTS AND DISCUSSIONS

The solubility of CO_2 in an aqueous blend of (TSP+PZ+K-Lys) was examined at total concentrations ranging from (1.0 to 3.0) $mol.kg^{-1}$, within a temperature range of (303.07 to 353.07) K and CO_2 partial pressure ranging between (10.08 to 20.08) Kpa. The corresponding experiment results for CO_2 loading are presented in table 2,3,4,5.

To study the effect of total amine concentration which varies from (1.0 to 3.0) $mol.kg^{-1}$ on CO_2 solubility, the experiments were performed at 313.07 K temperature and partial pressure at 15.4 Kpa and the mole ratio of TSP to PZ to K-Lys was maintained at 0.9 within the overall amine concentration of blend, as illustrated in figure 2. From figure 2, It is clear that there is decrease in CO_2 solubility with the increase in absorbent concentrations of blend.

Table 2 Experimental Data for CO_2 Capture in Total Aqueous (TSP+PZ+K-Lys) Blend Concentrations at X1= 0.9, p_{CO2}= 15.4 kPa and T= 313.07 K

(CT)/mol· (kg H_2O)$^{-1}$	**CO_2 Loading**
1.0	0.892
1.5	0.791
2.0	0.750
2.5	0.699
3.0	0.610

➢ *Graphical Representation*

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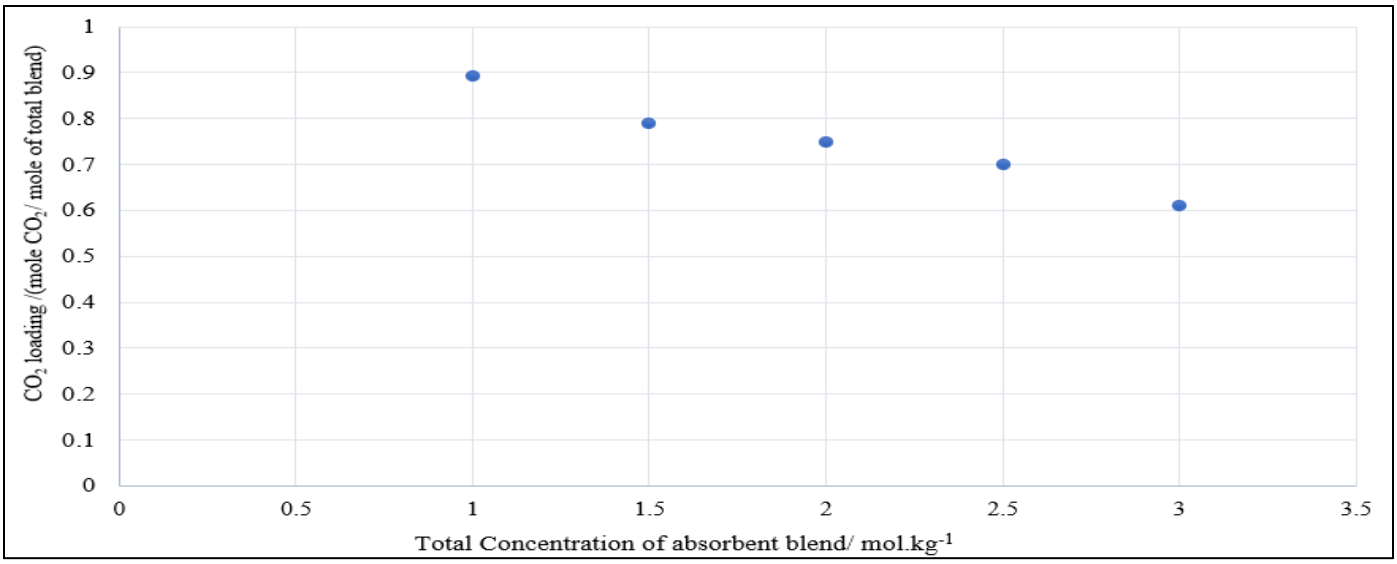

Fig 2 Study of the CO_2 Capture in Total (TSP+PZ+K-Lys) Blend Concentration at pCO_2 = 15.4 kPa, T =313 K, and Mole Ratio of TSP to PZ to K-Lys in the Aqueous Blend = 0.8

For studying the effect of partial pressure on CO_2 loading, experiments were conducted at a temperature of 313.07 K, with inlet partial pressure ranging from (10.08 to 20.08) Kpa and mole ratio varying from (0.5 to 3) in 1 mol.kg^{-1} absorbent concentrations, as shown in figure 3. From Figure 3, the results demonstrates that there is increase in CO_2 loading with the increase in inlet partial pressure.

Table 3 Experimental Data for CO_2 Capture with Different Partial Pressure in Inlet Gas (CO_2+N_2) Stream at C_T = 2.0 mol. (kg H_2O)$^{-1}$ and T= 313.07 k

pCO_2/ kPa	**X1**				
	3	**2.5**	**2**	**1.5**	**1**
	CO_2 Loading	**CO_2 Loading**	**CO_2 Loading**	**CO_2 Loading**	**CO_2 Loading**
10.18	0.748	0.709	0.655	0.624	0.578
12.87	0.787	0.736	0.674	0.634	0.609
15.29	0.817	0.755	0.699	0.657	0.624
17.24	0.868	0.783	0.713	0.682	0.636
20.36	0.889	0.817	0.785	0.701	0.648

➢ *Graphical Representation*

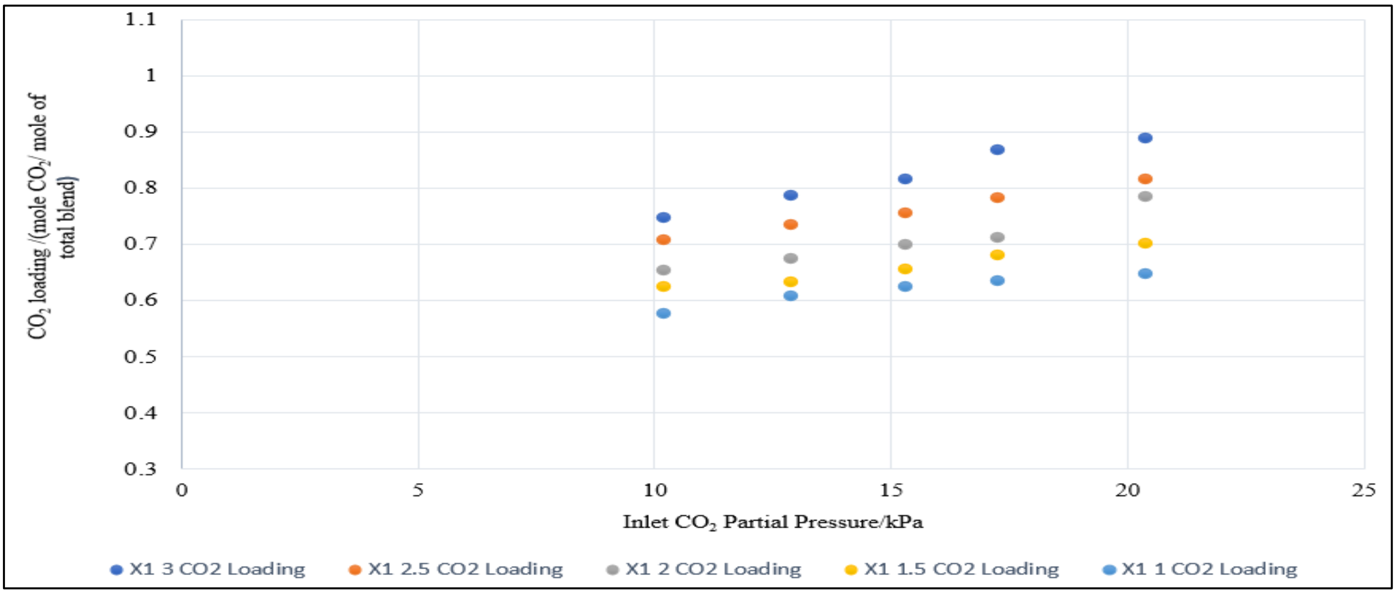

Fig 3 Study the Effect of CO_2 Partial Pressure in Inlet Gas (CO_2 + N_2) Stream on CO_2 Capture at T=313.07 K, Total Absorbent (TSP+PZ+K-Lys) Blend Concentration of 2.0 Mol.kg^{-1} and Mole Ratio of TSP to PZ to K-Lys

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Similarly, to study the effect of temperature on CO_2 loading, experiments were performed at a constant inlet partial pressure of 15.4 Kpa, a mole ratio of TSP to PZ to K-Lys is 0.5 and a temperature range of (303.07 to 353.07) k at a fixed absorbent concentration of 1.0 $mol.kg^{-1}$, as expressed in figure 4. From figure 4, it is observed that with increase in temperature, the CO_2 loading doesn't decrease gradually, it decreases up to 15 to 20% with increase in temperature from (303.07 to 353.07) K. These results indicate that this blended absorbent is suitable for CO_2 capture at higher temperature.

Table 4 Experimental Data for CO_2 Capture with Different Temperature at C_T = 2.0 mol. (kg $H_2O)^{-1}$ and pCO_2 = 15.4kPa at X1 = 0.5

T/K	CO_2 Loading
303	0.889
313	0.845
323	0.798
333	0.785
343	0.768
353	0.718

➢ *Graphical Representation*

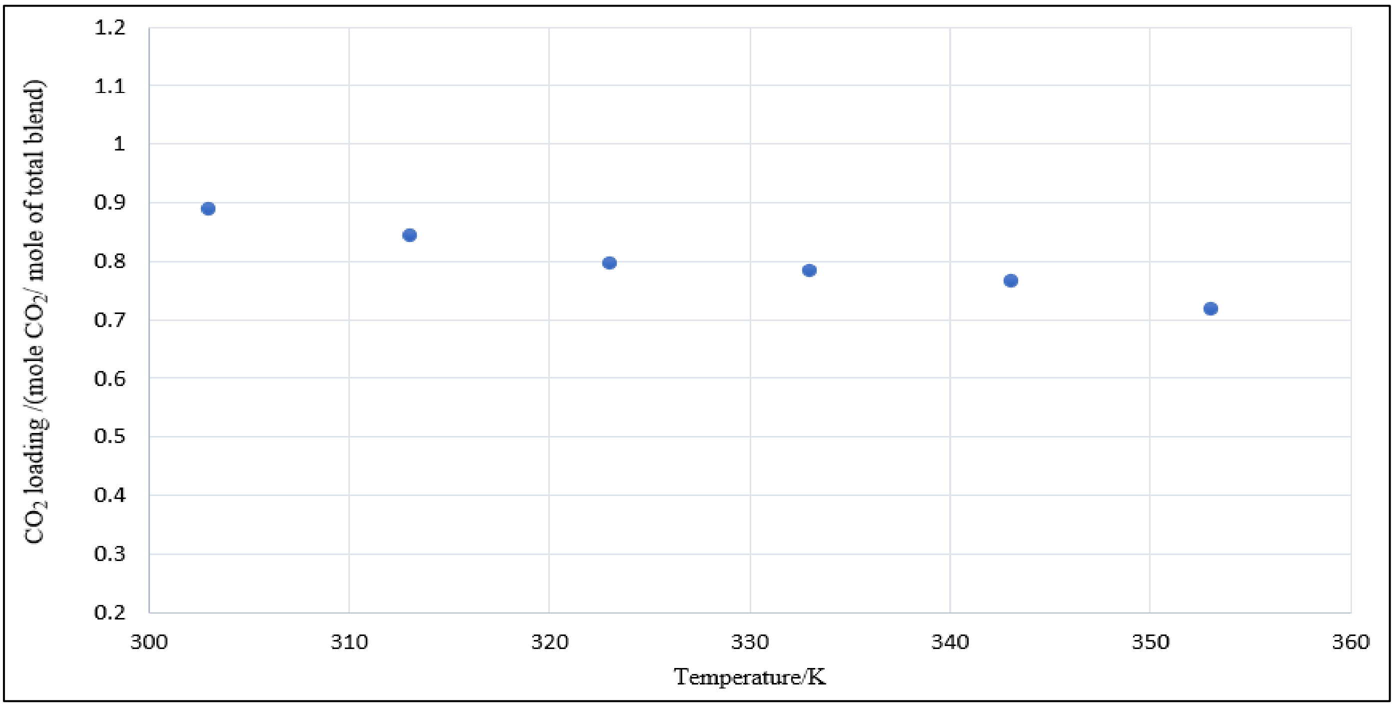

Fig 4 Study of the Effect of Temperature on CO_2 Capture in Total Aqueous (TSP+PZ+K-Lys) Blend Concentrations

And lastly, to study the effect of mole ratio of TSP to PZ to K-Lys on CO_2 absorption, experiments were carried out at 313.07 K temperature and 15.4 Kpa partial pressure with the mole ratio varied from (0.5 to 3) and fixed total amine concentration ranging from (1.0 to 2.5) $mol.kg^{-1}$, as illustrated in figure 5. From figure 5, the result is observed that the solubility of CO_2 increases with increase in mole ratio of absorbents and this result shows that the addition of TSP and K-Lys enhances the CO_2 capture efficiency of the blended system. Various blended absorbents have been reported in the literature for efficient capture of CO_2.

Table 5 Experimental Data for CO_2 Capture with Different Mole Ratio at p_{CO2} = 15.4kPa and T= 313k

X1	C_T/ mol. (kg $H_2O)^{-1}$			
	1.5	2.0	2.5	3.0
	CO_2 Loading	CO_2 Loading	CO_2 Loading	CO_2 Loading
0.5	0.751	0.734	0.703	0.684
1.0	0.754	0.737	0.705	0.687
1.5	0.758	0.740	0.708	0.691
2.0	0.761	0.743	0.711	0.695
2.5	0.764	0.747	0.715	0.697
3.0	0.769	0.750	0.719	0.701

➢ *Graphical Representation*

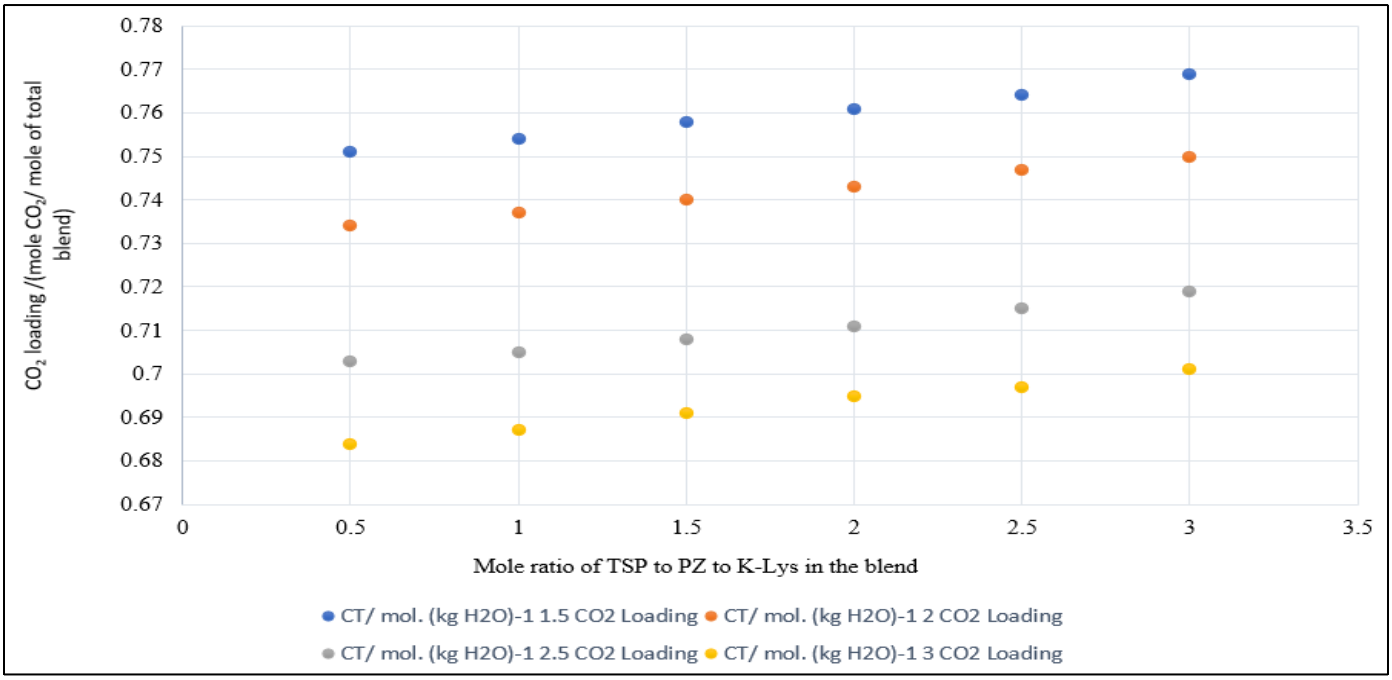

Fig 5 Study of the CO_2 Capture with Different Mole Ratio of TSP to PZ to K-Lys in the Aqueous Blend at pCO_2 = 15.4 kPa, T= 313 K and Total (TSP+PZ+K-Lys) Blend Concentration

In the present work, various key parameters were considered to evaluate the performance of blends containing (TSP+PZ+K-Lys) such as CO_2 partial pressure, temperature, total absorbent concentration and mole ratio.

V. CONCLUSION

In this work, the solubility of CO_2 determined by an aqueous blend of (TSP+PZ+K-Lys) were experimentally investigated to obtained new data on CO_2 loading at total concentrations ranging from (1.0 to 3.0) mol.kg-1, temperature between (303.07 to 353.07) K and CO_2 partial pressure ranging from (10.08 to 20.08) KPa with the help of a bubbling absorber. The results showed that, the solubility of CO_2 increases with increases in inlet partial pressure but decreases with increases in temperature. compared to data available in the literature, the (TSP+PZ+K-Lys) blend demonstrated higher CO_2 absorption capacity, indicating that this blend could serve as an efficient and promising absorbent for CO_2 capture applications.

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