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Integration of CO₂ capturing from flue gases using Aqueous Ammonia for Low Emissions Urea Production



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Abstract

Carbon Capture and Utilization is one the potential solution to mitigate global warming. In this study, aqueous ammonia is used for capturing CO_2 from flue gases, the produced slurry is then utilized for urea production. In this work, modification is conducted to the original solid controlled formation chilled ammonia process. During this, ammonium carbonate slurry is produced, which can play a crucial part as intermediate element in urea synthesis. Process stream integration and waste energy utilization are considered in many points, in addition to, urea revamp to accommodate this modification.

The proposed modification is simulated in Aspen Plus using extended thermodynamics model. Due to this modification and process integration, the regeneration section and effluent treatment section were completely removed which greatly decreased energy consumption. It is found that, energy consumption in the solid controlled formation process decreased by 23.4%. Moreover, through the proposed energy integration with the urea production plant, a zero-energy consumption is reached together with an increase in urea production by 8 t/hr. This also has an environmental impact as the amount of associated CO_2 emissions decreased by 6% which affected the carbon footprint of the plant. Our work is in agreement with the United Nation Sustainable Development Goals; goals number 2, 7 and 13. Utilizing carbon dioxide emissions initiated a transformative shift in industrial practices in alignment with sustainability requirements.

Keywords: Carbon Capture and Utilization (CCU), Aqueous Ammonia Process, Post-combustion Capture, Urea Production, Carbon Footprint, Sustainable Urea.

1. Introduction

In 2023, about 37.4 billion tons of carbon dioxide (CO₂) was emitted to the atmosphere [1], which increased the impact of global warming. According to International Panel of Climate Change (IPCC) [2], cooperative efforts are needed to limit the increase in global average temperature to below 2° C compared to the pre-industrial level. To achieve this goal, global CO₂ emissions must be reduced by 50% by the year 2050 [3]. Around 25% of global greenhouse gases (GHGs) emissions come from the industrial sectors [4]. Carbon capture and storage (CCS) is used to reduce direct CO₂ emissions from point sources such as industrial processes and power plants. CO₂ is captured then transported and stored in underground aquifers. This prevents CO₂ from entering the atmosphere and contributing to climate change. CCS can be integrated with conventional industrial processes where the captured CO₂ is used as a feedstock for the production of various chemicals and fuels [5]. According to current studies [6], about 2500 CCS units with a capacity of 1.5 million tons of CO₂ absorption per year should be utilized by 2040 to limit the average world temperature increase to below 2 °C compared to the pre-industrial level. There are three main types of CCS technologies: pre-combustion, oxy-fuel, and post-combustion. Post-combustion capture is the most suitable and readily available technology for the industrial sector because it can be easily retrofitted to existing installations without disrupting operations [4-5]. In post-combustion capture, CO₂ can be directly captured from flue gases, however, its implementation is governed by economic and environmental factors, such as operating cost and energy consumption Amine scrubbing is the most accepted and reliable choice by many petrochemicals-based industries. The CO₂

however, its implementation is governed by economic and environmental factors, such as operating cost and energy consumption. Amine scrubbing is the most accepted and reliable choice by many petrochemicals-based industries. The CO_2 recovery rate using amines is about 98%, and the purity of CO_2 is more than 99% [7] when using low concentration CO_2 streams. Although amine scrubbing is a mature technology, it has many drawbacks; high energy consumption, corrosivity, and toxicity. Researchers are currently examining and developing new solvents to address these challenges [8].

*Corresponding author e-mail: <u>rehab.elmaghraby@suezuniv.edu.eg</u>.; (Rehab M. El-Maghraby). Receive Date: 21 May 2024, Revise Date: 26 July 2024, Accept Date: 28 July 2024 DOI: 10.21608/ejchem.2024.291337.9749 ©2025 National Information and Documentation Center (NIDOC) CO₂ capturing from flue gases using aqueous ammonia is currently under investigation to replace traditional amine-based technologies. It was found that aqueous ammonia has high affinity to CO₂, and low regeneration energy [9] when compared to amine. However, using aqueous ammonia as a solvent has some challenges, such as high auxiliary loads for chilling and for controlling ammonia emissions, and the formation of solids at high ammonia concentrations and high CO₂ loadings [10-11]. These challenges can increase cost and introduce operational difficulties; hence, more investigation is needed [12].

The first ammonia-based technology is the chilled ammonia process (CAP); where high concentration aqueous ammonia (nearly 28 wt.%) is used at low temperature below 10 °C to capture CO₂. The CO₂-rich solution is pumped to a regeneration unit where the CO₂ is stripped out and compressed for storage or use [13]. The main challenges of the CAP are the high energy consumption rate associated with cooling, ammonia slip and wash water regeneration [13]. Moreover, solid precipitation at high ammonia concentrations and high CO₂ loadings is a critical challenge that can lead to equipment clogging, plant shutdown, and increased costs. The second ammonia-based technology is Commonwealth Scientific and Industrial Research Organization (CSIRO) process which uses low concentration aqueous ammonia (6 wt.%) in order to avoid solid formation in compensation for the efficiency of the process [14]. However, it has high energy consumption rate associated with liquid circulation and CO₂ stripping from the aqueous ammonia solution [10,15]. The third ammonia-based technology is the Research Institute of Industrial Science and Technology (RIST) process; in this process, low concentration aqueous ammonia solution less than 10% is used. It is an energy intensive process; however, Rhee et al. [16-17] outlined the economic feasibility of this process by recovering low- and mid-temperature waste.

Follow-up researchers devised other possible solutions to the solid formation challenge associated with ammonia-based technologies. According to the work done in [18-20]; solid formation and partial phase separation were used to increase the CO₂ loading of the rich stream in the CAP technology. This can reduce the flow rate and energy demand of the regeneration process. The solid-liquid interaction in the complex CO₂-NH₃-H₂O system is outlined in details in the literature [21-24]. Researchers have identified the critical conditions for solid formation in the CAP technology using a comprehensive thermodynamic analysis and the ternary phase diagrams at various conditions [20-21]. J. Gaspara and M. Arshad [19] modified the CAP technology to overcome the associated solid formation problem by adding a solid handling section to the CAP in solid controlled formation (SCF-CAP process).

According to the available data in the literature, the integration between CO_2 capturing from flue gases by using aqueous ammonia and utilizing it in urea production was not studied before. The main focus of this work is to capture CO_2 from flue gases using SCF-CAP process then utilize the resulting ammonium carbonate reach slurry to produce more urea after conducting the required adjustment. The work conducted by J. Gaspara and M. Arshad [19] was adopted in our study as a reference case. Instead of dealing with the solid waste disposal problem in the CAP technology and the global warming problem associated with CO_2 emission, an environmentally friendly solution is introduced in this study. Adjustments and modifications were investigated to utilize the solid waste for urea granules production which will increase the amount of produced urea. This work is in agreement with United Nation Sustainable Development Goals (UN SDGs) number 2, 7 and 13.

2. Methodology

2.1. CAP and SCF-CAP Technology

In a normal CAP technology, flue gases are first cooled to 30 °C then treated with an aqueous solution of ammonia in a two-stage absorber. The CO₂ rich solution is directed to a regenerator to separate the CO₂ and recover the aqueous ammonia solution. A modification is proposed in [19] to add a solid handling section to the CAP, Figure 1-(a). In the solid controlled formation CAP (SCF-CAP) process, the CO₂ rich solution exiting the absorber is sent to a saturation reactor to obtain a slurry rich in ammonium bicarbonate. The slurry is then directed to a crystallizer to maximize the solid ammonium bicarbonate content of the slurry to 70 wt.%, this is achieved by cooling down the slurry to 15 °C. The liquid and solid phases of the stream exiting the crystallizer are separated by using a filter. The slurry flows to a thermal reactor to decompose the solid ammonium bicarbonate and regenerate the solvent. The liquid coming out of the filter is mixed with the regenerated solvent and recirculated back to the first absorber. This configuration solves the challenges faced by existing aqueous ammonia capturing processes and minimizes the energy penalties associated with CO₂ capture.

2.2. Urea process.

Our study is based on the Stamicarbon urea production process. In urea production plant, ammonia and carbon dioxide are mixed under 145 bar and 108 °C in a *high-pressure carbamate condenser (HPCC)* to form ammonium carbamate. The reaction is exothermic, with a conversion rate of nearly 75%. The produced ammonium carbamate is then converted into urea and water is produced as by product in the *urea synthesis reactor* at 145 bar. In the *high-pressure scrubber*, the unreacted gases from the *urea synthesis reactor* are captured and recycled back to the *HPCC*.

The urea solution is then concentrated to 80% by stripping out the unreacted ammonia and CO_2 by using a gas stream. The water is evaporated from the urea solution to reach a concentration of about 98.5 % wt. The concentrated urea solution is then granulated to form urea granules. The process condensate, which contains ammonia, CO_2 , and urea, is directed to *Ammonia Water Tank*. The condensate is then heated in the *desorption section* to extract ammonia and CO_2 , and to decompose urea, they are then recycled back to production cycle.

2.3. Our Proposed Modification

A closer look on the CO₂ capturing process by using aqueous ammonia as a solvent, according to Eq (1 to 4), ammonium carbonate and ammonium carbamate are produced. The produced ammonium carbamate [25] according to Eq. (4) is an intermediate product in the urea production process, hence, it can be dehydrated and converted into urea according to Eq. (5) [26]. This will eliminate the need for regeneration and will reduce the associate costs.

 $CO_{2}(g) \leftrightarrow CO_{2}(aq) \quad Eq. (1)$ $2NH_{3}(aq) + H_{2}O(l) + CO_{2}(aq) \leftrightarrow (NH_{4})_{2}CO_{3}(aq) \quad Eq. (2)$ $(NH_{4})_{2}CO_{3}(aq) + CO_{2}(aq) + H_{2}O(l) \leftrightarrow 2(NH_{4})HCO_{3}(aq) \quad Eq. (3)$ $(NH_{4})_{2}CO_{3}(aq) \leftrightarrow NH_{2}CO_{2}NH_{4}(aq) + H_{2}O(l) \quad Eq. (4)$ $NH_{2}CO_{2} NH_{4}(aq) \leftrightarrow H_{2}O(l) + NH_{2}CONH_{2}(aq) \quad Eq. (5)$

The CO_2 rich solution in normal CAP technology cannot be directly integrated to an existing urea plant. This is due to the high-water content (up to 70%) in the rich solution [19], which can greatly affect the conversion of urea. In order to utilize this rich stream for urea production, the water to urea balance must be kept at nearly 1.7 mole H₂O / mole urea, this will impose high energy utilization for water evaporation. However, the slurry formation unit introduced in [19] minimized the water content in the slurry through crystallization, this will facilitate the integration between the CAP-SCF and urea production plants. In our study, modifications were done on the solid controlled formation CAP (CAP-SCF) unit [19] in order to utilize the produced slurry for urea production.

Our proposed modification and integration involve three steps: modifying the CAP-SCF unit, adjusting the produced slurry and urea revamp by using process simulation. The aim is to separate the ammonium bicarbonate slurry from the rich solution, adjust its concentration to meet the urea synthesis conditions and send it for processing in the urea plant.

2.3.1. Modified CAP-SCF Unit

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Fig. 1: (a) Schematic of CAP-SCF for CO₂ capturing [19], (b) Our proposed modification and integration between

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In the CAP-SCF [19], *Figure 1-(a)*, the flue gases are injected into two-stage absorber, to get in contact with the ammonia solution. The lean gas is produced from the top of the absorber and directed to the acid wash, *Figure 1-(a) green line*. However, in the proposed modification, *Figure 1-(b)*, the lean gas coming out from the top of the second absorber is directed to *the scrubber* in the urea production plant, see *Figure 1-(b) green line*. In this case, the effluent treatment section was replaced by existing urea plant scrubber, hence a reduction in the capital cost is achieved.

In the normal CAP-SCF configuration [19], the CO₂ recycle stream produced from the regeneration of the CO₂ rich solvent is utilized in the saturation reactor, see *Figure 1-(a) red line*. In the proposed modification, a CO₂ stream from an ammonia production plant is directed to the CAP-SCF saturation reactor, see *Figure 1-(b) red line*.

In addition, according to *Figure 1-(a) blue line*, in the normal CAP-SCF unit, the aqueous ammonia solution coming out from the filter is recycled back to the first absorber after processing. However, in this proposed modification, *Figure 1-(b)* the *blue line*, the aqueous ammonia solution produced from the filter is directly mixed with a makeup ammonia water source taken from *Ammonia Water tank* in urea plant. This stream is directed to the first absorber in the modified CAP-SCF unit. During normal operation in the urea plant, the *Ammonia Water* source stream coming out from the urea plant is considered a liquid disposal that needs to be treated, so it is normally directed to a *desorption unit* in the urea plant for environmentally safe disposal which consume energy. In this proposed integration, this stream is now consumed in the production of more urea which increases the profit.

The final and main step in this proposed integration is to direct the ammonium bicarbonate rich slurry produced from the filter to urea production after adjustment, as shown in *Figure 1-(b) yellow line*. In the normal CAP-SCF, this slurry is directed to the thermal reactor for regeneration, see *Figure 1-(a) yellow line*. This mean that, in this proposed integration, the regeneration section in the CAP-SCF unit is removed completely, which reduces the associated energy consumption. These steps are important in order to maximize profit, by utilizing the captured CO_2 for sustainable urea production by integrating the modified CAP-SCF unit with urea plant.



Fig. 2. Tertiary phase diagram of the CO2-NH3-H2O system.

2.3.2 Slurry Adjustment

The produced slurry from the modified CAP-SCF unit (*yellow line Figure 1-(b)*) contains 70% solid ammonium bicarbonate. The slurry is at low temperature 15 °C and atmospheric pressure. In order to utilize the produced slurry in urea production, the slurry needs to be altered in order to fulfil the urea synthesis conditions and convert the ammonium bicarbonate into ammonium carbamate. In this case, the slurry loading will be adjusted to 0.5 CO₂ and the temperature and the pressure of the slurry will be increased to 108 °C and 142.7 bar [27] respectively. Slurry is mixed with make-up ammonia and with condensate from urea plant to change its CO₂ loading from 70% to 50%. Slurry temperature is raised from 15 °C to 108 °C by using a heater, while the slurry delivery pressure is increased to 142.7 bar by using pumping station, see *Figure 2*.



Fig. 3. Slurry adjustment section overview.

According to the tertiary phase diagram of the CO₂-NH₃- H₂O system, *Figure 3*, adopted from [28]; at the start, the slurry will be at *point A* which corresponds to 70% ammonium bicarbonate and 15 °C. As ammonia is added to the slurry to decrease the loading, the equilibrium shifts from **point A** to **point B**, and ammonium carbonate is formed. When adjusting the operating condition to that of urea plant (142.7 bar and 108 °C) the equilibrium shifts again from **point B** to **point C** and ammonium carbonate formation is favored, which is the target.

2.3.3 Urea Plant Modifications

One of the proposed changes to implement in the urea production plant is the splitting of the CO_2 feed stream, see *Figure* 4. 90% of the CO_2 feed stream is directed to the urea production plant, *blue line Figure 1-(b)* and *Figure 4*, while the remaining 10% utilized in the CAP-SCF saturation reactor, *green line Figure 1-(b)* and *Figure 4*.

The second modification is to inject the adjusted slurry (*yellow line Figure 1-(b*)) into the High-pressure carbamate condenser (HPCC), as shown in *Figure 4*, the *red line*. This will maximize the amount of urea produced by utilizing the captured CO_2 as ammonium carbamate.



Fig. 4. Modification made to Urea production plant.

2.4. Process Simulation

The proposed modifications are simulated in Aspen Plus using the extended UNIQUAC thermodynamics model for solidliquid-vapor equilibria and thermal properties estimation [21,29]. The normal CAP-SCF unit in [19] is utilized as a reference case for comparison with the proposed modification in this study. First the simulation is built and validated using the reference case. Adjustments are made to the flow rate to fit the capacity of the urea production plant under study, *Table 1*. The excess ammonia available in the actual ammonia plant is nearly 5 t/hr., it reacts with 5.8 t/hr. CO₂ to produce urea.

Hence, the target capacity in this modified CAP-SCF unit is 5.8 t/hr CO₂. The case was downgraded from 130 t/hr capacity to 5.8 t/hr to meet the capacity of the Ammonia-Urea plant. The simulation study of this modified CAP-SCF is shown in *Figure* 5. The stream data is shown in *Table 2*.

Table 1 Adjustment made to the flow rate of the CAP-SCF	process in the reference case to fit the	ie capaci	ty of our urea	production pl	ant
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Inlet process parameters	Reference case	Our study	Units
Flue gas flow rate	2448.2	38.4	t/hr.
Flue gas inlet Temperature	30	30	С
Flue gas inlet mole fraction	3.9	11.5	mole %
Lean solvent flow rate	1667	75	t/hr.
Lean solvent inlet temperature	26	26	С
Ammonia inlet concentration	15	15	%
Design specifications	Reference case	Our study	Units
Capture rate	90	90	%
Rich loading	0.55	0.55	-
Slurry solid mass fraction	70	70	%
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Cooling water temperature	10	10	°C
Cooling water temperature Crystallizer operating temperature	10 15	10 15	°C °C

Table 2 Composition of the different streams in our proposed modification in the simulated case for CAP-SCF integration with urea plant.

CAP (6.5 t/hr.)	Flow	CO_2	NH_3	H_2O
	t/hr.	wt.%	wt.%	wt.%
Pure CO ₂	5.84	1.00	0	0
Lean solution	74.90	0.12	0.15	0.73
Flue gas	110.00	0.06	0	0
Gases effluent to scrubbing	105.00	0.01	0.01	0
Slurry to adjustment	20.22	0.58	0.23	0.19
Liquid out filter	65.72	0.13	0.08	0.79
Ammonia water to mixer	9.18	0	0.65	0.40

3. Result and Discussion

3.1. Evaluation of the Proposed Modified in CAP-SCF

The proposed modification in the CAP-SCF unit results in the elimination of the regeneration section. The regeneration section consists of; thermal reactor, water wash, and CO_2 compressor. This elimination deceased the energy specific consumption. The specific energy consumption per kg CO_2 is calculated only for the boundary shown in *Figure 6*, including the adjustment section heating and pumping duties, see *Table 3*.



Fig. 5. Our proposed modification for CAP-SCF for integration with urea production plant using Aspen Plus software.

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Fig. 6. Simulated section boundary from the reference case (CAP-SCF) for energy consumption calculations.

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Equipment	Energy consumption for CO ₂ capturing, MJ/kgCO ₂				
	Modified CAP-SCF requirement				
Crystallizer	1.48				
Chilling	0.22				
Cooling	0.06				
Pumps	0.10				
Total modified CAP-SCF	1.86				
Slurry adjustment requirement					
Heating Duty	1.29				
Pumps	0.02				
Energy savings					
HPCC condensation	-1.99				
Slurry Heating integration	-0.99				

Table 3	Energy	consumption	during CO	2 capture v	within the sy	stem boundary
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Moreover, the solvent used for capturing can be directly utilized from any ammonia production plant in close proximity to the urea plant. It is demonstrated that 90% efficiency can be achieved using a 15 wt.% aqueous ammonia solution even when operating the absorber above 10 °C as in our case [30].

According to the reference case [19], 80% of the captured CO₂ can be retained in the solid phase, while the remaining 20% will be circulated. The produced slurry from the modified CAP-SCF unit is 20.22 t/hr, see **Table 2**, it contains 70% solid ammonium bicarbonate, with 0.95 loading. The produced slurry is at 15 °C and atmospheric pressure. In order to integrate the slurry with the urea production plant, the slurry must be adjusted in order to meet urea synthesis conditions, which is; 0.5 loading, 108 °C temperature and 142.7 bar pressure. 4.2 t/hr ammonia was added to the slurry to change its loading to 0.5. In addition, temperature was increased from 15 °C to 108 °C by using heater, the heater duty consumed 1.29 MJ/kgCO₂ of energy, see **Table 3**. In addition, the pressure of the slurry was increased from atmospheric to 142.7 bar by using high pressure pump, this consumed 0.02 MJ/kgCO₂ of energy as pumping duty, see **Table 3**.

The two factors which mainly decreased the specific energy consumption are; the elimination of regeneration section and taking the advantage of steam production in urea plant HPCC. This reduced the total energy consumption of the modified CAP-SCF unit to 1.86 MJ/kgCO₂ compared to 2.43 MJ/kg CO₂ in the case of original CAP-SCF [28,31].

3.2. Integration of the Modified CAP-SCF and Urea Plant Adjustment

The allowed increase in the load for the urea plant revamp is limited to only 10% of the design load. In order to achieve this load, nearly 4.5 t/hr. of ammonia is selected to meet the design margin of the equipment without major changes.

In order to connect the modified CAP-SCF unit with urea plant, some steps need to be considered. The first step is to select the injection point of the slurry from the modified CAP-SCF into the urea synthesis plant. In this case, the HPCC was selected because it is the starting point in the urea process reactions, and the ammonium carbamate condensation reaction occurs in this section, see *Figure 4*.

The second step is to minimize the process energy consumption. This was achieved through two modifications. The first one is to utilize the energy produced from the exothermic condensation reaction in the HPCC section to produce low pressure (LP) steam which account for 1.99 MJ/kgCO₂ energy reduction, see *Table 3*. The second proposed energy saving modification is to utilize the wasted heat energy in the urea production plant. During normal operation of the urea production plant, steam condensate of 30 t/hr is cooled before being directed to a cooling tower as a makeup stream, this results in 7.67 GJ/hr of wasted heat duty. In order to achieve energy reduction, this wasted heat duty can be utilized in heating slurry to 85 °C during slurry adjustment step. This integration will reduce the required heating duty of slurry in the modified CAP-SCF unit by 75% and will save cooling duty of the cooling tower in the urea synthesis plant. This reduction is equivalent to 0.99 MJ/kgCO₂.

Considering the energy consumption listed in *Table 3*, and the energy integration proposed in the second step, the total energy consumption of the modified CAP-SCF unit will be kept to a minimum of 0.19 MJ/kgCO₂.

The third step is to integrate process streams when possible. In normal urea synthesis plant, the *Ammonia Water tank* is used to store the polluted condensate stream containing 3% aqueous ammonia solution before being directed to the *desorption unit* for treatment. This 3% aqueous ammonia stream can be directed to the modified CAP-SCF unit make-up stream, as shown in Figure 1-b, *blue line*. This modification will decrease the desorption unit load by 11% and hence the associate running cost and energy consumption will decrease.

3.3. Cabon footprint and Environmental impact

The carbon footprint of urea fertilizer is the total amount of greenhouse gases emitted during its production and use. It is a significant contributor to climate change [32]. The carbon footprint of urea fertilizer varies depending on several factors, including the energy source used for urea production, the transportation distance, and the application method. However, it is generally estimated that the carbon footprint of urea fertilizer is between 1 to 3 tons of CO₂eq per ton of urea produced [33].

The Well-to-gate approach is the greenhouse gas emissions associated with the production of a product, from the extraction of the raw materials to the delivery of the finished product to the factory gate. In the case of urea fertilizer, well-to-gate emissions include the emissions from both ammonia and urea production.

In normal urea production plants without our modified CAP-SCF unit, the emissions from ammonia production account for 1.9 ton CO₂/ton NH₃, based on 50 t/hr ammonia produced. The emissions during urea production are calculated using *eq.* 6 and accounts for 1.81 ton CO₂/ton urea, based on 80.31 t/hr of urea production.

Urea emissions (ton CO₂/ton urea) = 0.566*ammonia emissions + 0.733 (CO₂ in urea) (Eq. 6)

Where; the numbers 0.566 and 0.733 are obtained based on eq. 7 by simple calculations the specific consumption for urea production equals 0.566 ton NH₃/ton urea and 0.733 ton CO₂/ton urea.

$$2NH_3 + CO_2 \leftrightarrow NH_2CONH_2 + H_2O \qquad \text{Eq. (7)}$$

In the case of the integration of the urea production plant with the modified CAP-SCF unit, the emissions from ammonia production account for 1.78 ton CO₂/ton. NH₃, based on 50 t/hr ammonia produced. The emissions from urea production are 1.74 ton CO₂/ton urea, based on 88.31 t/hr. of urea produced. Hence, the integration between modified CAP-SCF unit and urea plant produces a low emission environmentally friendly urea of 6% reduction in emissions, see *Table 4*.

	Without modified CAP-SCF	With modified CAP-SCF	Units
Specific emissions per ton urea	1.81	1.74	ton CO ₂ /hr
Specific emissions per ton ammonia	1.90	1.78	ton CO ₂ /hr
Ammonia production	50	50	ton Amm/hr
Amount of urea produced	80.31	88.31	ton Urea /hr
Total emissions NH ₃ based	95	89	ton CO ₂ /hr
Total emissions urea based	145.36	153.66	ton CO ₂ /hr
CAP-SCF Capacity	-	5.80	ton CO ₂ /hr

Table 4 Comparison of the emissions associated with the urea synthesis with and without using our modified CAP-SCF process.

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It is worthy to highlight that in [19] the power used in the normal CAP-SCF is assumed to be provided from renewable energy sources in order to assume zero CO_2 emissions, which is not practical. However, in our proposed modifications this was not proposed, to keep realistic practice.

Our proposed modification is environmentally friendly. The amount of produced urea increased by utilizing the captured CO_2 from flue gases through post combustion modified CAP-SCF technology. Through the integration of the modified CAP-SCF technology with the urea production plant, a zero-energy consumption is reached together with a reduction in the associated CO_2 emissions by 6%.

This work is in agreement with United Nation Sustainable Development Goals (UN SDG-s) goal number 2, 7 and 13. Through this work; CO₂ emissions to the atmosphere is reduced by capturing CO₂ from flue gases using aqueous ammonia (UN SDG no. 13), energy consumption was minimized by eliminating the regeneration section (UN SDG no. 7), and urea production capacity is increased by consuming ammonium carbonate for urea production (UN SDG no. 2).

4. Conclusion

In this study, the integration between CAP-SCF unit as a promising CO_2 capture process and sustainable urea production was discussed. This is intended not only to capture CO_2 from flue gases but also to utilize this CO_2 in urea production in order to produce more urea. Through this integration, the regeneration section and effluent treatment section in the CAP-SCF unit were completely removed. Process stream integration was also considered in many points in the urea production plant. A reduction in energy consumption and process capital cost, in addition to lowering in CO_2 emissions and increasing in urea production was observed. It was found that:

- Energy consumption decreased from about 2.43 MJ/kg CO₂ for the normal CAP-SCF unit to about 1.86 MJ/kg CO₂ in the modified CAP-SCF unit by removing the regeneration section.
- CAP-SCF slurry adjustment to the required urea production condition of; 0.5 CO₂ loading, 108 °C and 142.7 bar, converted the ammonium bicarbonate into more ammonium carbamate in favor of urea production. A total of 1.31 MJ/kg CO₂ energy was utilized.
- By utilizing the energy produced from the exothermic condensation reaction in the HPCC section to generate LP steam, an energy saving of 1.99 MJ/kgCO₂ was achieved.
- The proposed energy integration in this study decreased the total energy consumption of the modified CAP-SCF unit to 0.19 MJ/kgCO₂ when integrated with urea production plant.
- The utilization of the 3% aqueous ammonia solution as a make-up from *Ammonia Water tank* at the urea production plant into the modified CAP-SCF unit, decreased the desorption unit load by 11%.
- Environmental wise, the integration between modified CAP-SCF unit and urea plant produces environmentally friendly urea with 6% emissions reduction.

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