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**Review Article**

# Carbon capture technologies and sustainable transformation in fertilizer production

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**ABSTRACT**

The fertilizer sector is vital for Türkiye's agricultural sustainability but poses significant carbon emission challenges. Intensive energy use and direct emissions, especially in ammonia and urea production processes, increase the carbon footprint of this sector; therefore, technological solutions to reduce carbon emissions become a priority. In this paper, Carbon Capture, Utilization and Storage (CCUS) technologies stand out as a strategic tool to reduce emissions and ensure compliance with international regulations. In this report, the applicability of CCUS technologies is assessed within the framework of Türkiye's sectoral emission profile and the most suitable capture technologies are analyzed, especially in the context of fertilizer production processes. Post-combustion carbon capture technology came to the forefront due to its compatibility with the existing industrial infrastructure and ease of implementation, and it was determined that this technology has high applicability in the short and medium term. Furthermore, recommendations for policy makers and industry are presented, considering the Turkish legislation, the need for economic incentives and international developments. The results show that CCUS practices in the fertilizer sector will play a critical role both in achieving emission reduction targets and maintaining the competitiveness of the industry.

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## INTRODUCTION

The need for increasing food demand has increased day by day due to the rapid rise in the population. So, the sustainable transformation of agricultural industry is essential in this situation. The agricultural industry tries to improve crop efficiency and product yield by applying fertilizers, which are good nutrients for plants. However, they have certain environmental impacts such as climate change by the release of carbon dioxide ($CO_2$) and nitrous oxide emissions.

Food security, national revenue, employment, international trade, and agriculture-dependent industries are all bolstered by the agricultural sector. By 2050, the world population is predicted to reach 9.8 billion people, exacerbating the world's food security and making sustainable development one of the most crucial goals [1]. The agriculture sector is 3.2 times more effective than other sectors at reducing poverty [2].

There are 18 essential nutrients, three of which are carbon, hydrogen, and oxygen sourced from air (as $CO_2$) and water [3]. The other nine elements called micronutrients provide a small amount of effect on the growth of plants (Fig. 1).

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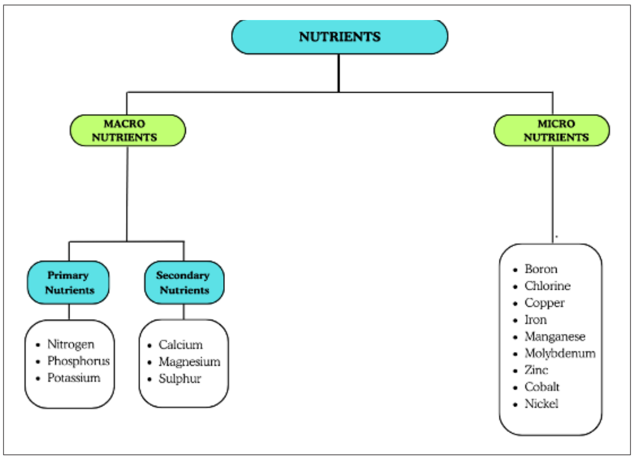

**Figure 1**. Essential nutrients for plants [3].

Fertilizers are used as a supplementary product to create nutrient-rich environment for plants and are commonly applied in agriculture due to a lack of essential minerals in the soil. There are two types of fertilizers: organic fertilizers and inorganic (i.e. synthetic) fertilizers. Organic fertilizers are derived from natural sources such as compost and animal manure. This type of fertilizers is important for its recycling properties. But organic fertilizers release the nutrients more slowly to feed the soil. Otherwise, inorganic fertilizers are produced from chemical processes (generally known as nitrogen (N), phosphorus (P), and potassium (K) fertilizers (NPK) and blended with other materials and provide specific nutrients to feed the plant.

**Nitrogen (N)** is the most essential and limited nutrient in soil, playing a critical role in plant growth, chlorophyll formation, and protein synthesis. For this reason, nitrogen fertilizers, especially urea, are the most important and most frequently used fertilizers in agriculture. However, urea is lost in large quantities through evaporation, leaching, and emissions due to its high solubility, low molecular weight, and low thermal stability. [4]. A large portion of nitrogen in the urea is lost through evaporation, leaching, and emissions, especially when applied to the soil surface in alkaline conditions [5]. These losses contribute to environmental issues, such as water pollution and eutrophication. Due to these side effects, mitigation methods such as controlled-release fertilizers and the development of green ammonia technologies have increased globally to prevent the environmental risk of emissions from leaching.

### Highlights

- CCUS technologies offer a promising pathway to reduce carbon emissions in the fertilizer industry.
- Post-combustion carbon capture stands out as the most feasible option for short-term implementation.
- Integrating CCUS into fertilizer production can support Türkiye's emission reduction targets and industrial competitiveness.

The global fertilizer market was valued at $184.60 billion in 2021 and is expected to reach $251.57 billion by 2030, growing at a CAGR of 3.55% from 2022 to 2030 [6]. Major producers include China, India, Russia, the U.S., and Canada (Fig. 2).

Nitrogen leads global NPK production, accounting for 57% of total production in 2020, with 123.5 million tons produced globally [7]. Around 54.8% of this came from China, India, the U.S., and Russia. Russia and the U.S. increased nitrogen production by 67% and 38% respectively, while China's production decreased by 17% in 2020 [7].

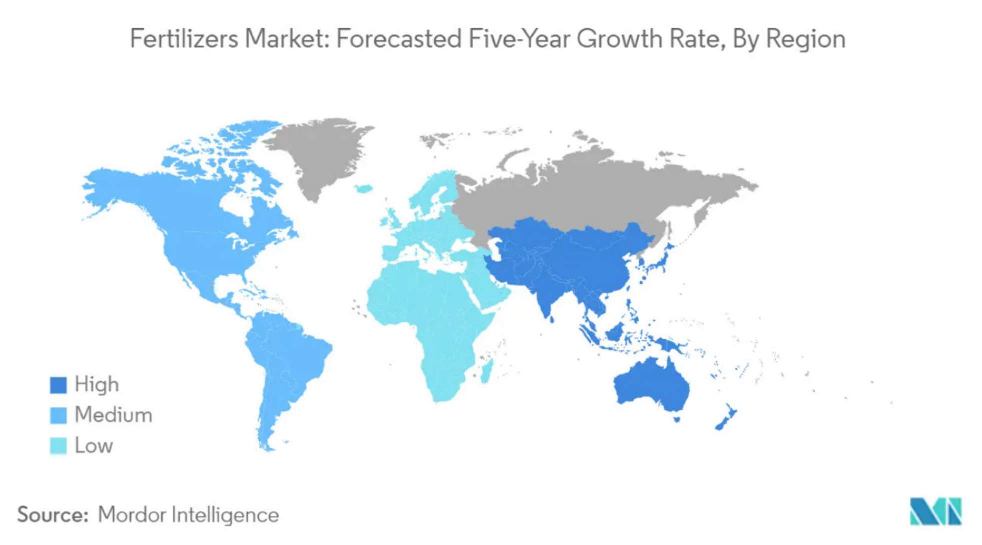

**Figure 2**. Distribution of the fertilizer industry worldwide [6].

The fertilizer market includes several product segments: straight fertilizers, complex fertilizers, conventional fertilizers, and controlled-release fertilizers (CRFs). Although straight fertilizers dominate the market in 2024 with a 72% share, CRFs are the fastest-growing segment due to their efficiency and environmental benefits [6].

In Türkiye, the fertilizer production began in 1939 and significantly developed after the 1970s due to increased investments. The first production took place at the Karabük Iron and Steel Factories through the reaction of ammonia gas with sulfuric acid, resulting in ammonium sulfate (21% N) [5]. Fertilizer exports from Türkiye remain low compared to other countries, primarily due to its high dependency on imports of certain raw materials.

On the other hand, the rising inflation and falling national currency have further made fertilizer imports expensive, negatively impacting Turkish farmers in recent years [7]. According to the Ministry of Agriculture and Forestry [7], Türkiye has consumed 7.03 million tonnes of fertilizers in 2023, with 5.2 million tonnes being imported due to limited domestic raw materials, except for phosphate in Mardin Mazıdağı. The country relies on imports of nitrogen, phosphate, and potassium fertilizers from various regions like Oman, China, North Africa, and the EU [7].

In Türkiye, The Ministry of Agriculture and Forestry banned ammonium nitrate in 2016 for security reasons and restricted the use of ammonium sulfate because it affects on soil pH [7]. These were largely replaced by urea-based and nitrogen-phosphate-potassium (NPK) compound fertilizers like 25-5-10 NPK (25% N, 5% P2O5, 10% K2O).

Climate change and environmental pollution are the main global threats. In response to these issues, the European Union launched the European Green Deal on December 11, 2019, aiming to reach a more sustainable future. A key component of the deal is the carbon border adjustment mechanism (CBAM), which will significantly affect international trade [8]. The EU emissions trading system (ETS) is the world's largest carbon pricing system and plays a central role in this regulation. According to trade map (2023), in 2022, the EU-27 accounted for 48.76% of Türkiye's fertilizer exports, alongside major shares in electricity, steel, cement, and aluminum exports.

With a projected 9% increase in global population, the demand for food and energy is rising, leading to higher emissions. As fertilizers are essential for food production, their usage—and related emissions—are also increasing.

The fertilizer industry currently accounts for around 5% of global greenhouse gas emissions [9]. Studies show that agriculture sector emit about 2.6 gigatonnes of $CO_2$ equivalent annually, exceeding emissions from global aviation and shipping combined. In synthetic fertilizer production, ammonia production is the main source of emissions. In Türkiye, the production of ammonia and nitric acid, which are key raw materials in fertilizer, is 50–65% more emission-intensive than that in the EU. To address this, most of the countries aim to reduce emissions by adopting innovative technologies like alternative processes and carbon capture systems. In line with the European Green Deal, global fertilizer and chemical producers are setting interim targets for 2030 and aiming to achieve carbon neutrality by 2050

## LITERATURE REVIEW

Soil is one of the largest carbon stocks and plays an important role in combating climate change by storing carbon through the soil carbon sequestration process. Carbon sequestration involves capturing and storing atmospheric $CO_2$, playing a significant role in mitigating climate change. Also, this process has benefits such as increasing agricultural yields, improving water quality and enhancing soil health [10].

Furthermore, $CO_2$ is known to accelerate plant growth by increasing the rate of photosynthesis while minimizing water loss through transpiration [11]. CCU (Carbon Capture and Utilization) is the process of capturing $CO_2$ and converting it into useful products, so that it can be utilized instead of being buried underground. In agriculture, this refers to the reuse of $CO_2$ in agricultural production. Although $CO_2$ obtained with direct air capture can provide a decline in both greenhouse gases emitted from the sector and in imports of fertilizers, this technology is not yet widespread [12].

### International Roadmaps and Strategies for Fertilizer Industry

By 2050, the European Green Deal [13] aims to achieve climate neutrality and build a resource-efficient and low-carbon economy. As part of this global transformation, during the COP (Conference of the Parties), countries have published their INDCs (Intended Nationally Determined Contributions) on the UNFCCC (United Nations Framework Convention on Climate Change) platform to demonstrate their commitments to combat climate change [14]. For example, the EU has targeted a 40% reduction compared to 1990 levels, while Canada, Korea, Australia, and Türkiye have also committed to reducing greenhouse gas emissions in line with their economic conditions. These targets necessitate the development of specific strategies and roadmaps for carbon-intensive sectors [15-19]. The Carbon Border Adjustment Mechanism (CBAM), developed for this purpose, aims to prevent carbon leakage by equalizing the carbon-related costs of imported products with those of domestically manufactured products within the EU [13]. Therefore, the European Union has developed various policy and financing instruments to accelerate the transformation of carbon-intensive industrial sectors. Within the framework of the European Green Deal, especially through the Innovation and Research Fund, CCUS projects have been supported at the industrial scale, and fertilizer and chemical industries are among the priority areas [20]. In addition, the applicability of CCUS technologies in the agri-food chain is also addressed in projects carried out under the Horizon Europe program. Carbon management has also started integrating into climate policies in developing countries. Major economies such as China, India, and Brazil are developing national strategies for CCUS technologies; while China focuses on infrastructure investments under the 14th Five-Year Development Plan, India supports carbon reduction targets with the National Hydrogen Mission [21]. However, structural barriers such as infrastructure deficiencies, high costs, and policy uncertainties limit the spread of CCUS applications in these countries [22]. Therefore, it is important to support these technologies with mechanisms such as carbon pricing, emission trading systems, and public incentives [22]. In Türkiye, sustainable transformation policies for the fertilizer sector aim to promote low-emission technologies, to encourage organic and microbial fertilizer production, and to integrate biogas and landfill gas facilities into production processes. In addition, steps such as supporting green and blue ammonia production and increasing energy efficiency in existing facilities could play a critical role in reducing the sector's carbon footprint. This transformation process also includes workforce requalification, social inclusion, and support for carbon-reducing practices. These national initiatives are integrated with global roadmaps and strategic frameworks in the fertilizer sector. Arrangements such as the Paris Agreement and the European Green Deal encourage countries towards carbon capture and low-emission technologies in line with their greenhouse gas emission reduction targets. Türkiye is investing in $N_2O$ catalysts and aims to reduce emissions by promoting the use of green-blue ammonia [23]. Similarly, the International Energy Agency's "Ammonia Technology Roadmap" report presents three scenarios for decarbonizing ammonia production and assesses the viability of low-carbon technologies. International roadmaps focus not only on technological transformation but also on financial support mechanisms, multi-stakeholder governance structures, and just transition principles [24].

## CCUS TECHNOLOGIES FOR FERTILIZER INDUSTRY

### Carbon Capture, Utilisation and Storage (CCUS) Systems

Carbon capture, utilisation and storage (CCUS) systems, one of the most critical technological tools in the fight against climate change, play a strategic role in the decarbonisation of high emission sectors. In line with Türkiye's net zero carbon emission target, transformation of high carbon emitting sectors such as power generation, cement, steel and fertiliser industries is of great importance. Considering that the majority of carbon emissions in these sectors come directly from the production processes, there is a need not only for reduction technologies but also for conversion technologies. CCUS systems play a critical role in this transformation; they reshape the carbon cycle by capturing $CO_2$ before it enters the atmosphere, converting it into an input with economic value, or storing it safely [25].

CCUS systems are structured around a value chain consisting of four main stages: carbon capture, transport, utilisation and storage. Each stage includes different technological methods and operational solutions. For example, carbon capture can be achieved by pre-combustion, post-combustion, oxy-fuel and direct air capture (DAC) technologies. Among these methods, post-combustion is the most widespread and stands out especially for its easy integration into existing industrial infrastructures [25].

Carbon capture technologies aim to capture $CO_2$ gas from the atmosphere and then store or utilise it [25]. $CO_2$ is emitted into the atmosphere together with other gases as a result of industrial processes, hydrocarbon-fired power generation, steel and cement production, hydrogen production, fertiliser production and fuel production in refineries. Carbon capture technology refers to the separation of $CO_2$ from other gases emitted into the atmosphere. There are many different technologies used in the capture, transport and geological storage of carbon. These processes are technologies that will help reduce greenhouse gases. It has a key role in combating climate change [26].

There are four main carbon capture technologies. These technologies can be used before combustion, after combustion or with oxy-fuel.

- Absorption: It is the separation of $CO_2$ with chemical solvents by dissolving it in liquid medium.
- Adsorption (Surface Retention): The retention of $CO_2$ by binding to a solid surface (e.g. activated carbon, zeolite or MOF). This method is particularly favoured at low $CO_2$ concentrations (e.g. direct air capture).
- Membrane Separation: It is the separation of $CO_2$ through special polymeric or inorganic membranes by utilising molecular permeability differences.
- Cryogenic Separation: It is the separation of $CO_2$ from other gases by turning it into liquid or solid at low temperatures. Although this method is energy intensive, high purity $CO_2$ can be obtained when combined with hybrid systems [26].

### Carbon capture technologies in blue ammonia and fertilizer sector

Ammonia is an essential chemical, especially in the production of agricultural fertilizers, and 85% of its production is directed to this field. However, since 95% of the production is based on fossil fuels, and the production process consumes large amounts of energy, ammonia production generates high levels of $CO_2$ emissions. This process accounts for about 2% of global energy demand and 1.3% of $CO_2$ emissions [27].

To address this issue, blue ammonia production involves the integration of carbon capture and storage systems into the Haber-Bosch process, which uses hydrogen produced by conventional steam methane reforming (SMR). Through this integration, $CO_2$ generated during production is separated by absorption technologies (e.g. MEA solutions) and either injected underground or converted into a reusable form. The product obtained by this method is called "blue ammonia" [27].

Blue ammonia systems fall into two main categories: Gen 1 systems integrate carbon capture into existing fossil-based production, while Gen 2 systems utilise renewable energy sources to produce hydrogen, making the process lower emission. However, the integration of CCS technology alone is not sufficient; the emission impact of the entire production system must be assessed through life cycle analysis. In particular, the risk of "fossil lock-in" may give the impression that production is only decarbonised on the surface [27].

Carbon capture and utilization (CCU) systems have the potential to reduce climate impact, but risk fossil lock-in if production processes remain based on fossil resources. As stated in the TfS guidelines, the system extension approach attributes $CO_2$ emission reductions only to by-products, while the main product (e.g. ammonia) continues to carry the same climate burden as conventional production. This increases the risk of making fossil-based production structurally unsustainable [27]. Furthermore, in scenarios with high methane leakage, the short-term climate impact of blue ammonia production may be more negative compared to green alternatives [28]. Therefore, in CCU applications, not only the $CO_2$ benefit but also the energy profile and long-term impacts of the whole system should be considered.

In the system depicted in Figure 3, $CO_2$ capture technology is integrated directly into the ammonia production process. The $CO_2$ gas generated during the production of blue ammonia exits the reactor as a gas stream. This $CO_2$ is directed to an absorption tower containing a solution of monoethanolamine (MEA). MEA chemically reacts with the $CO_2$, keeping it in solution. This solution is then sent to a separator unit to recover the $CO_2$. Here it is heated and the $CO_2$ is separated again, resulting in high purity captured $CO_2$. The $CO_2$ captured in this system is treated as a by-product of the production process. No system expansion or allocation procedure is applied; the multiple output is accepted directly [27].

When direct air capture (DAC) technology is added to blue ammonia systems, the system boundaries are further extended; $CO_2$ captured from the atmosphere replaces $CO_2$ generated in the production process, resulting in a lower net emission structure. Modelling studies in Germany have shown that such integrated systems reduce climate change impact by up to 20% compared to grey ammonia production [27].

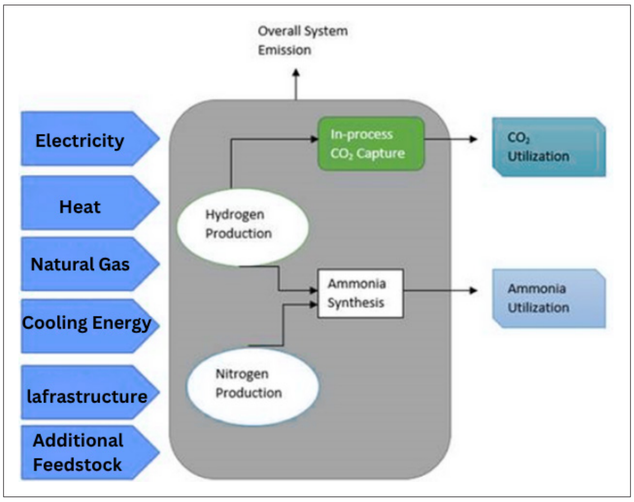

**Figure 3**. System boundaries for blue ammonia production.

The conventional SMR (steam methane reforming) method produces 1 kg of grey ammonia without $CO_2$ capture. $CO_2$ capture is integrated into the ammonia production process. When producing 1 kg of blue ammonia, $CO_2$ is captured at the same time. Three different production approaches are compared in the study. Gray ammonia production is based on conventional steam methane reforming (SMR), does not involve $CO_2$ capture and its functional unit is 1 kg of ammonia. The production of blue ammonia includes $CO_2$ capture technology integrated into the process, with the functional unit defined as 1 kg of blue ammonia along with the $CO_2$ captured during production. In addition, in the production of blue ammonia where direct air capture (DAC) is incorporated, in-process $CO_2$ capture as well as $CO_2$ obtained through DAC replaces the byproduct, so that the functional unit is 1 kg of blue ammonia and the associated $CO_2$ capture. In this case, in order to solve the multiple output problem, the limits are expanded to include DAC and the environmental impacts of ammonia and $CO_2$ are examined separately [27].

In research projects and industrial applications, the most common method in carbon capture processes are amine-based technologies, particularly based on monoethanolamine (MEA) sorption. These methods generally achieve $CO_2$ capture efficiencies of 85-90% in environments. The amine solutions saturated with $CO_2$ are separated from $CO_2$ by thermal treatment; thus, both $CO_2$ and the amine solution are obtained and made suitable for reuse. The captured $CO_2$ is compressed and transported by pipelines to storage or utilisation areas. A detailed life cycle inventory including transport of storage processes was presented; 90% of $CO_2$ purity, 30 years capture unit and 18 years compressor lifetime were assumed in the analysis [27].

Direct (airborne) carbon capture (DACC) captures $CO_2$ from air. This reduces the level of $CO_2$, helps to reduce emissions and stabilise the amount of $CO_2$ in the air [25].

Figures 3 and 4 represent the system boundaries used in the life cycle analysis (LCA) to assess the climate impacts of blue ammonia production. Figure 3 presents a system boundary limited to the production process, including only the in-process carbon capture unit, while Figure 4 reflects a scenario where the captured $CO_2$ is replaced by an external direct air capture (DAC) system, thus expanding the environmental contribution of the system [27].

This approach, in line with TfS guidelines, defines the benefit of captured $CO_2$ not as a direct reduction, but also in terms of avoided GHG emissions. $CO_2$ is thus included in the functionality of the system as a by-product and not just waste, which more realistically reflects the distribution of impacts between products in multifunctional processes. Thanks to the system extension, the climate benefit of the $CO_2$ generated during the production of blue ammonia can be analysed [27].

However, the environmental impacts of this systematic framework largely depend on methane leakage in the natural gas supply chain. Leakage rates in the production and transportation of natural gas are particularly decisive for short-term climate impacts. Indeed, TWP (Technology Warming Potential) analyses show that blue ammonia production can only be climate competitive with green ammonia under low leakage rates. For example, even at a leakage rate of 2.2%, the total thermal impact of the blue ammonia system is higher than the green alternative and can only be equalized at very low rates of 0.2% [28]. These system boundaries therefore reveal not only the technical flux, but also the impact of methodological choice in climate assessment on climate outcomes. Redefining the role of $CO_2$ within system boundaries could offer a strategy to reduce fossil lock-in, but only if the energy source is low-carbon and methane leakage is under control.

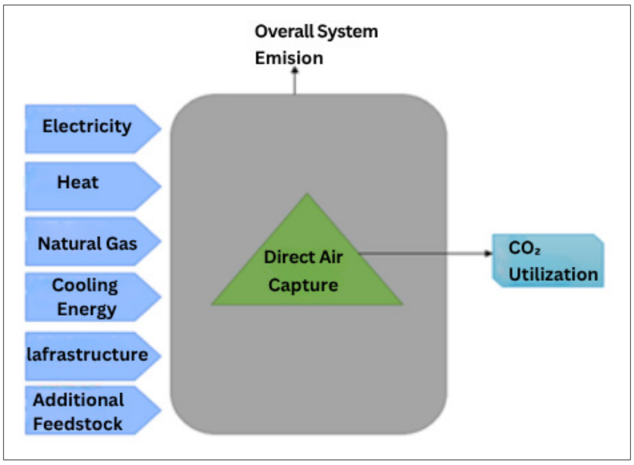

**Figure 4**. System boundaries for $CO_2$ production from DAC.

**Carbon storage technologies**

Geological storage methods are used for the long-term disposal of $CO_2$. In this context, $CO_2$ is injected into deep underground reservoirs in a supercritical state. The main storage environments are depleted oil and gas fields, deep saline aquifers and coal seams. The Enhanced Oil Recovery (EOR) method traps $CO_2$ underground, simultaneously increasing oil productivity. ADNOC Shah Gas project stores 2.3 million tonnes of $CO_2$ per year with this method. Effective storage requires >1000 m depth, porous reservoirs, seal rocks and leakage risk management [26].

**CCUS projects**

Large-scale projects demonstrating the feasibility of carbon capture, utilisation and storage (CCUS) technologies have been implemented around the world. These projects are remarkable in terms of integration of technologies into sectors, geographical suitability and cost-effectiveness.

***Yara – Sluiskil Plant – Netherlands (2022)***

Part of the Northern Lights project in Norway, this facility liquefies $CO_2$ emissions from the steam methane reforming (SMR) process used for hydrogen production by sequestering them through chemical absorption and transporting them to geological formations beneath the North Sea. The project aims to permanently store approximately 800,000 tonnes of $CO_2$ per year. This project is one of the first full-scale CCS applications directly integrated into the fertiliser sector and serves as a pioneering example in the sector's transition to carbon neutrality [29].

***CF Industries – Yazoo City Facility –USA (2024)***

At the ammonia production facility, $CO_2$ generated by the steam methane reforming (SMR) process is separated by chemical absorption. It is typically captured from the $CO_2$ gas stream using solvents such as monoethanolamine (MEA), then compressed and injected into underground formations through ExxonMobil's infrastructure. This project, planned to permanently store approximately 500,000 tons of $CO_2$ annually, is one of the pioneering applications in the US fertilizer industry aimed at reducing carbon emissions [30].

***Saudi Aramco Blue Ammonia Shipment - Saudi Arabia - Japan (2020)***

Saudi Aramco successfully delivered the world's first shipment of carbon capture and utilisation (CCU)-based blue ammonia to Japan in 2020. In this process, $CO_2$ generated during blue ammonia production was captured and transported for use at the Uthmaniyah oil recovery pilot plant in Saudi Arabia and the methanol production plant in Jubail [27].

***Pupuk Indonesia - Pertamina - Mitsubishi Joint Venture - Indonesia***

Pupuk Indonesia, Pertamina, Mitsubishi Corporation Located in Southeast Asia, this initiative aims to assess the feasibility of establishing a supply chain for hydrogen and ammonia through carbon capture, utilisation and storage (CCUS) [27].

***Pupuk Indonesia Production Capacity- Indonesia***

It is a major facility in Indonesia with an annual production capacity of over five million tonnes, accounting for approximately 3% of global ammonia production [27].

***Mexico Technical Research Project- Mexico***

The environmental impacts of carbon capture, utilisation and storage (CCUS) in an ammonia plant for applications such as an advanced oil recovery system, carbonated beverages and urea synthesis were investigated in detail [27].

***CCU Based Blue Ammonia Modelling- Germany***

In a modelling study conducted in present-day Germany, it was shown that the impact of CCU-based blue ammonia on climate change is reduced by 20% compared to grey ammonia [27].

***ADNOC Shah Gas CCS Project- Shah, Abu Dhabi, United Arab Emirates (2019)***

Under KBR's responsibility, this project has the capacity to capture, utilise and store 2.3 million tonnes per annum (MTPA) of carbon at ADNOC's ultra-acidic gas production facilities [31].

***Northern Lights CCS Project- Eastern Norway (2017)***

With an annual capacity of 1.5 million tonnes of $CO_2$, the project includes an onshore $CO_2$ receiving and storage terminal, an offshore pipeline and a subsea injection system [31].

***Quest CCS Project- Canada (2013)***

Located at Shell's Scotford complex, this project is designed to capture 1.1 million tonnes of $CO_2$ per year in a steam methane reformer. The captured $CO_2$ is sent to underground storage at a depth of 2,300 metres, 80 km from the plant [31].

***Gorgon CCS Project- Barrow Island, Western Australia (2005)***

The Gorgon Project is one of the largest CCS projects in the world with an annual injection capacity of 3.4 to 4.0 million tonnes of $CO_2$. $CO_2$ separated from natural gas production and liquefaction processes is injected into the saline aquifer layer 2.3 km below ground via a 7 km long pipeline [31].

### Carbon Capture Efficiency of Processes and Carbon Emission Amount

CCUS systems differ greatly in cost, energy usage, $CO_2$ capture efficiency, and scalability [32]. Hanson et al.[33]'s study assessed different carbon capture technologies from various perspectives and evaluated parameters such as cost, efficiency and scalability for comparison. Parameters for different technologies including absorption, membrane separation, adsorption, direct air capture, cryogenic capture, and bio-based technologies are given in Table 1 [33].

According to the Fertilizer Sector Policy Document prepared by TOB-TAGEM, the Turkey Sectoral Low Carbon Roadmaps prepared by the Ministry of Industry and Trade of the Republic of Turkey, and data from the Directorate-General for Agricultural and Rural Development prepared by the European Commission, 547,000 tons of urea-based fertilizer and 234,400 tons of NPK-based fertilizer are produced in Turkey, while 5.4 million tons of urea-based fertilizer and 17.3 million tons of NPK-based fertilizer are produced in Europe. In a study conducted by TOB-TAGEM to calculate the carbon footprint of fertilizer, emission intensity data were reported as 1.49 tons $CO_2$/tons product for urea-based fertilizers in Türkiye [7], 1.05 for NPK based fertilizers in Türkiye, 1.34 tons CO2/tons product for urea-based fertilizers in Europe, and 0.54 tons $CO_2$/tons product for NPK based fertilizers in Europe [34-36].

**Table 1.** Parameters for absorption, membrane separation, adsorption, direct air capture, cryogenic capture, and bio-based technologies.

| CCUS technologies | Cost (USD/ton $CO_2$) | Energy consumption (MJ/ton $CO_2$) | $CO_2$ capture efficiency (%) | Scalability (TRL) |
|---|---|---|---|---|
| Absorption | 50-100 | 3-5 | 90-95 | 9 |
| Adsorption | 30-80 | 2-4 | 70-85 | 7 |
| Membrane separation | 60-120 | 2-3 | 85-90 | 6 |
| Cryogenic capture | 70-150 | 4-6 | 95-99 | 5 |
| Bio-based technologies | 40-90 | 1-2 | 60-80 | 4 |
| Direct air capture | 100-600 | 8-12 | 80-90 | 5 |

## MATERIALS AND METHODS

One of the parameters that is effective in finding the optimum carbon capture process based on fertilizer sector is carbon capture capacity. The level of development of countries causes differences in the amount of carbon emissions. Therefore, in this study, carbon capture capacities for different processes were calculated based on the carbon emission amounts of Turkey and the European Union for urea and NPK based fertilisers and the efficiency of the processes was analyzed by using Equation 1.

$$\text{CO}_2\ \textit{Capture Capacity} = \textit{Fertilizer Amount} \times \textit{Emission Intensity} \times \textit{Process Efficiency} \qquad [1]$$

## RESULTS AND DISCUSSION

In the study, the efficiency, energy consumption, and carbon capture capacities of carbon capture technologies in the fertilizer industry were taken into consideration and the technologies were compared for the fertilizer sector. Carbon capture capacities specific to the fertilizer sector could not be found in the literature, so carbon emission and carbon capture capacities were calculated according to the urea and NPK based fertilizer production amounts in Türkiye and Europe. The data and calculations from the literature are summarized in Table 2 and 3. According to Table 2 and 3, the absorption process has an efficiency of 90–95%, with an energy consumption of 3–5 MJ/ton $CO_2$, a carbon capture capacity of 0.73–0.77 million tons for urea and 2.22–2.34 million tons for NPK in Türkiye, and 6.51–6.87 million tons for urea and 8.41–8.87 million tons for NPK in Europe. Adsorption has an efficiency of 70–85%, energy consumption of 2–4 MJ/ton $CO_2$, a capture capacity of 2–4 million tons for urea and 1.72 – 2.09 million tons for NPK in Türkiye, and 5.07–6.15 million tons for urea and 6.54–7.94 million tons for NPK in Europe. Membrane separation shows an efficiency of 85–90%, energy consumption of 2–3 MJ/ton $CO_2$, a carbon capture capacity of 0.69–0.73 million tons for urea and 2.09–2.22 million tons for NPK in Türkiye, and 6.15 – 6.51 million tons for urea and 7.94–8.41 million tons for NPK in Europe. Cryogenic capture has an efficiency of 95–99%, energy consumption of 4–6 MJ/ton $CO_2$, a capture capacity of 0.77–0.81 million tons for urea and 2.34–2.44 million tons for NPK in Türkiye, and 6.87–7.16 million tons for urea and 8.87–9.25 million tons for NPK in Europe. Bio-based technologies have an efficiency of 60–80%, energy consumption of 1–2 MJ/ton $CO_2$, a carbon capture capacity of 0.49–0.65 million tons for urea and 1.48–1.97 million tons for NPK in Türkiye, and 4.34–5.79 million tons for urea and 5.61–7.47 million tons for NPK in Europe. Direct air capture has an efficiency of 80–90%, energy consumption of 8–12 MJ/ton $CO_2$, a carbon capture capacity of 0.65–0.73 million tons for urea and 1.97 – 2.22 million tons for NPK in Türkiye, and 5.79–6.51 million tons for urea and 7.47–8.41 million tons for NPK in Europe.

The comparative evaluation of Carbon Capture, Utilization and Storage (CCUS) technologies reveals significant variation in terms of efficiency, energy consumption, maturity, and carbon capture capacity— each influencing their

**Table 2.** Carbon capture performance of CCSU processes for urea production.

| CCSU process | Efficiency (%) | Energy consumption (MJ/ton $CO_2$) | Carbon Capture capacity in Türkiye (Mt) | Carbon capture capacity in Europe (Mt) |
|---|---|---|---|---|
| Absorption | 90–95 | 3–5 | 0.73–0.77 | 6.51–6.87 |
| Adsorption | 70–85 | 2–4 | 0.57–0.69 | 5.07–6.15 |
| Membrane separation | 85–90 | 2–3 | 0.69–0.73 | 6.15–6.51 |
| Cryogenic capture | 95–99 | 4–6 | 0.77–0.81 | 6.87–7.16 |
| Bio-based technologies | 60–80 | 1–2 | 0.49–0.65 | 4.34–5.79 |
| Direct air capture | 80–90 | 8–12 | 0.65–0.73 | 5.79–6.51 |

**Table 3.** Carbon capture performance of CCSU processes for NPK production.

| CCSU Process | Efficiency (%) | Energy consumption (MJ/ton $CO_2$) | Carbon capture capacity in Türkiye (Mt) | Carbon capture capacity in Europe (Mt) |
|---|---|---|---|---|
| Absorption | 90–95 | 3–5 | 2.22–2.34 | 8.41–8.87 |
| Adsorption | 70–85 | 2–4 | 1.72–2.09 | 6.54–7.94 |
| Membrane separation | 85–90 | 2–3 | 2.09–2.22 | 7.94–8.41 |
| Cryogenic capture | 95–99 | 4–6 | 2.34–2.44 | 8.87–9.25 |
| Bio-based technologies | 60–80 | 1–2 | 1.48–1.97 | 5.61–7.47 |
| Direct air capture | 80–90 | 8–12 | 1.97–2.22 | 7.47–8.41 |

suitability for implementation in the fertilizer sector. Furthermore, the carbon capture capacities estimated for urea and NPK production plants in Türkiye and Europe demonstrate clear differences that reflect both the scale of production and the nature of each process. Overall, NPK plants exhibit a higher carbon capture potential compared to urea plants across all CCSU methods. This higher capture potential of NPK plants is associated with the generation of high-concentration, stable $CO_2$ process streams from nitric and phosphoric acid production units, which are technically more suitable for efficient CCS deployment [37].

Carbon absorption stands out as the most mature and widely used method (TRL 9), particularly in post-combustion applications. With a $CO_2$ capture efficiency of 90–95% and a moderate energy consumption rate (3–5 MJ/ton $CO_2$), it offers both technical viability and operational compatibility with existing fertilizer production infrastructure. As shown in Table 2 and 3, this method also has one of the highest potentials of carbon capture capacities in Türkiye (0.73 – 0.77 million tons for urea and 2.22 – 2.34 million tons for NPK) and Europe (6.51 – 6.87 million tons for urea and 8.41 – 8.87 million tons for NPK). However, the trade-off lies in its high operating costs, primarily due to solvent degradation, corrosion, and energy required for solvent regeneration [38].

Membrane separation technology provides an attractive alternative with lower energy consumption (2–3 MJ/ton $CO_2$) and a solid efficiency range of 85–90%. Its estimated capture capacity in Türkiye is also significant (0.69 – 0.73 million tons for urea and 2.09 – 2.22 million tons for NPK). Despite being less mature (TRL 6), it offers the advantage of modular design and chemical-free operation, positioning it as a promising candidate for future integration, particularly where cost and space efficiency are critical [39].

Cryogenic capture exhibits the highest efficiency (95–99%) and recovery purity, making it suitable for applications requiring ultra-pure $CO_2$. As seen in the table, it offers the highest carbon capture potential for both Türkiye (0.77 – 0.81 million tons for urea and 2.34 – 2.44 million tons for NPK) and Europe (6.87 – 7.16 million tons for urea and 8.87 – 9.25 million tons for NPK). However, its high energy demand (4–6 MJ/ton $CO_2$) and low maturity level (TRL 5) restrict its practicality for widespread industrial deployment, relegating it primarily to a final purification role [40].

Adsorption technologies, with efficiencies ranging from 70–85% and moderate energy consumption (2–4 MJ/ton $CO_2$), strike a balance between performance and cost (50–150 USD/ton $CO_2$). Their carbon capture potential in Türkiye is between 2 – 4 million tons for urea and 1.72 – 2.09 million tons for NPK. However, limitations such as the need for frequent regeneration and reduced sorbent performance over time hinder their long-term stability and scalability [41].

Bio-based technologies and Direct Air Capture (DAC) remain less commercially viable due to lower maturity levels and energy challenges. Bio-based systems show the lowest energy requirement (1–2 MJ/ton $CO_2$) but also the lowest efficiency (60– 80%), and their maximum estimated capture capacity in Türkiye is only 0.49 – 0.65 million tons for urea and 1.48 – 1.97 million tons for NPK. DAC, although offering a capture efficiency of 80–90%, suffers from the highest energy consumption (8–12 MJ/ton $CO_2$), and its economic feasibility is still limited despite its long-term climate potential [42].

Table 2 and 3 highlights that while cryogenic and absorption methods provide the highest capture capacities, membrane and adsorption offer more energy-efficient solutions with potential for mid-term cost-effective adoption. Meanwhile, bio-based and DAC approaches, though promising for long-term innovation and negative emission goals, currently face barriers in scalability and affordability. Carbon absorption remains the most strategically advantageous option for immediate deployment in the fertilizer sector due to its maturity, integration ease, and high efficiency. Membrane technologies may serve as a compelling next-generation solution pending further R&D. Hybrid solutions combining multiple methods or regionally tailored systems are also recommended to optimize performance and cost across diverse industrial scenarios. Ultimately, expanding integrated CCUS infrastructure and investing in innovation will be key to ensuring sustainable decarbonization in fertilizer production [43].

According to Table 2 and 3, Türkiye's carbon capture capacity grows from 0.49 to 0.81 million tons for urea and from 1.48 to 2.44 million tons for NPK, whereas Europe's capacity spans from 4.34 to 7.16 million tons for urea and from 5.61 to 9.25 million tons for NPK. This steady trajectory shows a proportionate alignment, with better carbon capture capacity in Türkiye corresponding to enhanced capacities in Europe. The data show that regional carbon capture potential scales in tandem, indicating a consistent pattern that might represent common technical improvements or linked regulatory frameworks across both areas.

## CONCLUSION

Carbon Capture, Utilization, and Storage (CCUS) technologies stand out as a strategic tool in the fight against climate change. Considering Türkiye's current industrial structure and GHG emission profile, the most appropriate sector-based CCUS approaches are concentrated in areas with high emission intensity, such as power generation, cement, iron-steel and petrochemicals. The post-combustion technology applied in these sectors stands out as the most logical option in terms of ease of integration into existing infrastructure, technological maturity and economic viability. Especially in fossil fuel fired power plants and industrial facilities, this method is expected to be the most widespread and effective solution in the short term.

Current projections indicate that CCUS technologies will play an important role in both reducing carbon emissions and achieving sustainable economic transformation as they become more widely adopted over the next decade. However, the widespread adoption of the technology depends on many factors such as infrastructure investments, economic incentive mechanisms, and social acceptance. While there are already pilot studies in Türkiye, there is a need for comprehensive and integrated projects.

In this framework, among the recommendations for policymakers, increasing R&D activities on CCUS technologies, developing incentive mechanisms, establishing a legislative infrastructure and supporting cross-sectoral collaborations come to the forefront. In terms of industry, integrating CCUS solutions into the carbon management strategies of sectors with high emission intensity will both contribute to national emission targets and increase their competitiveness in the international market.

## AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

## STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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