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Review

A systematic review: The role of emerging carbon capture and conversion technologies for energy transition to clean hydrogen

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ABSTRACT

The exploitation of fossil fuels in various sectors, such as power and heat generation, and the transportation sector has been the primary source of greenhouse gas (GHG) emissions, which are the main contributors to global warming. Qatar's oil and gas sector notably contributes to CO_2 emissions, accounting for half of the total emissions. Globally, it is essential to transition into cleaner fossil fuel production to achieve carbon neutrality on a global scale. In this paper, we focus on clean hydrogen, considering carbon capture to make hydrogen a viable low carbon energy alternative for the transition to clean energy. This paper systematically reviews emerging technologies in carbon capture and conversion (CCC). First, the road map stated by the Intergovernmental Panel on Climate Change (IPCC) to reach carbon neutrality is discussed along with pathways to decarbonize the energy sector in Qatar. Next, emerging CO_2 removal technologies, including physical absorption using ionic liquids, chemical looping, and cryogenics, are explored and analyzed regarding their advancement and limitations, CO_2 purity, scalability, and prospects. The advantages, limitations, and efficiency of the CO_2 conversion technology to value-added products are grouped into chemical (plasma catalysis, electrochemical, and photochemical) and biological (photosynthetic and non-photosynthetic). The paper concludes by analyzing pathways to decarbonize the energy sector in Qatar via coupling CCC technologies for low-carbon hydrogen, highlighting the challenges and research gaps.

1. Introduction

Global warming is a global challenge that has united 195 nations in a common goal to reduce global greenhouse gas (GHG) emissions and reach carbon neutrality by 2050 (Horowitz, 2016; Jafari et al., 2022). Carbon dioxide (CO_2) is a crucial contributor to global warming; despite substantial efforts to reduce CO_2 emissions, its concentration has risen by 1.7% globally (Regufe et al., 2021). In 2020, the IEA reported a 5.8% decrease in global CO_2 emissions due to the pandemic negatively impacting the demand for oil and coal (see Fig. 1) (International Energy Agency, 2021). However, CO_2 emissions from global energy consumption during this period remained at 31.5 Gt; this marks a 50% increase since the start of the Industrial Revolution.

Global energy consumption still relies on fossil fuels. Coal combustion constitutes 27% of the worldwide energy demand and is responsible for 44% of the CO_2 emissions (Bui et al., 2018). In 2021, an expected rebound in coal use potentially increased global CO_2 emissions by approximately 640 Mt CO_2. Meanwhile, natural gas consumption is rapidly growing with an annual growth rate of 1.9% and is projected to exceed coal consumption by 2030 due to its availability and lower emissions. CO_2 emissions mainly come from three sectors: power, industry, and surface transport, as depicted in Fig. 2. It is noted that the power sector is the highest contributor, accounting for 46% of global emissions (International Energy Agency, 2022).

In 2015, the United Nations Framework Convention on Climate Change (UNFCCC) established a mechanism to limit temperature increase to below 2 °C, aiming for 1.5 °C (Fragkos, 2020). Following the publication of the Fifth Assessment Report (AR5) (Stocker et al., 2013), studies estimated that a 200 to 415 $GtCO_2$ carbon budget between 2011 and 2100 is necessary to maintain a temperature increase below 1.5 °C. Additionally, a 400 $GtCO_2$ limit was suggested for energy-related CO_2 emissions by 2100. The IPCC special report on 1.5 °C (IPCC, 2018) proposed an expanded CO_2 budget range of 570–770 $GtCO_2$, corresponding to 67% and 50%, respectively. The discussed strategies rely on CO_2 removal and utilization methods, renewable energy, and hydrogen to establish net-negative emissions after 2050, ensuring alignment with

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the 1.5 °C target (see Fig. 3).

With the second largest natural gas reservoir, Qatar ranks among the largest energy providers globally; its current liquefied natural gas production rate is at 77 million tons. In 2020, Qatar's CO_2 emissions were estimated at 106.65 million tons per year, as reported by the United Nations published report (Nations United Programme, 2020). While the total CO_2 emissions in Qatar are the lowest among the other GCC countries, it has the highest CO_2 emissions per capita (37.02 tons). The primary sources of these emissions are 64.7% from the oil and gas sector, 22% from power generation, and 32.2% from other activities, as shown in Fig. 4.

Qatar is intensifying efforts to mitigate GHG emissions, primarily focusing on decarbonizing the industrial sector via investments in renewable energy despite challenges of intermittency and grid stability and exploration of non-carbonaceous fuels like hydrogen, which are vital steps towards deep decarbonization (Rajabloo et al., 2022). Hydrogen production using versatile feedstocks, including fossil fuels, electrolysis, and biomass, is crucial in Qatar's production strategy. However, while economical, hydrogen production from natural gas (grey hydrogen) results in significant CO_2 emissions (89.1 CO_2/MJ) (Birol, 2019). An alternative is blue hydrogen, which combines grey hydrogen production with carbon capture, resulting in a lower carbon intensity (22.4 CO_2/MJ) (Regulator, 2020) and aligns with the UNFCCC's target to limit temperature rise to 1.5 °C (IEA, 2017).

Additionally, Qatar has made significant progress in carbon capture and sequestration (CCS), aiming to expand its storage capacity for captured CO_2 to over 5 million tons annually by 2025 (Zeynep Beyza Kilic, 2019). In 2012, Qatar Petroleum, Shell, Imperial College, and Qatar Science & Technology Part formed a $70 million research partnership to establish the Qatar Carbonates and Carbon Storage Research Centre (QCCSRC). Also, the largest blue ammonia project led by Qatar Fertilizer Company (QAFCO) with an integrated CCS facility is anticipated to capture 11 million tonnes per annum of CO_2 (Ingram, 2022). Qatar Energy's North Field East (NFE) project, which invested $28.75 billion, has incorporated CCS technology as one of its crucial environmental aspects (Up et al., 2016). Given Qatar's limited sequestration sites, carbon capture and utilization (CCU) presents a viable alternative for CO_2 utilization. It involves essential CO_2 utilization technologies to address some of CCS's shortcomings. A study by (Al-Yaeeshi et al., 2018) explored the potential of CCU deployment within Qatar's industrial parks, demonstrating economic viability and environmental benefits. This research showed that retrofitting CCU technologies can significantly reduce CO_2 emissions, making it an excellent strategy for sustainable industrial growth and meeting the 1.5 °C targets.

Summarizing these facts and considering the existing literature on decarbonization, this review aims to provide a holistic view of opportunities to decarbonize the Qatari energy sector through suitable CCU pathways presented in the scientific literature. This paper provides an overview of the concept and associated commercialization challenges of emerging CCU technologies discussed in the literature over the past ten years. Although there is extensive separate literature on each technology, to the best of the authors' knowledge, no research discusses the potential of incorporating novel CCU technologies within existing natural gas industrial sectors in Qatar. The rest of this review is organized as follows: Section 2 presents a systematic literature review methodology and the publication trends over the past 10 years that pertain to the studied topic. Section3 discusses the role of industries in CO_2 management. Section 4 reviews emerging CCU technologies and their challenges. Section 5 explores major hydrogen production pathways, their advantages and limitations, and the potential of integrating them with novel CCUs for cleaner production.

2. Methodology

Selecting and analyzing peer-reviewed publications was conducted using SCOPUS as the primary database. The search covered the topics of carbon capture, carbon conversion pathways, and hydrogen production from 2010 to 2022. The methodology used to conduct the literature work is grouped into three primary areas: carbon capture, carbon conversion, and blue hydrogen. The keywords that pertain to these categories are summarized in Table 1. 495 articles were obtained using these keywords during this first phase of the literature search.

Fig. 5 illustrates the time trends for the publications of the stated categories between 2010 and 2022. A trend of continuously increasing publication in the three categories is noticed, indicative of the growing interest and importance of industrial sector decarbonization. The number of publications on carbon capture increased after the Paris Agreement 2015. As for hydrogen production, research interest in coupling the existing carbon capture technologies with steam reforming technologies began to increase between 2018 and 2022, and this trend is in line with the global energy outlooks and scenarios on the key role that hydrogen is expected to play in the energy transition. The interest in carbon conversion started in 2014 and has grown to almost 15 publications in 2022, reflecting the growth in emerging technologies being developed for carbon management.

In phase 2, the relevance or similarities of the selected publications to the research objective were identified, and any duplicates were excluded. Studies related to the three main areas of interest were selected for analysis, and as a result, 238 articles were retained. The distribution of these articles is presented in Table 1. Fig. 6 summarizes the approach used to select the articles included in this literature review.

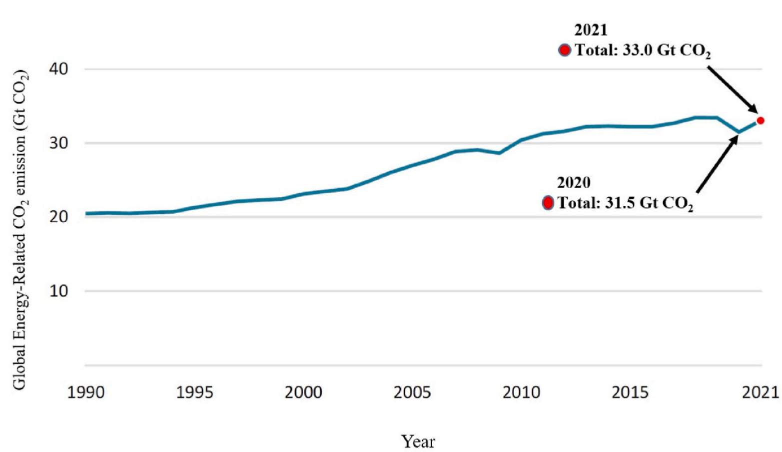

Fig. 1. Global energy-related CO_2 emissions during 1990–2021 (International Energy Agency, 2021).

3. CO_2 management by industry

Extensive research on cleaner fuels demonstrates the need for significant investment in commercialization and global deployment, as fossil fuels meet over 80% of the world's total energy demand. CCS encompasses technologies that capture CO_2 emissions from power plants and industrial facilities and store them in viable geological sites (see Fig. 7). While being a recognized mitigation alternative in the Clean Development Mechanism and EU Emission Trading Scheme (ETS), CCS faces challenges in investment cost, efficiency of carbon capture systems, and safety issues related to geological storage (Bruhn et al., 2016).

There are 27 large-scale CCS projects globally, as shown in Fig. 8. Initially, they focused on primarily using the captured CO_2 to enhance oil recovery (EOR), with CO_2 sourced from natural wells and small to medium-scale industry plants. Projects like Boundary Dam and Kemper County have recently started utilizing the captured CO_2 from power plants. Over the years, the advancement and implementation of CCS technologies have increasingly gained momentum worldwide. Most of these CCS initiatives are retrofitted to coal-based, oil-based, and fuel-based processing plants. Efforts toward increasing the number of industrial-scale CCSs in the power sectors are ongoing, and it is anticipated that these CCSs will begin operation in the following decades. Based on this data, a projection can be developed on the availability of CCS technology worldwide (Salvi and Jindal, 2019).

CCU provides economic incentives for different sectors by reducing reliance on fossil raw materials (Bruhn et al., 2016). Despite the similar approach for both CCS and CCU at the initial process of carbon capture, CCU follows a different method by either utilizing the captured CO_2 in non-conversion methods like EOR or chemically converting it into value-added products (Alper and Yuksel Orhan, 2017). There are 25 CCU projects active worldwide, as shown in Fig. 9 (Tcvetkov et al., 2019), indicating a potential to deploy CCU on an industrial scale. Despite its limited scale, CCU partially offsets CCS costs and generates revenue, which can incentivize investing in carbon capture, transportation, and distribution, eventually facilitating scalability. In this review, the primary focus will be on CO_2 capture and conversion and the acronym that will be used to denote this term is "CCC".

4. Advances in CO_2 capture and conversion technologies

4.1. Technologies for CO_2 capture

Capturing CO_2 methods include pre-combustion, post-combustion, and oxyfuel. Their respective advantages and disadvantages are summarized in Table 2. CO_2 removal technologies fall into five main groups: absorption, adsorption, membrane, chemical looping cycle, and cryogenic (Song et al., 2019a). Each technology has a different separation concept and is chosen based on the emission source to ensure an efficient CO_2 removal system (Kirchner, 2020). Industrially matured technologies, including chemical absorption with conventional amines (e.g., Monoethanolamine MEA), adsorption (e.g., pressure swing adsorption/vacuum swing adsorption), and membranes (see Fig. 10), are effective in reducing carbon emissions, with drawbacks being high regeneration energy. Significant advancements have been made to address these issues; the details are found in previous literature work (Jujie et al., 2016; Kim et al., 2016; Ribeiro et al., 2014; Song et al., 2019a). The advantages and limitations of these carbon capture systems are summarized in Table 5. Noting that existing literature primarily focuses on traditional carbon capture techniques like adsorption and absorption, this review paper examines the forefront of emerging technologies that harmonize with the energy transition strategy anticipated to take place over the next 15–20 years. These emerging technologies are considered candidates to support the expansion of blue hydrogen production.

4.1.1. Absorption technology

CO_2 absorption from gas streams is an industrially mature technology and primarily contains two significant units: an absorber and a desorber/stripper, as shown in Fig. 11. This method uses solvents to remove CO_2 from complex gas mixtures. However, this approach has drawbacks, including the corrosive nature of the solvents and reduced overall efficiency due to cooling requirements for the gas stream before entering the process for optimum separation (Sifat and Haseli, 2019). The solvents used in CO_2 separation can be categorized into chemical and physical solvents. Chemical solvents absorb and react with CO_2 and form chemical compounds, whereas physical solvents soak CO_2 without changing the chemical identities of CO_2 and solvents.

4.1.1.1. Physical absorption. Physical absorption, especially ionic liquids (ILs), is a practical approach among CO_2 separation technologies.

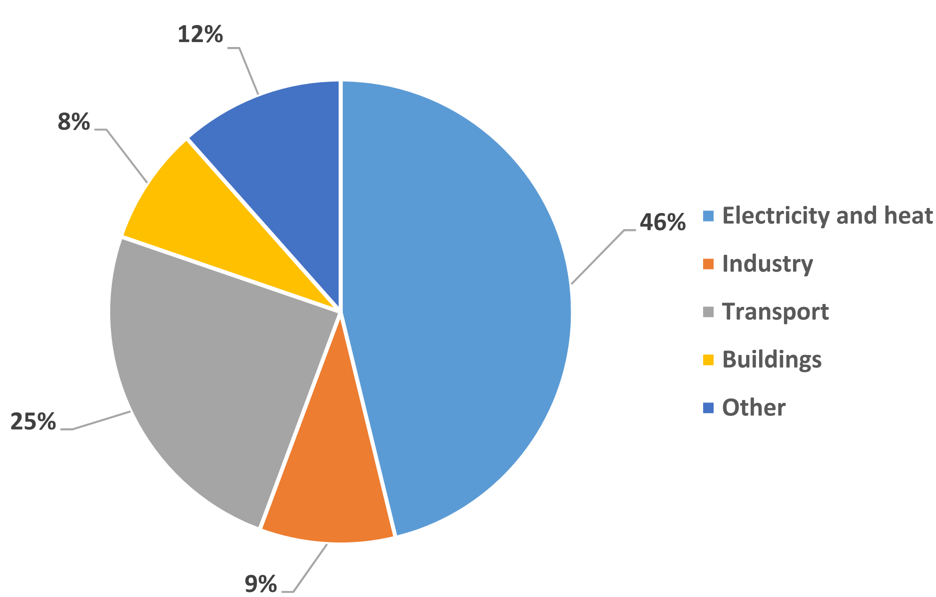

Fig. 2. Repartition of global CO_2 emissions (%) by sector in 2020 (Reproduced from Ref (International Energy Agency, 2022).).

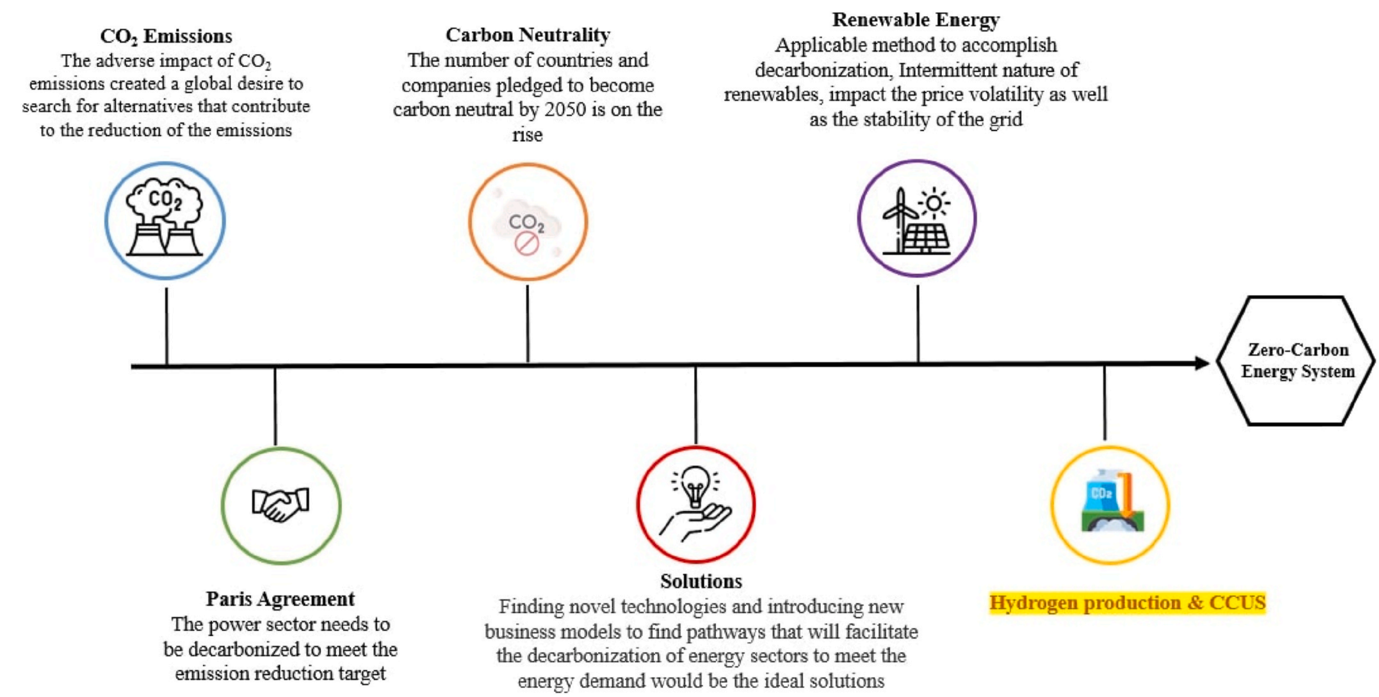

Fig. 3. Roadmap to a zero-carbon energy system.

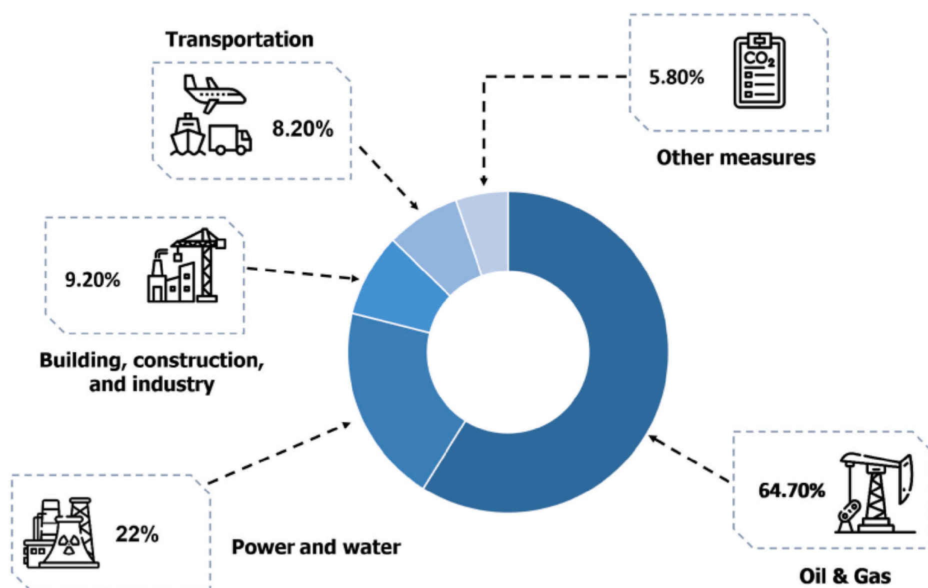

Fig. 4. Sector-wise distribution of CO_2 emissions in Qatar in 2016 (data from Ref. ("Qatar National Climate Change Action Plan, 2030," 2021)).

ILs are advantageous due to their non-corrosive nature, low heat regeneration requirements compared to chemical absorption, low vapor pressure, and tunable physicochemical character (Ma et al., 2018). They have been used in several applications, including upgrading absorption-based biogas and packed bed adsorption as activated carbon (Luo et al., 2016). An innovative approach mainly involves incorporating N or O atoms into a modified amino-functionalized IL for CO_2 capture (Luo et al., 2016). This novel solvent reduces viscosity and increases mass transfer rate with decreased column size. Overall, the high viscosity, low working capacity of ILs, and limited experimental data of novel ILs are the main drawbacks that limit their deployment in carbon capture. Furthermore, there is a need for targeted design and investigation for ILs that absorb CO_2 at moderate pressure, and that can be regenerated at acceptable energy penalties.

4.1.2. *Chemical looping combustion*

Chemical looping combustion (CLC) is a novel technology in CO_2 capture. The combustion reactions are divided into reduction and intermediate oxidation, conducted in two separate fluidized bed reactors. These reactors utilize metal oxide (such as Fe, Mn, Cu, Ni, Mo, Nb, Ce, and Co) as an oxygen carrier circulating between them. These oxygen carriers are utilized in lieu of pure oxygen, where they are oxidized in the air reactor. Next, they are sent to the fuel reactor, where fuel is oxidized to form CO_2 and water, and the metal content is recycled. Pure CO_2 is obtained without energy utilization, and condensation removes water (Mondal et al., 2012). CLC is considered a cost-effective

Table 1
Keywords used in this research work.

Category	Keywords	Number of Selected Articles
Carbon Capture	"Carbon Capture" OR "CO_2 Capture" OR "Carbon Dioxide Capture" OR "CO_2 Removal" AND "CCS" OR "Carbon Capture and Storage" AND "*Decarbonization*"	114
Carbon Conversion	"Carbon Capture" OR "CO_2 Capture" OR "Carbon Dioxide Capture" AND "CCU" OR "Carbon Capture and Utilization" OR "Carbon Capture and Conversion" AND "Decarbonization" AND "Recycling" AND "Value-added Chemicals"	48
Hydrogen Production	"Hydrogen Production" OR "Hydrogen Production Technology" AND "Steam Reforming" AND "Carbon Capture"	76

technology with a high CO_2 capture efficiency (>90%) (Osman et al., 2021). It is identified as an environmentally friendly process, as the exhaust gas from the air reactor only contains N_2 (Song et al., 2019a). Fig. 12 illustrates a typical CLC technology with two combustion reactors.

This process faces significant challenges to the stability of the current oxygen carriers and high oxidation/reduction activity. Furthermore, high-pressure operating conditions are required for high efficiency and fuel desulfurization (see Table 5).

4.1.3. Cryogenic

Cryogenic separation technology, known for its high CO_2 purity and recovery, removes CO_2 from flue gases via the difference in boiling points (Song et al., 2019a). Cryogenic distillation, a well-established method within this technology (Kirchner, 2020), involves cooling the feed gas in a pre-cooler and further chilling in a heat exchanger. The cooled gas is then fed to a distillation column, where CO_2 condenses and is gathered at the bottom. Part of the CO_2-rich stream is then purified and removed from the separator, while the remainder is reheated and recirculated to the column. Process details are shown in Fig. 13 and further described by (Song et al., 2019a). Despite its merit, cryogenic distillation has drawbacks like high refrigeration energy penalties and potential CO_2 freeze-out (see Table 5). An alternative within the cryogenic systems, known as the unconventional method, offers a less energy-intensive solution (see Table 3). It involves novel technologies such as Stirling coolers, V–S packed beds and heat exchangers for effective separation of vapor-solid. Details of each technology are explained elsewhere (Kirchner, 2020; Song et al., 2019a).

4.1.4. Carbon capture technology commercialization challenges

The primary challenge in deploying carbon capture technology lies in its cost, which encompasses capital expenditure (CAPEX) and operational expenditure (OPEX). These costs are mainly for capturing and transporting compressed materials (Alhajaj et al., 2016). The cost of utilizing MEA-based chemical absorption is estimated at 40–100 $/ton CO_2, attributed to high energy requirements and MEA's corrosive nature, increasing maintenance costs (Papers et al., 2011). ILs, while less commercially available, have lower associated CAPEX due to their low vapor pressure, allowing complete recovery during the regeneration and less energy duty (4–6 GJ/tCO_2) compared to amines, where some quantity evaporates during the desorption, increasing material and energy demands. Shiflett et al. (2010) demonstrated that ILs have higher CO_2 purity (98.7%) compared to MEA (95.3%), and total investment costs and equipment footprint was reduced by 11% and 12%, respectively. Moreover, blending amines with ILs can significantly reduce the desorption energy compared to amines (Yang et al., 2014). Huang et al. (2014) found that IL-amine hybrid solvents reduce regeneration duty by 15%, energy penalty by 12%, and CAPEX by 13.5% compared to the MEA-based process. However, ILs' commercial availability is limited, and they are utilized on a lab scale, which is far from the commercial scale regarding operational cost and efficiency, see Table 4.

The cryogenic process offers lower CAPEX and OPEX than traditional chemical absorption and desorption, mainly due to smaller equipment sizes and no regeneration cost. The novel cryogenic packed bed technology has a high CO_2 recovery of 99.9% with an energy duty (2.5–5.2 GJ/tCO_2) less than the conventional methods, with the advantage of removing water and CO_2 simultaneously. However, many challenges need to be overcome before commercialization. For instance, the process has a low TRL of 3 (Kirchner, 2020), and the energy consumption may substantially increase when a refrigerator is used if liquefied natural gas (LNG) is unavailable, potentially weakening the energy-saving advantages. Also, improving thermal insulation is imperative to reduce latent and sensible heat loss.

CLC process offers almost pure CO_2 (99.85%) without additional equipment for gas removal, has no direct energy penalty, less energy duty (0.3 GJ/tCO2), and a CO_2 recovery of 98%. These values are based on pilot plant studies as the technology is considered new with a TRL of 3. Regarding OPEX and CAPEX, a study compared the CLC process with

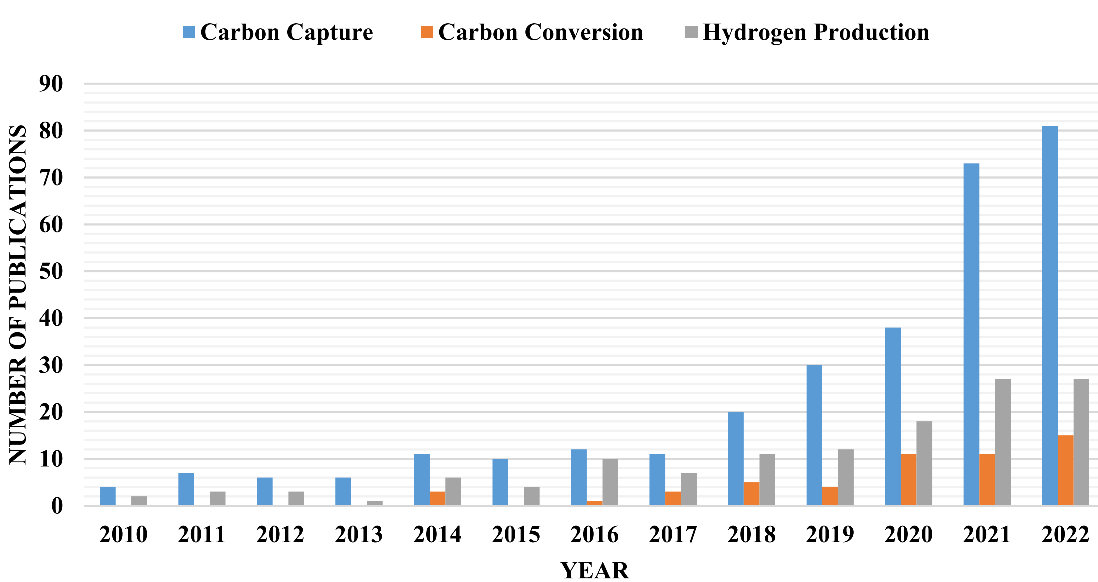

Fig. 5. Number of published articles on carbon capture, carbon conversion, and hydrogen production as identified in SCOPUS.

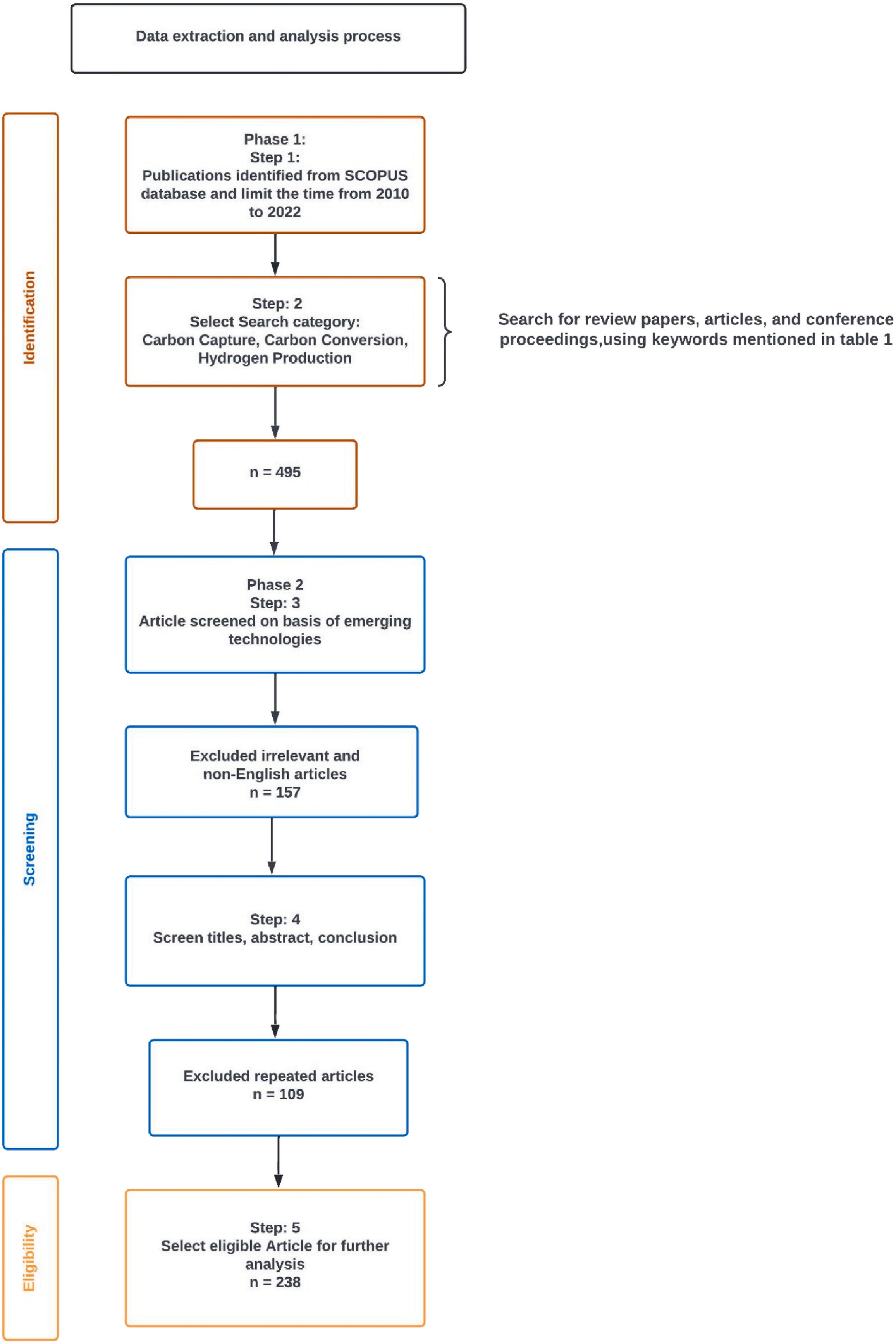

Fig. 6. The methodology followed for the data collection process.

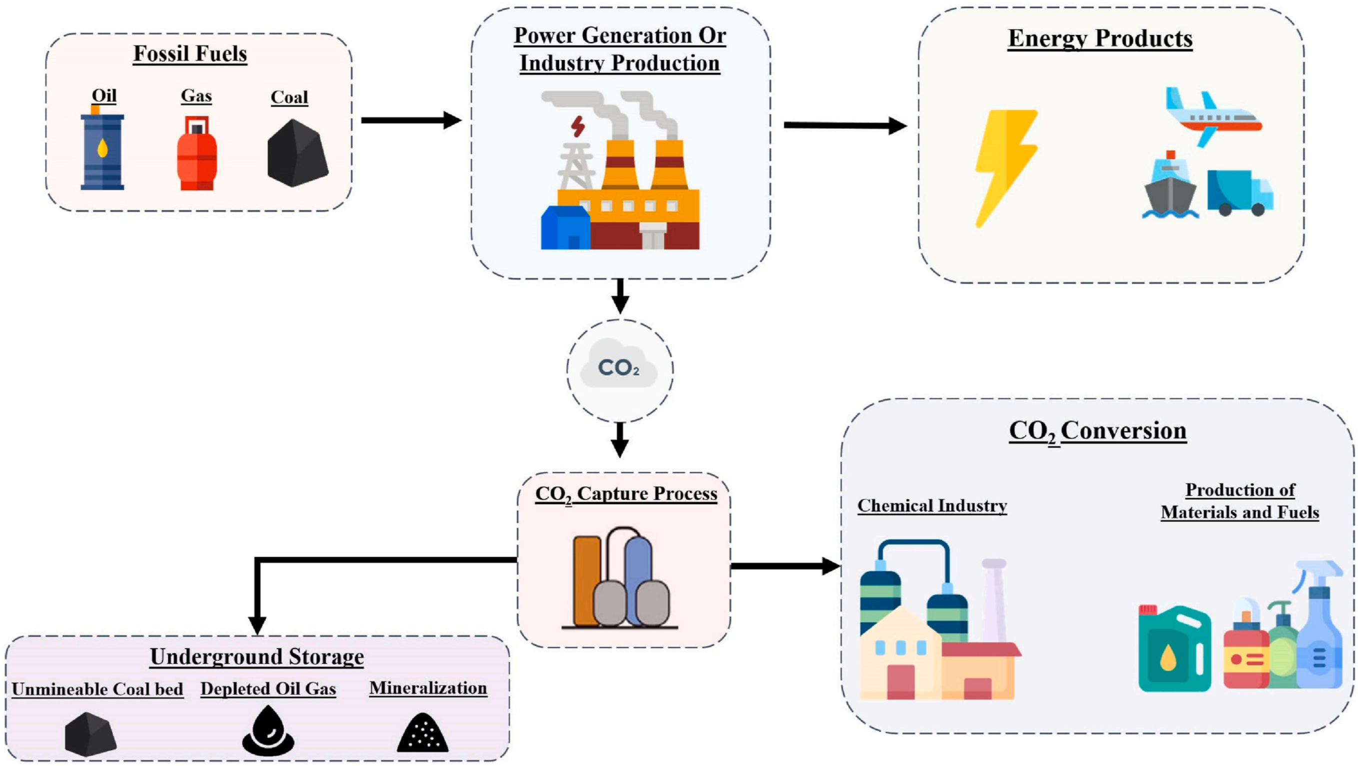

Fig. 7. The significant steps involved in CCUS.

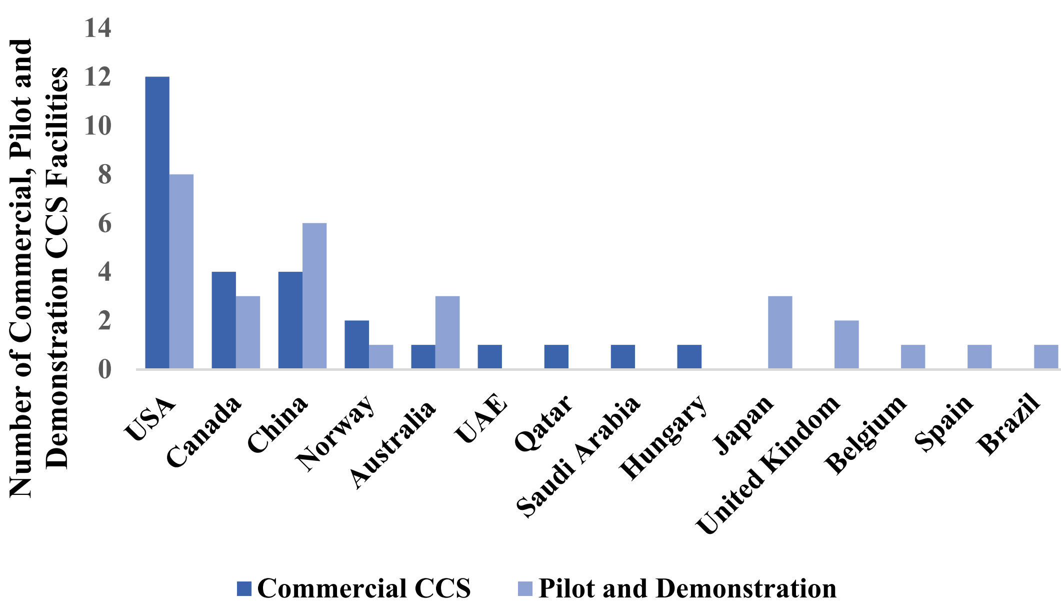

Fig. 8. Worldwide commercial, pilot and demonstration CCS Facilities (Global CCS Institute, 2020).

amine absorption (MEA 30%) concerning a power unit of 630 MW_e. Results showed that the separation of CO_2 using CLC lowered the CAPEX and OPEX by 6% and 14%, respectively (Czakiert et al., 2022). However, the challenge with scaling up the CLC process is that a desulfurization unit is required to prevent carrier sulfidation, which involves high-added costs.

4.2. Technologies for CO_2 conversion

CO_2 conversion technologies are categorized into chemical conversions (e.g., hydrogenation, electrochemical reduction, mineralization, and photochemical) and biological conversion (e.g., non-photosynthetic and photosynthetic), as shown in Fig. 10. The TRL for these technologies varies; for instance, CO_2 hydrogenation for methanol is at TRL 8, whereas ethanol production is at 1–2 (Chauvy et al., 2019; Kamkeng et al., 2021). Mineralization and photosynthetic have TRLs of 4–7 and 7–9, respectively (Jarvis and Samsatli, 2018; Kamkeng et al., 2021). Thermal hydrogenation has gained interest for its high CO_2 conversion efficiency (87 % (Khojasteh-Salkuyeh et al., 2021),), but it is considered energy-intensive (Fan and Tahir, 2022). In addition to these established methods, several emerging converging technologies are gaining attention, including photo-thermal hydrogenation, plasma hydrogenation,

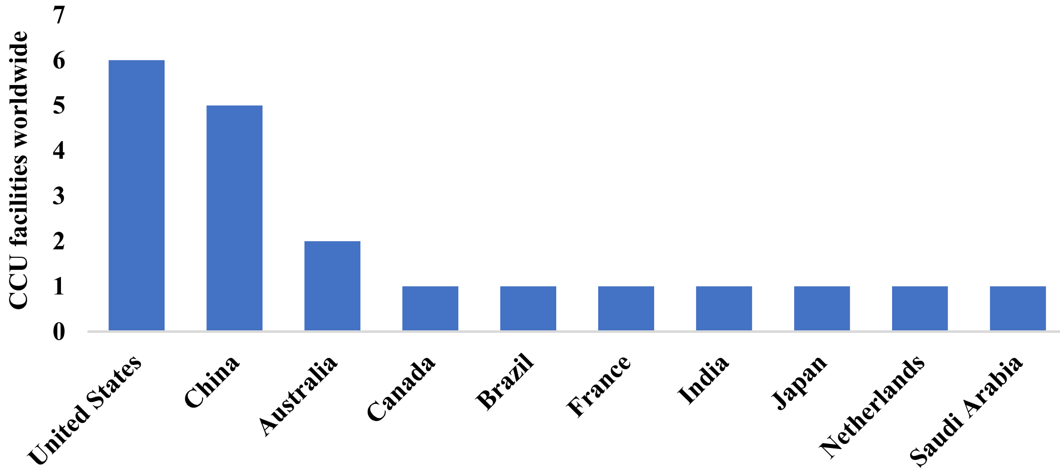

Fig. 9. Active facilities of CCU worldwide (Tcvetkov et al., 2019).

Table 2
Advantages and disadvantages of carbon capture pathways (Leung et al., 2014; Lip et al., 2016).

Pathway	Advantages	Disadvantages
Pre-Combustion	- High CO_2 Concentration and high partial pressure, -Can be retrofitted to existing plants, -Low regeneration energy, -Generation of syngas/H_2 as an alternative fuel, -Low water consumption	-Intensive operating conditions (190–210 °C and 15–20 bar), -Severe energy loss due to regeneration of sorbents, -Issues with temperature swings in syngas
Post-Combustion	-Highly mature technology with numerous industrial applications, -Ability to be retrofitted with ease into existing plants	-Low CO_2 concentration near atmospheric pressure impacts the capture efficiency, -Significant energy penalty due to amine scrubbing process,
Oxy-Fuel	-High CO_2 concentration in the flue gas improves the absorption process, -Potential to be retrofitted to existing plants, -Require smaller equipment size	-Significant efficiency drops and expensive processes, -Energy-intensive due to air separation unit (ASU), -Corrosion problems may occur (Corrosion rate 2.87 mm/year)

electrochemical reduction, photochemical, non-photosynthetic and photosynthetic. This section discusses these novel technologies, their process descriptions, and their drawbacks.

4.2.1. Chemical conversion technologies

4.2.1.1. Hydrogenation. Photo-thermal hydrogenation technology, utilizing solar energy as a heating source, has gained interest for its ability to convert solar energy into heat, effectively increasing the system temperature and improving redox reactions. It combines electronic excitation from ultraviolet radiation adsorption using a semiconductor with thermal energy from exothermic reactions. The catalyst transforms photons into thermal energy, reaching temperatures optimal for hydrogenation reaction (see Fig. 14) (Fan and Tahir, 2022). However, its CO_2 conversion rate is lower than that of conventional thermal hydrogenation (the range of CO_2 yield is in μ mo1.g^{-1}.h^{-1}), and drawbacks like inefficiency of light absorption, and the high cost of renewable hydrogen production limit its large-scale application (Tahir and Tahir, 2020). Photo-thermal reactors encompass three primary aspects: reactor type, heating source, and mode of operation. Structured reactors, preferred for their large surface area for catalyst deposition, include fixed bed reactors, which offer perfect contact between feed and catalyst under light irradiation (Fan and Tahir, 2022). While batch reactors show higher yield efficiency and production rate due to the longer contact time, continuous reactors are widely used in large-scale applications.

Another emerging technology gaining interest is plasma hydrogenation technology. Plasma is an ionized gas consisting of various species, including molecules, radicals, ions, electrons, and excited species, making it highly reactive and beneficial in multiple applications (Snoeckx and Bogaerts, 2017). There are two categories of plasma technology: thermal and non-thermal plasma. Thermal plasma can be created either at elevated gas pressure or high temperatures (4000 K to 20,000 K), with electrons and heavy particles reaching equilibrium temperature (Snoeckx and Bogaerts, 2017). Non-thermal plasma is generated using two parallel electrodes to create an electric field, breaking down gas into ions and electrons. The collisions in this process result in ionization, excitation, and dissociation, creating new compounds, emitting light and forming new gas products (Snoeckx and Bogaerts, 2017). Table 6 summarizes the advantages and disadvantages of thermal and non-thermal plasma.

4.2.1.2. Electrochemical reduction. The electrochemical reduction involves transforming CO_2 into value-added products using an electrolyte cell containing a cathode, an electrolyte, and an anode powered by electricity (Kamkeng et al., 2021). This process forms O_2 and electrons/protons at the anode from oxidation of H_2O, while CO_2 is converted into value-added products at the cathode (see Fig. 15). However, challenges such as low current density, low energy efficiency caused by pH gradient across the cell, and cost of electricity hinder its scalability (Price, 2015). Innovative devices, such as bipolar membranes (BPMs) and various continuous flow reactor configurations, have been developed to overcome these challenges. BPMs improve water auto-dissociation and resolve the pH gradient problems by maintaining a constant pH level at both electrodes (Cells et al., 2016). Continuous flow reactors can overcome the limitation of mass transfer and low CO_2 solubility by diffusing reactants and products from the electrode and utilizing gaseous electrochemical reduction (Liang et al., 2020). Promising device configurations like microfluidic cells, zero-gap electrolyzers, and multilayer electrolyzer stacks are explored for potential commercialization. Details of each device are explained in (Price, 2015).

4.2.1.3. Photochemical reduction. Photocatalytic reduction is an attractive technique for energy and environmental issues. It is an artificial photosynthesis technology in which photocatalysts absorb light to

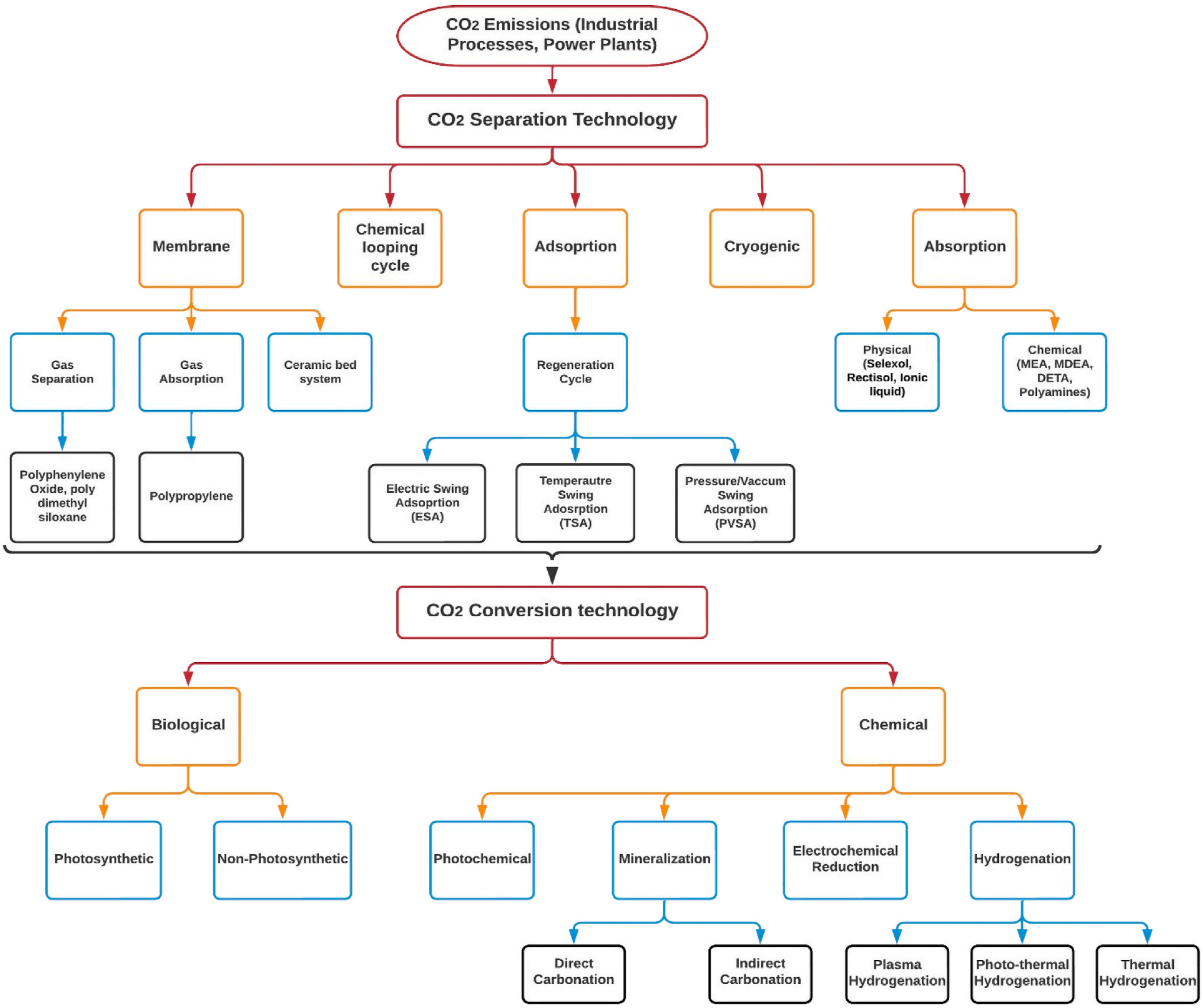

Fig. 10. Listed options of CO_2 capture and conversion technologies.

Table 3
Advantages and disadvantages of different non-conventional V–S separation.

Separation Technology	Advantages	Disadvantages	Energy Duty (MJ/ $kgCO_2$)	Ref.
Cryogenic liquids (Unconventional V–S)	•Can directly contact with the flue gas that contains CO_2, •Prevent freezing of CO_2, •Provide direct cooling	•Rely on types of contact liquid, •Low vapor pressure to prevent loss through evaporation, •Presents environmental risk	0.74	(Jensen et al., 2015; Kirchner, 2020)
Packed Beds	•CO_2 recovery achieved at high purity, •Operational at atmospheric pressure, •Simultaneous removal of CO_2 and H_2O, •Highly applicable for gas streams with a high CO_2 concentration,	•Not economically feasible for streams with diluted CO_2, •Depends on the LNG availability, •Requires high energy due to cooling, •Water removal is required	1.2–2.6	(Tuinier et al., 2011a, 2011b)
Heat exchangers	•Highly effective, •Operates with a relatively small temperature difference	•High installation costs, •Requires more cooling due to the formation of the CO_2 frost layer	1.37	(Kirchner, 2020; Song et al., 2017)

reduce CO_2 into high-energy products (Kamkeng et al., 2021). There are five significant sequential steps as shown in Fig. 16: (1) absorption of photons to generate electrons and hole pairs (h+), (2) spatial separation of these electrons and holes, (3) CO_2 adsorption onto photocatalysts surface, (4) electrons and holes can individually proceed with different half-reactions where electrons reduce CO_2 into value-added products, and holes oxidize water to oxygen, and (5) product desorption from the photocatalysts after reaction completion (Wu et al., 2017a). Significant progress in CO_2 reduction has been made in heterogeneous catalysis to design and fabricate an effective photocatalyst system. Several

Table 4
Summary of capturing capacity for different CO_2 capture technologies.

CO_2 Capturing Method	CO_2 Purity	CO_2 Recovery	Energy Duty (GJ/ tCO_2)	Scale	Ref.
Absorption (Chemical absorbent)	95.3%	60–95%	2.3–9.2	Large scale	Lip et al. (2016)
Absorption (Physical absorbent)	98.7%	90–98%	4–6	Small to large scale	Shiflett et al. (2010)
Adsorption (PSA)	39–57%	99.99%	6.8	Large scale	(Song et al., 2015; Voldsund et al., 2016)
Adsorption (VSA)	>97.0%	>90.0%	0.67–1.71	Large scale	(Salazar Duarte et al., 2017; Voldsund et al., 2016)
Adsorption (TSA)	89.7%	72.0%	4.39	Pilot scale plant	(Joss et al., 2017; Salazar Duarte et al., 2017)
Adsorption (ESA)	89.7%	72.0%	1.9	Small scale	(Ribeiro et al., 2014; Zhao et al., 2018)
Chemical looping cycle (CLC)	98%	99.85%	0.3	Pilot scale plant	(Shi et al., 2019; Zhao et al., 2022)
Cryogenic (Packed Bed)	99.99%	99.99%	2.5–5.2	Small scale	(Kirchner, 2020; Song et al., 2019b)
Membrane	80–95%	60–90%	0.5–6	Pilot scale plant	(Aghaie et al., 2018; Tcvetkov et al., 2019)

parameters are carefully considered, including adsorption and activation of CO_2 on the catalyst surface, which is essential for increasing the selectivity. Product selectivity is significant for generating valuable hydrocarbons and lowering product separation costs. Despite being a promising technology, CO_2 conversion via photocatalytic into sustainable chemicals requires significant efforts to make it a practical reality (Wu et al., 2017a).

4.2.2. Biological conversion technologies

4.2.2.1. Photosynthetic CO_2 fixation. Photosynthetic CO_2 fixation occurs via natural photosynthesis, with plants absorbing sunlight, CO_2, and water to produce energy-rich compounds like glucose and utilizing CO_2, inorganic nutrients, light and water to produce algae (Kamkeng et al., 2021). Algae cultivation occurs in open raceway ponds (RP) and closed photobioreactors (PBRs). Open RP systems involve lagoons and ponds as a medium for growth, whereas the PBRs system uses photobioreactors to control the growing conditions (Bhatia et al., 2019). However, locating ponds near CO_2 sources is challenging due to extensive land requirements and environmental variabilities (Baena-Moreno et al., 2019). Closed systems have advantages over the open system, including reduced water evaporation, minimized predator growth, huge illumination area, and good for algae immobilization (Razzak et al., 2013). Tubular photobioreactors, a closed system outdoors for sunlight exposure, contain a vessel for gas exchange and sunlight absorption for photosynthesis. Despite their advantages, tubular photobioreactors have limitations like pH gradients, costly construction materials, and large land space requirements (Xing Zhang, 2015). Fig. 17 shows a typical photo-bioreactor for photosynthesis CO_2 fixation.

4.2.2.2. Non-photosynthetic CO_2 fixation. This technique utilizes a source that contains high-energy electrons and microorganisms for CO_2 conversion into bio-products. It operates under two conditions: aerobic and anaerobic. For aerobic fixation, the microorganisms have direct exposure to the oxygen from the environment surrounding the system. In contrast, oxygen is blocked from accessing the system in the case of anaerobic (Hawkins et al., 2013). One significant merit of the non-photosynthetic method is that it can produce various bio-products, such as biomass and methane and operate under moderate conditions.

Table 5
Summary of advantages and limitations of carbon capture.

CO_2 Capturing Method	Advantages	Limitations	Ref.
Absorption (Chemical absorbent)	•Mature technology, •High removal rate (90%), •Cheap commercialized solvents	•High sorbent regeneration energy, •High oxidation and thermal degradation, •High corrosivity leads to significant CAPEX and OPEX	Lip et al. (2016)
Absorption (Physical absorbent)	•Suitable for pre-combustion, •Recoverable solvents during regeneration, •Require low heat regeneration, •Non-corrosive and stable solvent	•More economical only at high pressure, •Absorption efficiency highly depends on CO_2 concentration, •Potential adverse impact on the environment from solvent degradation	Hjeij et al. (2022)
Adsorption	•Mature Technology and low cost, •Reusable and recoverable adsorbents, •High adsorption efficiency at high pressure and low temperature	•High pressure and temperature requirements for CO_2 removal led to high energy penalties, •Sorbent regeneration happens periodically, causing sorbent degradation, •Low CO_2 selectivity	Ribeiro et al. (2014)
Chemical looping cycle	•Cost-effective and efficient technology, •Eco-friendly process, •Generates pure CO_2, •NO_x formation can be minimized during combustion	•Operates under high-pressure conditions, •Inclusion of desulfurization increases cost, •Oxygen carriers are not mechanically stable	Okonkwo et al. (2021)
Cryogenic	•Matured technology, •Produces pure CO_2 stream, •It can be retrofitted to post-combustion	•Only suitable for process streams with high CO_2 concentration, •Applicable at a very low temperature, •Energy-intensive due to refrigeration loops	Okonkwo et al. (2021)
Membrane	•High CO_2 recovery and purity of CO_2, •Fewer energy requirements, •Low CO_2 separation cost	•Relatively low selectivity of CO_2, •Not convenient for process operation with high temperatures, •Prone to corrosion, •Complex operation	Eljack and Kazi (2021)

4.2.3. Challenges for commercialization

To effectively mitigate climate change, the high volume of CO_2 conversion to value-added products would be a pragmatic approach. However, most carbon conversion technologies struggle to become economically feasible due to the high cost of electricity, CAPEX, and the uncertain market demand due to the lack of supportive regulation. Other technical limitations of carbon conversion technologies can still be addressed through research, especially for the technologies with lower TRL (Lamberts-Van Assche et al., 2022). Alternative system designs for these emerging technologies can overcome some economic challenges of scaling up operations; however, the current literature is thin. In terms of

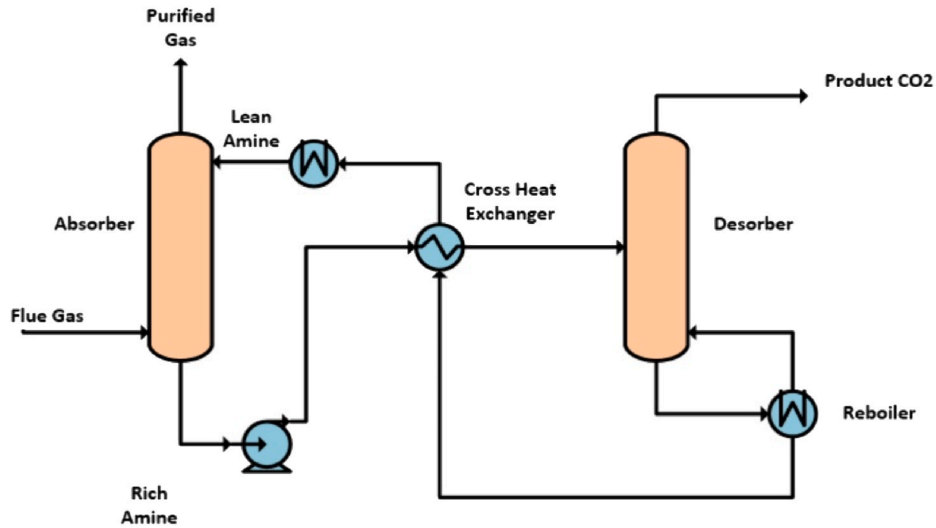

Fig. 11. Typical process flow diagram of CO_2 capture by the absorption process.

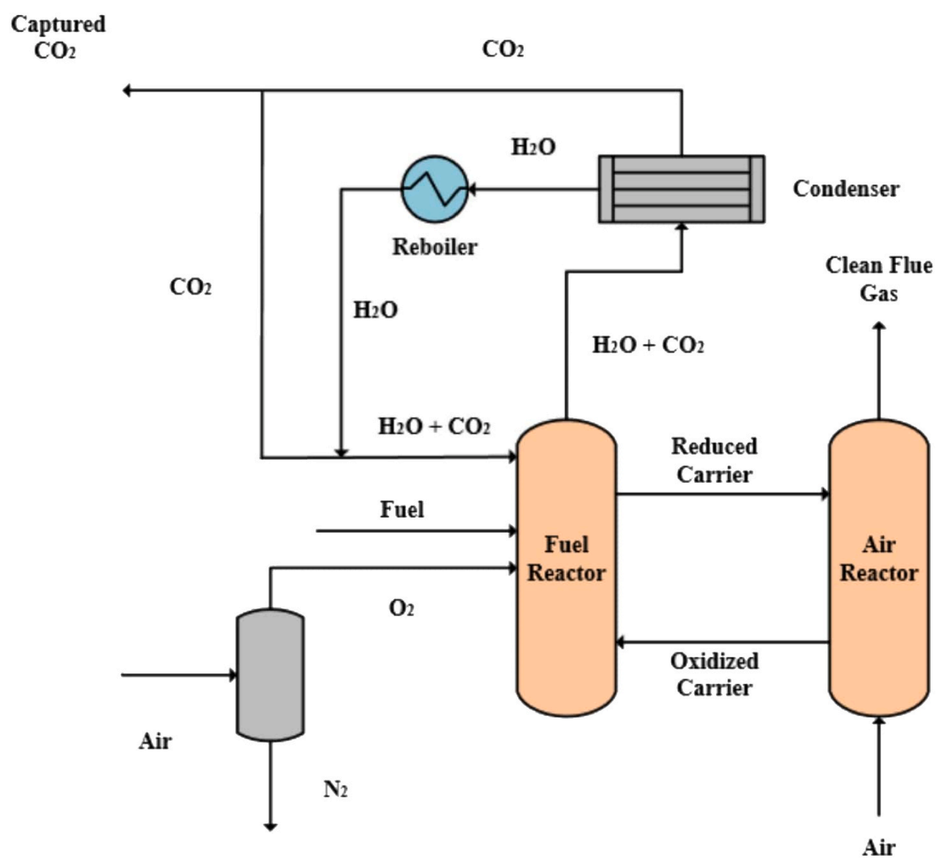

Fig. 12. Typical Chemical-looping process for CO_2 capture.

commercialization of conversion technologies, mineralization is a favorable option amongst others; it constitutes 43% of commercial projects (see Fig. 18). Due to their low TRL, it is noted that there are no commercial projects for electrochemical, non-photosynthetic, photo-chemical, and plasma catalysis.

Plasma catalysis (TRL between 1 and 3) is a promising technology and has some economic advantages, such as low investment and operating costs (see Table 7) (Snoeckx and Bogaerts, 2017). There is an issue with the scalability of plasma-based conversion technology; mainly, as the reactor size increases, the conversion rate is limited. If the plasma concentration is confined in the unit's center, it may impact the rector's efficiency. Notably, in large reactors, more molecules may not pass through the active plasma region (Bogaerts and Centi, 2020). Lamberts-Van Assche et al. (2022) investigated the techno-economic feasibility of CO_2 conversion using plasma catalysis through different reactor configurations. They concluded that longer space-time and the inclusion of packing material increase the operational cost of electricity (35 €M OPEX) and the CAPEX of power supply (80 €M CAPEX).

The electrochemical reduction (ER) technology is still at a pilot scale with a TRL of 3–5. Several advances are still required to address the

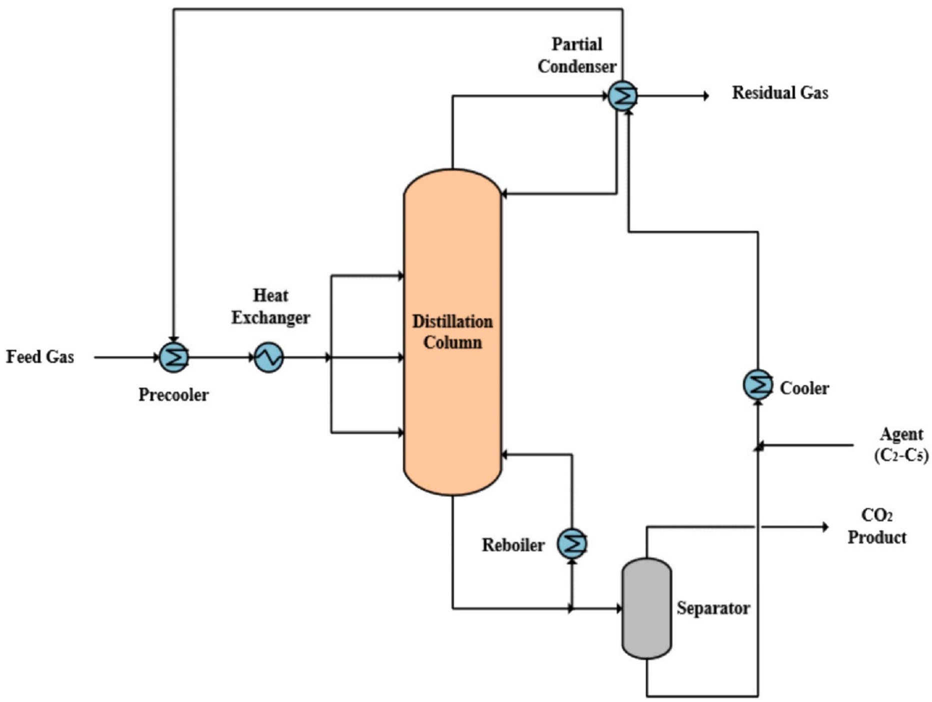

Fig. 13. Process flow diagram of Cryogenic distillation technology for CO_2 capture (Reproduced from Ref (Song et al., 2019a).

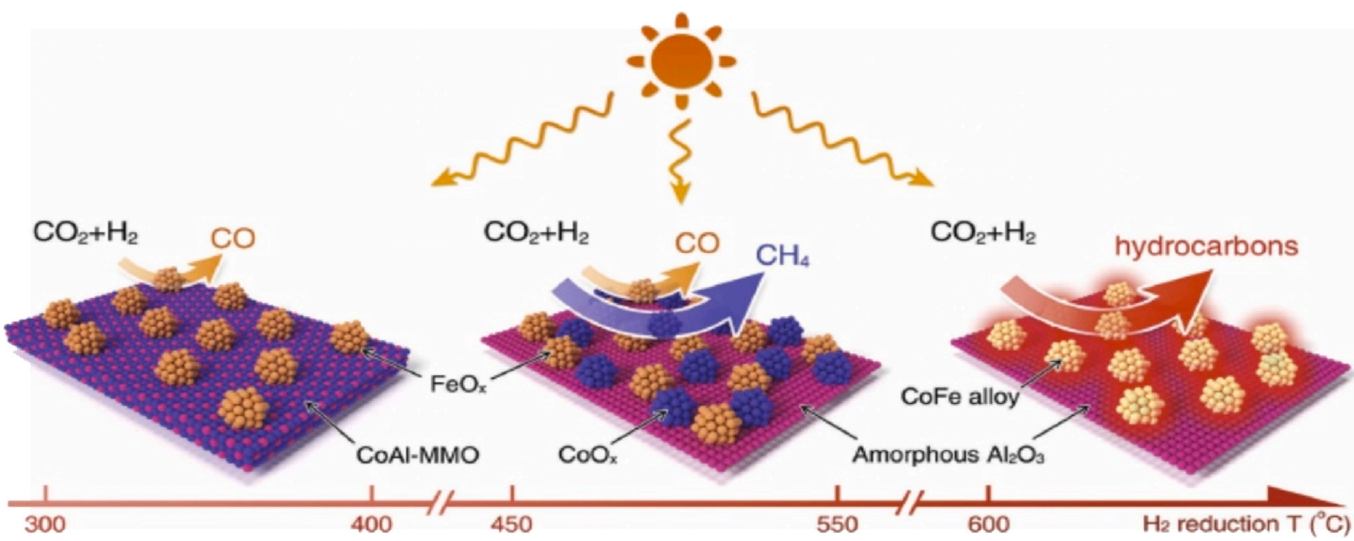

Fig. 14. Schematic diagram of CO_2 hydrogenation in the photo-thermal process (Chen et al., 2018).

current issues to ensure ER's commercial viability and sustainability (see Table 7). Many studies have focused on the economics-cost assessment of large-scale electrochemical reduction of CO_2 to see its viability. Rumayor et al. (2019) evaluated the techno-economic of CO_2 conversion via ER to produce formic acid (FA). The evaluation showed that ER technology has excellent environmental benefits; however, this technology is considered uncompetitive and not profitable according to the current market conditions. Agarwal et al. (2011) compared the economic viability of large-scale ER of CO_2 to formic acid and formate salts with the conventional CCS. Their findings showed that CAPEX (2.9 $M) for ER is less by around 40% compared to CCS (4.7 $M), but the OPEX (\$1150/tCO_2 mitigated) is three times larger than CCS (\$390/tCO_2 mitigated). Both options gave a negative net present value for a 25-year plant life, implying that ER is not profitable.

Despite the abovementioned uncertainties, CCC technologies are anticipated to play a significant role in applying clean energy production, particularly hydrogen production. The opportunity to couple novel CCC technologies with available and novel hydrogen production routes in Qatar entails several advantages to Qatar's economy; this is discussed in detail in the following section.

5. Hydrogen production pathways

There are different pathways available for hydrogen production. The choice of pathways often depends on the type of feedstock used. Hydrogen can be produced from non-renewable feedstock techniques such as steam reforming, coal gasification, and coal pyrolysis and renewable resources methods like biomass gasification, electrolysis, and photocatalysis.

Steam methane reforming (SMR), the most efficient (74–85%) and

Table 6
Advantages and disadvantages of thermal and non-thermal plasma technology (Models, 2022; Oost, 2022; Snoeckx and Bogaerts, 2017).

Technique	Advantages	Disadvantages
Thermal Plasma	•High temperature, and energy density, •Intense non-ionization radiation, •Directional and controllable heat source with steep thermal gradients that are independent of the chemistry, •Able to reach a temperature of 20,000 K in comparison to fossil fuels (limit 2300 K)	•Thermal plasma instability leads to inefficient CO_2 conversion, •High energy consumption
Non-thermal Plasma	•Highly energetic electrons can initiate a mixture of highly reactive chemicals at room temperature, •Affordable reactors	•Considered a non-selective plasma when the desired products are formed, •Limited CO_2 conversion rate

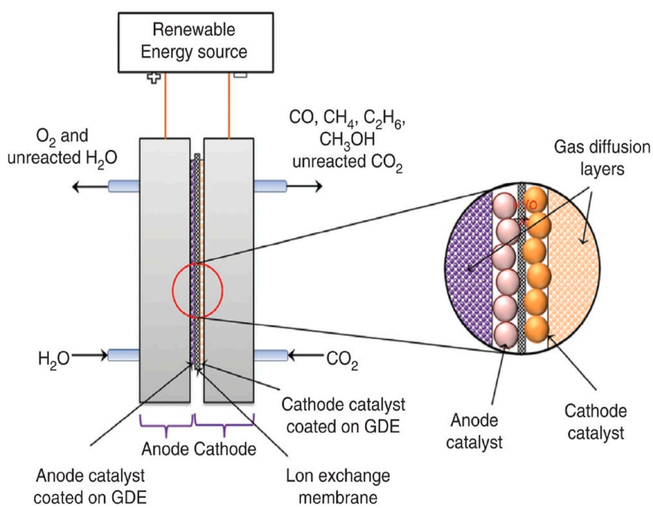

Fig. 15. Schematic diagram of electrochemical reduction of CO_2 (Malik et al., 2017).

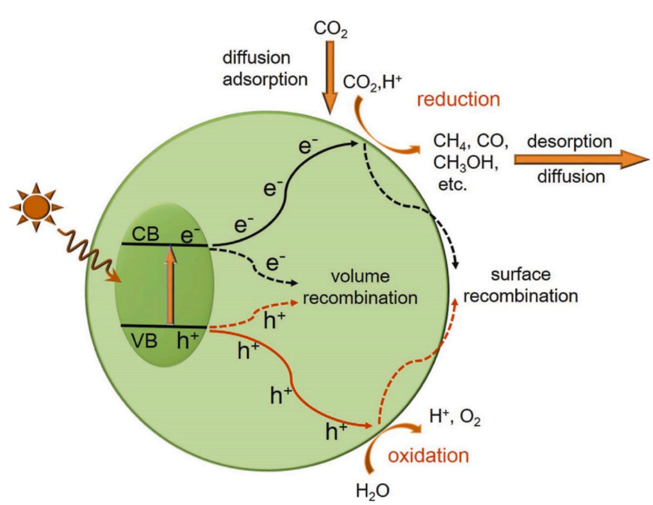

Fig. 16. Schematic diagram of the significant steps in CO_2 reduction by photocatalytic (Wu et al., 2017a).

cost-effective process for hydrogen production, uses an endothermic reaction to generate hydrogen from methane after heating and sulfur removal (Nikolaidis and Poullikkas, 2017). In this process, methane and steam react over a catalyst, producing hydrogen and CO, known as syngas. The SMR efficiency is further enhanced by the water gas shift reaction (WGS), generating CO_2 and more hydrogen. Partial oxidation (POX) combusts natural gas with pure oxygen in a reformer, resulting in a lower H_2/CO ratio. It functions with or without a catalyst, operating between 780 and 900 °C and pressure between 25 and 35 atm (Voldsund et al., 2016). POX offers quicker output and less sensitivity to gas compositions than SMR. Auto-thermal reforming (ATR) combines SMR and non-catalytic POX, operating at lower conditions but with potential hydrogen oxidation due to the high presence of oxygen. The critical limitation associated with these technologies is that they are highly dependent on fossil fuels, resulting in high CO_2 emissions (e.g. SMR: 11.35 $kgCO_2/kgH_2$, POX: 9–10 $kgCO_2/kgH_2$, ATR: 11.01 $kgCO_2/kgH_2$ (Muradov, 2017; Oni et al., 2022),). Despite this, they are mature and economically viable pathways for hydrogen production with high energy efficiency (see Table 8).

Coal gasification is a significant thermal process for hydrogen production, converting carbonaceous fuels, such as coal or biomass, into syngas (CO and H_2) (Wang and Zhang, 2017; Younas et al., 2022). The quality of the gas produced relies on various technical parameters and operating conditions and the hydrodynamic characteristics of the gasifier (Kuo et al., 2014). The fuel reacts with steam and oxygen at high pressures and temperatures during this process. While coal is an abundant feedstock, its use in gasification can have an inverse impact due to the production of sulfur oxides and high CO_2 emissions (20.8 $kgCO_2/kgH_2$ (International Energy Agency, 2021),). Biomass gasification process offers a renewable and economical alternative, achieving an efficiency of 35% with a neutral CO_2 impact. It operates at 700 and 1200 °C using steam, air, or oxygen, where steam processing increases the H_2 yield and generates pure nitrogen (Arregi et al., 2018). Catalysts, particularly nickel-based catalysts, are crucial in enhancing hydrogen yield from biomass gasification due to their affordability (Luo et al., 2018). However, a significant drawback is that the feedstock contains impurities that fluctuate the hydrogen yield.

Pyrolysis is a relatively new and CO_2-neutral process; it can produce more hydrogen with relatively high efficiency (35–50%). It operates at a high temperature (800–1000 °C) by heating organic materials without oxygen to produce syngas, liquid fuel, and solid charcoal (Younas et al., 2022). Despite its great potential, pyrolysis is still in its early stage of development. One of the significant drawbacks of pyrolysis is the deposition of char and tar on the catalyst surface, which decreases hydrogen yield and causes catalyst poisoning (Hu and Gholizadeh, 2019).

Electrolysis is a sustainable and clean pathway for generating hydrogen and oxygen from water, with an efficiency of 70%. This process is mainly powered by wind and solar energy. It comprises electrolysis cells containing electrolytes, anode-cathode electrodes, and a separator with alkaline electrolysis (AEL) (Li and Baek, 2021). Although only 4.0% of the hydrogen is produced from water electrolysis, it provides a pathway for hydrogen production independent of fossil fuel feedstock, requiring only water and electricity. However, electrolyzer utilizes energy from grids mainly powered by fossil fuel, affecting their environmental performance (Wang et al., 2014). Photocatalysis is the best alternative regarding overall environmental performance. It involves three steps on semiconductor particles (Tong et al., 2012): (1) absorption of photons, (2) creation of charge separation, and (3) surface chemical reactions. The recombination of photo-induced charge carriers is somewhat high in semiconductors, and their solar energy efficiency is minimal. Subsequently, the heterojunction of semiconductors is typically made with other semiconductors that possess favorable features like lower bandgap, electron mediators, and metals to ease the energy reduction barrier for hydrogen evolution (Buttler and Splietho, 2018).

Variables such as energy source, feedstock, capital, and hydrogen

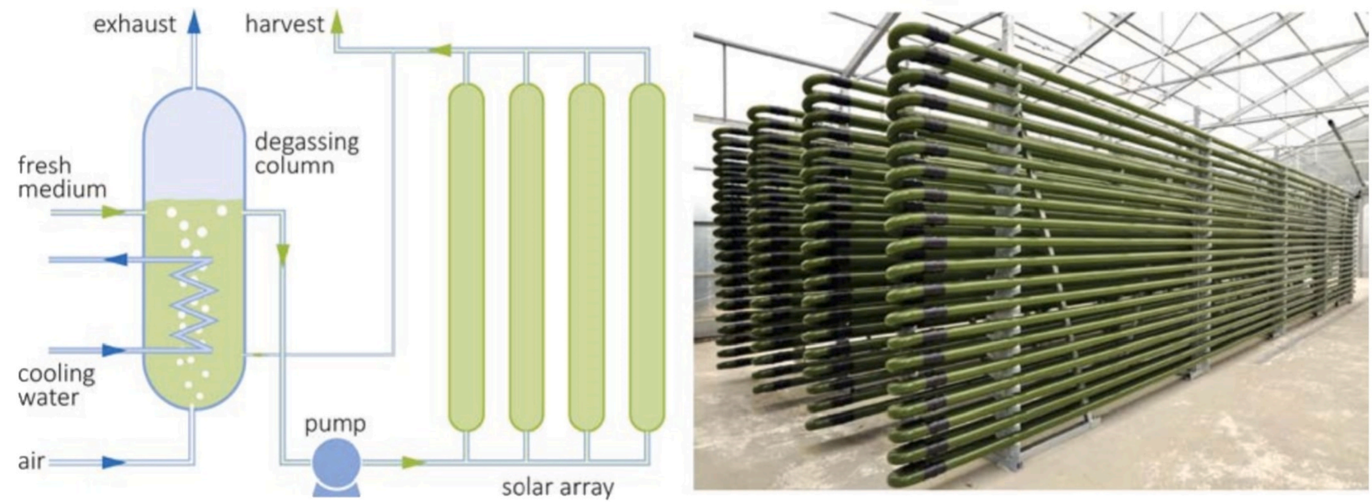

Fig. 17. A typical horizontal tubular photobioreactors for photosynthesis CO_2 fixation (Xing Zhang, 2015).

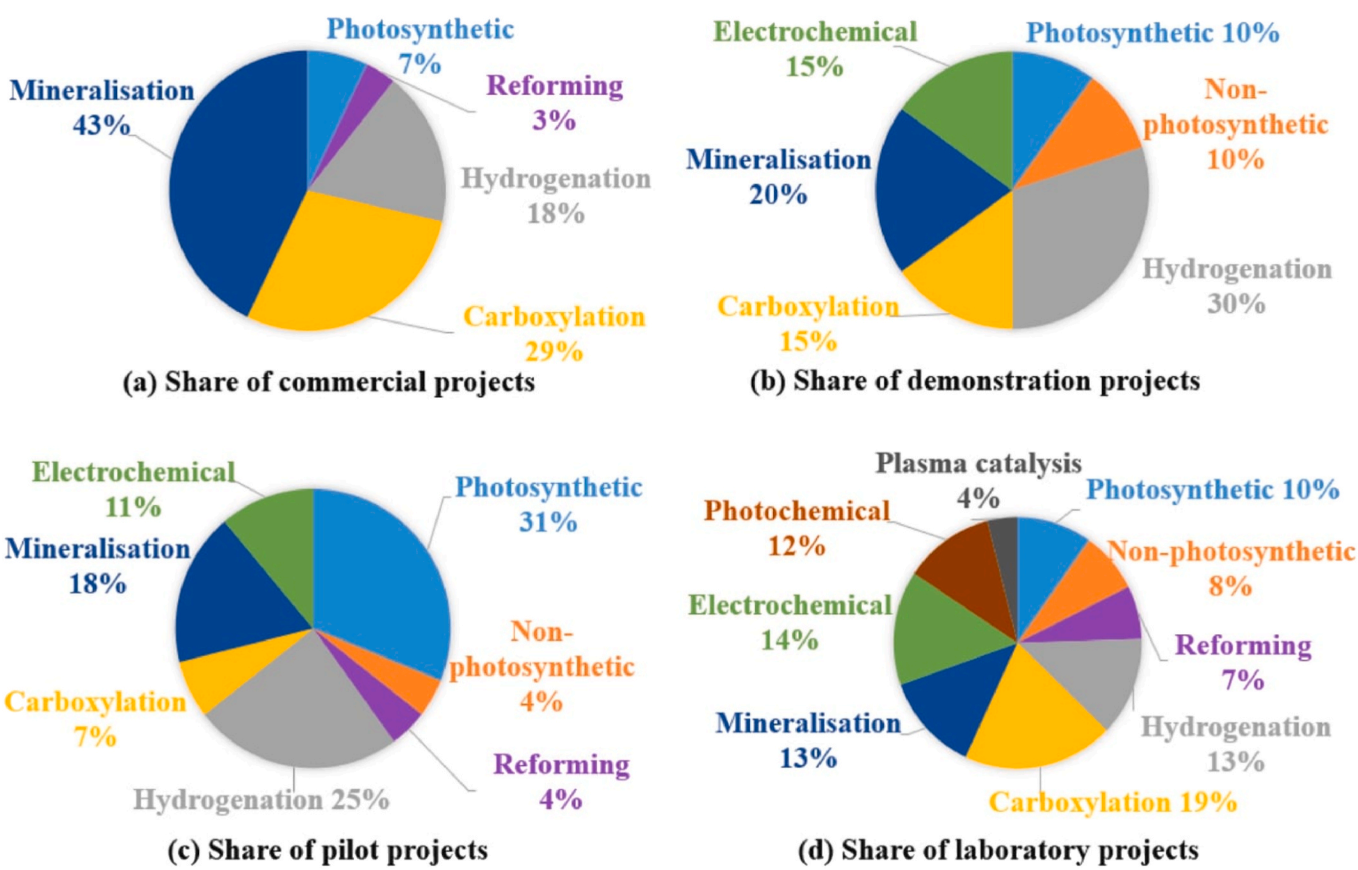

Fig. 18. Percentage distribution of project scale for different CO_2 conversion technologies (Kamkeng et al., 2021).

cost are crucial factors in qualitatively evaluating the costs for each hydrogen production pathway (see Table 9). For energy sources, some of the merits of hydrogen production methods that utilize standard fossil fuels include operating with existing equipment with reasonable capital costs and low hydrogen production costs ranging between 1.48 and 2.27 $/kg of Hydrogen. Further reduction in hydrogen production cost is expected from hydrocarbon pyrolysis ($1.59–1.70/kg). Nevertheless, these methods rely on fossil fuels and are considered disadvantageous since the CO_2 released from the reforming and coal gasification process requires additional costs associated with energy-intensive processes for carbon capture. The option to make the production cleaner with a lower carbon footprint and sustainable is to capture or utilize the CO_2.

Hydrogen from renewable routes has significantly improved performance and costs over the past few years and can offer a new market for low-carbon hydrogen in the long run. The cost of these pathways will decrease over time with cheaper raw materials. A reduction in hydrogen production costs is expected as biomass gasification is economically feasible with comparable production costs (1.77–2.05 $/kgH2) to conventional methods. High production costs are associated with water-splitting technology such as electrolysis, especially those that use solar

Table 7
Comparisons of CO_2 transformation technologies.

Technology	Advantages	Limitations	Efficiency	Scale	Ref.
Plasma Catalysis	•Generated by electricity instead of heat, •Mild operating conditions, •Relatively low cost, •Easy to upscale	•Energy efficiency varies with plasma type and operating condition, •Low selectivity, •Low conversion rate	47.8 %	Small scale	Bogaerts and Centi (2020)
Electrochemical	•Electro-catalyst and photovoltaic design are flexible, •Recycling electrolytes is possible, •Controlled reaction to facilitate the operation, •Easy to scale up	•Low reaction activity, •CO_2 reduction kinetics are slow, •Short catalytic life, •Economically not feasible	>80%	Pilot scale	(Wu et al., 2017b; Yaashikaa et al., 2019)
Photochemical	•Require less energy andtemperature, •Cost-effective, safe, and environmentally friendly, •Mild reaction conditions	•Difficult separation of catalyst and product, •Product selectivity is problematic and low yield, •Intricate design of photo-reactor process	>10%	Small scale	(Wu et al., 2017b; Yaashikaa et al., 2019)
Biological	•Algae utilization is cost-effective, •Possible direct CO_2 injection to enhance productivity, •Less energy requirement for CO_2 capture	•Climate conditions limiting algae growth, •Low energy harvesting and efficiency, •Low adsorption capacity	2–5%	Pilot to Demonstration scale	(Bhatia et al., 2019; Zhang et al., 2017)
Mineralization	•The reaction is exothermic, •Ecofriendly, •A profusion of feedstocks, •Industrial waste utilization	•Reaction kinetics are slow, •Expensive process, •Feedstocks require pretreatment, •Environmental issues attributed to the mining of feedstock	74%	Commercial scale	(Agarwal et al., 2011; Khojasteh-Salkuyeh et al., 2021)

Table 8
Advantages and limitations of several hydrogen production methods along with cost and efficiency.

Hydrogen Production Method	Advantages	Limitations	Efficiency	Ref.
Steam Methane Reforming (SMR)	•The cost of production is low, •High GHG emissions,	•High yield efficiency •Operates at high temperatures, •Depletion of fossil fuels	74–85%	(Neeraj and Yadav, 2020; Nikolaidis and Poullikkas, 2017)
Partial Oxidation(POX)	•Exothermic reaction is mild, •The operating temperature can be reduced via a catalyst, •94% hydrogen yield can be obtained by air and oxygen	•The process is complex, •Formation of soot and petroleum coke	60–75%	(Hjeij et al., 2022; Sadati et al., 2015)
Auto-thermal Oxidation(ATR)	•Straightforward design, •Utilizes alcohols such as methanol, ethanol, etc., •Larger CO_2 capture potential (more than 90%)	•High temperature causes deposition of carbon, reducing reformer performance	60–75%	(Hjeij et al., 2022; Shiva Kumar and Himabindu, 2019)
Gasification(Coal)	•Efficiently convert the ash content and moisture into useful output, •Produce syngas with a high calorific value	•Condensation occurs and creates ash and tar in gasification fuel that causes metal corrosion	28.5–51.2%	(Mazzella et al., 2016; Tong et al., 2012)
Gasification(Biomass)	•High efficiency in terms of energy and exergy, •Co-gasification generates more hydrogen, •Less GHG emissions	•Requires high operating temperature, •Production of tar, •Gasifier has a short life span, •Depletion of fossil fuels	35%	(Shiva Kumar and Himabindu, 2019; Yan et al., 2021)
Pyrolysis	•Fewer carbon footprints, •Cheap and abundant feedstock, •CO_2 neutral, •Lower energy demand than SMR	•Early stage of development, •Pressure resistance, hydrogen aging, and corrosion problem, •Auxiliary equipment required for end product purification, •Seasonal availability	35–50%	(Hu and Gholizadeh, 2019; Shiva Kumar and Himabindu, 2019)
Electrolysis	•Effective way to produce hydrogen from renewables, •Responsible for 4% of total production worldwide, •Established technology, •Oxygen as a byproduct	•Energy-intensive and high maintenance cost, •Problem with transportation and storage.	60–80%	Eljack and Kazi (2021)
Photocatalysis	•Feedstock found in abundance, •Oxygen as a byproduct, •Low principal cost	•Expensive catalysts, •Regeneration is difficult, •The development of low-cost semiconductors is a challenge, • High energy band gap	0.06%	(Alok et al., 2022; Wang and Zhang, 2017)

Table 9
Summary of the costs of different hydrogen production processes (Kazi et al., 2021; Khojasteh Salkuyeh et al., 2017; Nikolaidis and Poullikkas, 2017).

Process	Energy source	Feedstock	Capital cost (M$)	Hydrogen cost ($/kg)
SMR	Fossil fuels	Natural Gas	180.7	2.27
POX	Fossil fuels	Hydrocarbon	128.95	1.48
ATR	Fossil fuels	Natural Gas	326	1.48
Methane Pyrolysis	Internally generated steam	Natural Gas	–	1.59–1.70
Gasification (Coal)	Fossil fuels	Coal	435.9	1.96
Gasification (Biomass)	Internally generated steam	Woody Biomass	149.3–6.4	1.77–2.05
Photocatalysis	Solar	Water	–	9.00
Electrolysis (Solar PV)	Solar	Water	12–54.5	5.78–23.27

as an energy source. The high energy consumption and maintenance cost increased hydrogen production from electrolysis (5.78–23.27 $/kgH_2$). Photocatalysis has the highest hydrogen production cost (9.00 $/kgH_2$) with efficiency as low as 0.06%, making this technology the least cost-effective pathway currently available.

5.1. Role of CCC for deployment of large-scale hydrogen production

The urgent need to reduce carbon intensity from industrial activities, including large-scale hydrogen production, is critical in the global transition to clean energy by 2050. As Qatar is committed to reducing carbon emissions and transitioning into a low-carbon energy era, investing in CCC technologies could be a valuable addition to its clean energy initiatives. Incorporating CCC technology into the nation's hydrogen production strategy constitutes a milestone that aligns with Qatar National Climate Change Action Plan, 2030 of sustainable growth and economic diversification.

Integrating CCC technologies with large-scale blue hydrogen production can reduce the need for CO_2 sequestration and offset the overall production cost of hydrogen. Hence, conducting studies to identify viable CCC pathways using Qatar's existing infrastructure and establishing a framework to explore the techno-economic-environmental evaluation of blue hydrogen production with CCC technologies is necessary. As shown in Table 10, some recent papers have explored the applicability of integrating CCC with blue hydrogen production, offering recommendations and perspectives.

Based on the data shown in Tables 8 and 9, it is worth mentioning that the SMR process is an excellent pathway for hydrogen production in Qatar due to its maturity and cost-effectiveness. Integrating a convenient CCC can be an efficient method to expedite the transition into the low-carbon economy in the mid-term. With a long-term goal of carbon neutrality within the next 15–30 years, these studies should consider the existing commercialized CO_2 capture systems, carbon conversion technologies, emerging alternatives, and their life cycle assessment (LCA) in a broader context. Deploying such technologies is essential to pave the way for a sustainable future. By exhaustively exploring all possible avenues and considering novel technologies, informed decisions can be made that will result in the successful implementation of CO_2 mitigation.

6. Conclusion and outlook

With the growing concerns about global warming, decarbonizing the energy sector is crucial for mitigating industrial CO_2 emissions and achieving carbon neutrality. Qatar has several potential decarbonization routes, including low-carbon hydrogen production and solar energy. This paper systematically reviews a pathway toward decarbonization, focusing on CO_2 capture and CO_2 conversion and opportunities to integrate CCC technologies with low-carbon hydrogen. The paper has identified several technological advancements that are still required for the energy transition. The main conclusions are:

- Physical absorption with ionic liquids (ILs) has multiple advantages for carbon capture, making them favorable alternatives. However, their tunability makes it challenging to identify the optimum candidate for CO_2 capture from the thousands of potential candidates. CLC is one of the most efficient and environmentally friendly CO_2 capture technologies for fuel-based power plants, though it has significant setbacks like mechanical stability and high oxidation/reduction activity. The novel unconventional vapor-solid cryogenic technology is proven to be less energy-intensive than the conventional vapor-liquid pathway.
- CO_2 conversion technologies are a growing area of research due to their potential environmental benefits. However, further development is required for emerging technologies like photo-thermal and plasma hydrogenation to overcome challenges related to lack of data and inefficient CO_2 conversion. Electrochemical reduction has disadvantages that limit scalability, such as low energy efficiency due to pH gradient. Innovative devices like BPMs have been recommended to address this issue. Photochemical reduction is a promising technology for addressing energy and environmental concerns, but it requires more attention to enhance product selectivity and yield. The closed system has demonstrated advantages over the open system,

Table 10
Recent papers on coupling CCC with hydrogen production technologies.

Hydrogen production methods	CCC pathways	Objectives	Recommendations and future prospects	Ref.
SMR	•Carbon capture: Chemical absorption (MEA), •Carbon conversion: Electrochemical reduction of CO_2	•Investigate the techno-economic parameters that impact the cost of blue hydrogen production with CCC options	•Explore additional opportunities for low-cost CO_2 conversion from blue hydrogen production, •Detailed understanding of full life-cycle benefits of deploying CCC in different applications	Ali Khan et al. (2021)
Pyrolysis/ gasification (Biomass)	•Carbon capture: Chemical absorption (MEA), •Carbon conversion: CO_2 reforming	•Investigate the performance of integrating CCC with pyrolysis/gasification to test the applicability for further development	•For high CO_2 conversion, solid carbon should be added in the reforming stage and regulate operating conditions, •The findings of this work are valid for the large-scale deployment of pyrolysis/gasification with CCC	Chai et al. (2022)
Gasification (coal)	•Carbon capture: Chemical absorption (MEA), • Carbon conversion: CO_2 reforming	•Develop a conceptual design that can produce syngas based on process intensifications, •Lower the exergy destruction, •Enhance performance in terms of carbon emissions, cost, and energy requirements	•Further investigation is required for challenges related to catalyst deactivation due to coke formation	Alibrahim et al. (2021)

such as reduced water evaporation and an excellent environment for algae immobilization. Nevertheless, climate conditions are a significant drawback for algae growth.

- Hydrogen, as a clean energy carrier, is believed to play a vital role in decarbonizing the energy sector and meeting the growing demand for energy. However, extensive research is required to make hydrogen play a critical role in the energy system. Hydrogen can be produced by different technologies with SMR, a widely used technique. Cleaner routes to produce sustainable hydrogen, including coal gasification, pyrolysis, electrolysis, and photocatalysis, have also been discussed in this review. Gasification and pyrolysis are both economically viable and could be a competitive alternative to conventional technologies with limitations that hinder their large-scale application.
- Qatar's abundant natural gas resources can position the country as a global leader in low-carbon hydrogen providers. Integrating established and emerging CCC technologies is vital to offset the cleaner hydrogen production cost. However, a critical analysis of the emerging CCC technologies is needed to ensure their economic viability.

CRediT authorship contribution statement

Sadah Mohammed: Writing – original draft, Investigation, Conceptualization. **Fadwa Eljack:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Saad Al-Sobhi:** Writing – review & editing, Conceptualization. **Monzure-Khoda Kazi:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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