

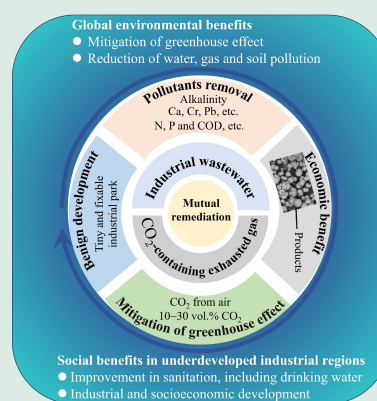
# Mutual remediation of CO<sub>2</sub> emissions and industrial wastewater: feasibility, application, and ecological impact

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## HIGHLIGHTS

- Mutual remediation of wastewater and CO<sub>2</sub> gas is reviewed as a new concept.
- CO<sub>2</sub> is absorbed, and industrial wastewater is preliminarily purified by this method.
- The evaluation shows that this method might have good technical economy.
- This strategy can work well in small and flexible industrial parks.
- Industrial-enviro conflict may ease in weak industrial areas by using this method.



**ABSTRACT:** Wastewater and CO<sub>2</sub> generated and discharged in scattered sites from small-scale factories and workshops in underdeveloped industrial regions have posed a serious threat to global ecology and health for decades. Interestingly, it has been demonstrated that some industrial wastewater can absorb carbon dioxide from exhaust gas. This presents a cost-efficient solution to mitigate pollution from carbon emissions. This review introduces the innovative concept of large-scale mutual remediation of these two types of wastes. By closely examining existing research on the subject, the potential challenges of implementing such a remediation strategy are thoroughly evaluated. Specifically, the process of mutual remediation yields positive results for both air and water quality: 1) direct absorption of carbon dioxide from tail gas or air; 2) removal of aqueous alkalinity, calcium, and heavy metals from various types of industrial wastewater; 3) transformation of nitrogen, phosphorus, and organic pollutants found in industrial wastewater; and 4) generation of valuable byproducts such as carbonates and biomass. Barriers to the widespread adoption of this remediation method include high cost, insufficient treatment, and difficult collection and transportation of wastes, which can be overcome by increasing product value, integrating the method with other processes, and building small-scale low-carbon industrial parks, respectively. Finally, current research gaps and future work are highlighted to advance

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Article history: Received 6 December 2024, Revised 1 April 2025, Accepted 1 April 2025, Available online 16 May 2025

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the development of mutual remediation of wastewater and carbon emissions in underdeveloped industrial areas and facilitate green industrial development.

**KEYWORDS:** Industrial wastewater, Carbon dioxide, Mutual remediation, Scattered pollution, Underdeveloped industrial regions

## 1 Introduction

Industrial wastewater and exhaust gas are crucial factors affecting the global environment (Jassby et al., 2018), public health (Tobler and Culumber, 2016), and industrial and socioeconomic development. The large-scale discharge of these wastes is generally centralized and managed in the form of wastewater treatment plants (Martinez-Alcala et al., 2018) and waste gas recycled stations (Guo et al., 2015). The intermittent release of wastewater and exhaust CO<sub>2</sub> from small-scale factories and workshops also pose a great threat to the environment, owing to their substantial total emissions on a global scale (Fu et al., 2022). The annual discharge of scattered industrial wastewater has exceeded 800 billion cubic meters in recent years, representing 40% of the global outflow (Resources: UNEP). Additionally, the dispersed emissions from many factories and workshops release a significant amount of CO<sub>2</sub> into the atmosphere, despite efforts to control carbon emissions.

Many of these factories and workshops are located in regions with low industrial activity (Wang and Li, 2022), characterized by numerous small dispersed facilities and few large plants. Handling pollutants from these locations in a centralized manner poses challenges (Destek et al., 2024). More than 80% of the world's population resides in these areas (Marshall and Farahbakhsh, 2013), which cover deserts, villages, post-war regions, and islands across continents and oceans. Underdeveloped industrial regions, particularly in Asia (Morgan, 2016), Africa, Latin America, and Antarctica, as well as parts of the Atlantic, Pacific, Indian, and Arctic oceans (benzerrouk et al., 2021), pose unique challenges because many methods for tackling pollution in industrialized countries are too difficult or costly to implement (Mulcahy, 2022).

In these regions, wastewater treatment accounts for less than 28% of the total wastewater, even less than 8% in some regions and far lower than over 70% in industrialized countries (UN-Water, 2017). For example, certain regions in South Asia and Africa heavily rely on small factories and workshops for light industry production and imported e-waste processing (Benneyworth et al., 2016). In Bangladesh, more than 230 rivers and even groundwater are contaminated by

textile factories, leather workshops, and domestic wastes, accounting for 8.5% of total deaths and endangering the health of 35–77 million people due to chronic arsenic exposure (Hasan et al., 2019). Similarly, gas pollution, particularly CO<sub>2</sub>-containing exhaust gas in these regions (Ding et al., 2022), accounts for approximately 52% of global emissions, with a significant portion originating from small-scale sources (Lu et al., 2023).

The lack of infrastructure and technology for the large-scale treatment of these wastes continues to plague local governments and industry stakeholders, leading to an escalating conflict between industrial development and environmental conservation.

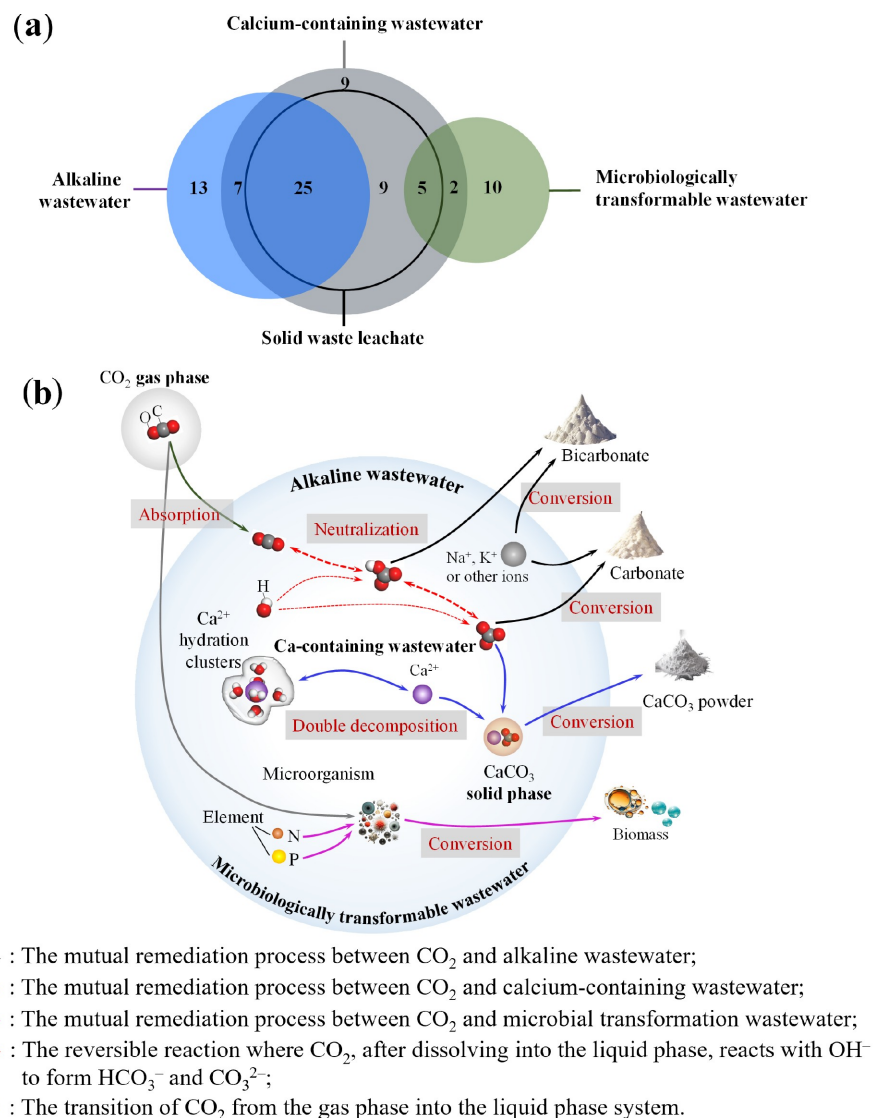
In addition to essential governmental and legislative restrictions on waste disposal (Danish and Ulucak, 2020), it is urgent to identify easy, affordable, and feasible measures to control the release of wastes. Numerous investigations have found that CO<sub>2</sub>-containing exhaust gas and industrial wastewater can both be cleaned to some extent by wastewater absorbing CO<sub>2</sub>. As an acidic oxide, CO<sub>2</sub> is highly reactive and can interact with alkaline industrial wastewater, thereby facilitating the removal of CO<sub>2</sub>. The absorption efficiency of CO<sub>2</sub> is typically greater than 70%, and this absorption also helps normalize the pH levels of the wastewater, reducing them from 11.4 to 5.6 (Xu et al., 2022). In calcium-rich industrial wastewater, CO<sub>2</sub> can participate in a double decomposition reaction that produces CaCO<sub>3</sub>, effectively removing Ca<sup>2+</sup> ions and several heavy metal pollutants from the water, including Cu, Pb, Zn, Cd, Th, Ba, Sr, and Cr (Habibul et al., 2016; Poletini et al., 2016). Furthermore, microorganisms present in industrial wastewater may assimilate nitrogen and phosphorus contaminants, as well as utilize and convert CO<sub>2</sub> from gas, thereby contributing to the remediation of both CO<sub>2</sub> and the wastewater itself (Kong et al., 2022). This mutual remediation method offers several advantages, including ease of operation, low technical requirements, and broad applicability.

This review offers a novel perspective on this widely reported and simple method, providing insightful analysis of its application potential. The mutual remediation of industrial wastewater and CO<sub>2</sub>-

containing exhaust gas represents a straightforward and practical solution tailored for underdeveloped industrial areas. It holds promise in ameliorating pollution stemming from dispersed waste within specific regions and bridging the gap in wastewater and waste gas treatment in vulnerable industrial settings. Drawing from over two decades of research, this review assesses the feasibility of this method, suggesting pathways for enhancing product value, process efficiency, and economic returns. Furthermore, it provides reference implementation strategies to bolster the practicality of deploying this method in underdeveloped industrial regions.

## 2 Methodology

Interactions between CO<sub>2</sub> and industrial wastewater mainly occur in the following three scenarios: alkaline wastewater absorbs CO<sub>2</sub>, Ca-containing wastewater produces CaCO<sub>3</sub> products through carbonation reactions, and microorganisms sequester carbon in industrial wastewater. As such, these types of wastewater have been broadly classified into three categories: alkaline, calcium-containing (including solid waste leachates), and microbologically transformable. Figure 1(a) shows the relationships among these categories, along with the corresponding



**Fig. 1** (a) Chart showing the relationship between different types of industrial wastewater that can absorb CO<sub>2</sub> and the corresponding numbers of published articles concerning these wastewater types in this review; (b) diagram illustrating the representative reaction processes and mechanisms of CO<sub>2</sub> absorption in different types of industrial wastewater.

number of instances of each type of wastewater. There is some overlap between these groups; for instance, some wastewater exhibits both alkaline and calcium-containing properties, while some calcium-containing wastewater can be transformed by microorganisms. However, many microorganisms can not survive in an alkaline environment; thus, most transformable wastewater is not alkaline. Additionally, a significant portion of industrial wastewater containing calcium is generated through the leaching of solid waste.

These industrial wastewaters often absorb CO<sub>2</sub> through absorption, neutralization, double decomposition, or conversion processes, as illustrated in Fig. 1(b). Both CO<sub>2</sub> consumption and some wastewater purification are accomplished through this process, which may also produce pollutants.

## 2.1 Innovation of this review

Recent reviews have predominantly focused on the elimination of specific pollutants (Queiroz et al., 2022; Wang et al., 2024a) or the employment of advanced technology (Ahmad et al., 2021; Li et al., 2021a) and high-end materials (Zhao et al., 2020; Li et al., 2021b) to process industrial wastewater or CO<sub>2</sub>. These technologies can address waste issues in industrialized areas, but they are hard to implement swiftly in more rural areas characterized by unpredictable and small-scale pollution output. However, the direct absorption of CO<sub>2</sub> by industrial wastewater is a potential solution, constituting the focal point of this paper. The practical application of mutual remediation methods offers a straightforward approach to mitigating environmental pollution and fostering industrial growth in underdeveloped industrial regions worldwide.

## 2.2 Literature research

For this review, Google Scholar, Web of Science, and Elsevier databases were queried using the following keywords: 1) industrial wastewater & CO<sub>2</sub>, 2) industrial wastewater and carbon capture, and 3) industrial wastewater & CO<sub>2</sub> absorption. Figures 2(a) and 2(b) show the distribution of published articles based on these keywords retrieved from Web of Science and Elsevier, respectively. Then, these publications underwent manual screening, checking the title and reading the abstract for relevancy (Wang et al., 2021). Approximately 150 papers were selected for the scope of this review, of which 80 articles aligned closely with the thematic focus and were selected for comprehensive analysis and summary.

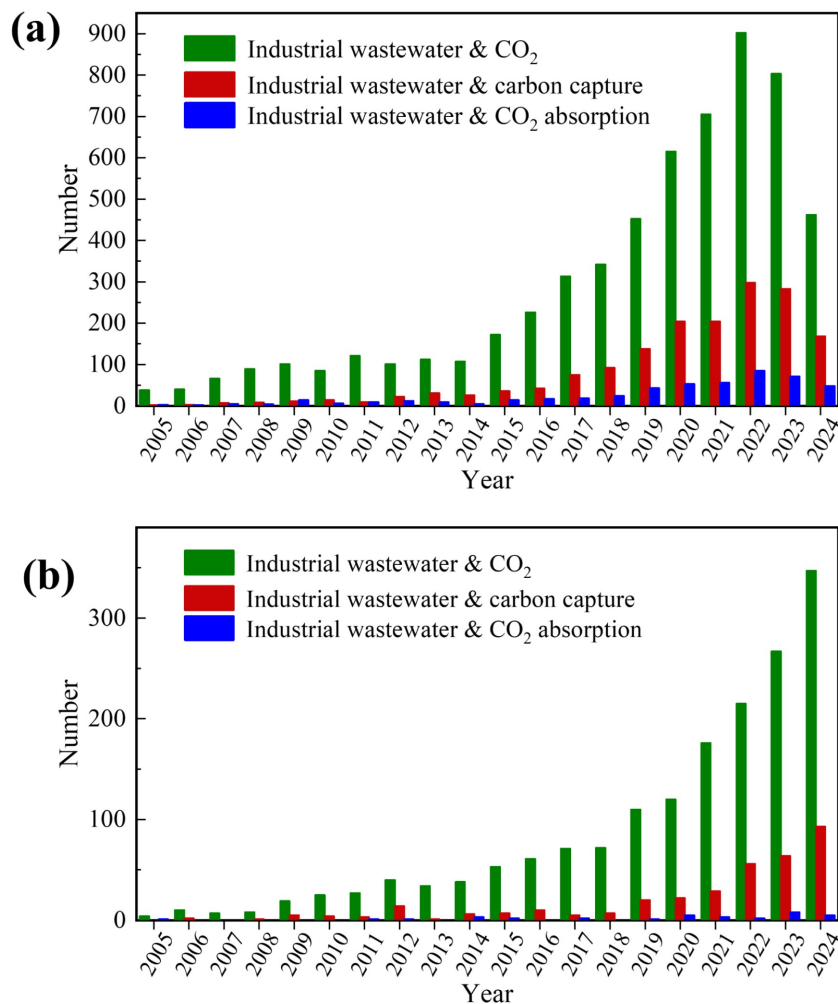
## 3 Mechanism and feasibility analysis

### 3.1 Absorption of CO<sub>2</sub> via alkaline wastewater

Alkaline wastewater (pH > 10) primarily originates from manufacturing facilities, as shown in Table 1. The discharge of this wastewater corrodes pipelines and hydraulic structures, impairs the self-purification capacity of water, disrupts the ecological aquatic balance, and may even contribute to soil salinization (Xiao et al., 2019). The discharge of untreated alkaline wastewater contaminates local water bodies in underdeveloped industrial areas. This contamination disrupts the ecological balance, resulting in significant mortality among aquatic organisms and adversely affecting locals' health by compromising drinking water quality, leading to metabolic and digestive disorders. It also causes soil salinization, damaging crop root systems and reducing nutrient absorption, ultimately decreasing agricultural yields. These effects pose serious challenges for less developed industrial regions that rely heavily on agriculture (Li et al., 2020).

Conventional treatment methods for alkaline wastewater often involve the addition of hydrochloric acid, sulfuric acid, and other acidic chemicals to neutralize alkalinity. However, this approach may result in the accumulation of high levels of NaCl, which can disrupt the ecological balance and corrode infrastructure and processing equipment. Using CO<sub>2</sub> as a neutralizing agent offers a promising alternative to mitigate these challenges. The carbonation reactions of CO<sub>2</sub> to neutralize alkaline wastewater are spontaneous (Eloneva et al., 2008) and exothermic (Bacocchi et al., 2009). Using CO<sub>2</sub> as a direct treatment of alkaline wastewater minimizes the risk of over-neutralization and potentially offers a cheaper and cleaner production process than conventional sulfuric acid or hydrochloric acid (Hannam et al., 2015; Larsen, 2015). In this method, the absorption efficiency of CO<sub>2</sub> typically exceeds 70%, as indicated in Table 1, leading to a favorable reduction in wastewater alkalinity, often achieving a pH range of 5.0–8.0 (Bove et al., 2018). For instance, a pilot-scale operation successfully neutralized basic oxygen furnace slag filter effluent, with an initial pH between 11.5 and 12.0, using CO<sub>2</sub> for two years (Hussain et al., 2014).

Building upon the advantages of CO<sub>2</sub> neutralization, this approach can be effectively implemented through simple gas-liquid absorption devices, such as bubble columns, making it particularly suitable for underdeveloped regions. The process can be further enhanced by integrating it into industrial chains through inter-balanced recycling systems. For instance, brewery



**Fig. 2** Distribution of published articles over the past two decades (from January 1, 2005 to November 15, 2024) from (a) Web of Science and (b) Elsevier.

wastewater neutralized by absorbing CO<sub>2</sub> from biogas can be directly treated through anaerobic digestion (Rao et al., 2007), as illustrated in Fig. 3. This integrated system utilizes an absorber for CO<sub>2</sub> absorption and an up-flow anaerobic sludge blanket reactor for degradation, significantly reducing costs compared to conventional sulfuric acid treatment. Similarly, in petroleum refineries, CO<sub>2</sub>-treated alkaline wastewater (pH 7.2–7.8) can be reused as a pH regulator to enhance nitrification efficiency. Furthermore, an AI-driven control system for treating alkaline wastewater with carbon dioxide in a small tubular reactor has been created (Bardeeniz et al., 2025).

### 3.2 Absorption of CO<sub>2</sub> via calcium-containing wastewater

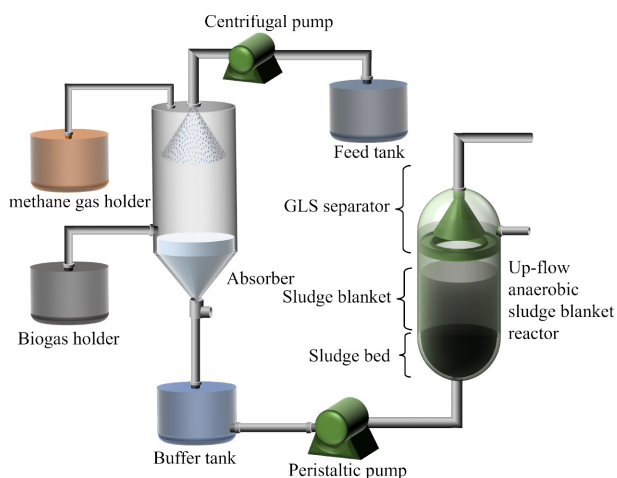
Although cations such as Ca<sup>2+</sup> and Mg<sup>2+</sup> are not

hypertoxic, their elevated concentrations, particularly when combined with anions such as SO<sub>4</sub><sup>2-</sup> and OH<sup>-</sup>, can lead to the precipitation of salts that are likely to block pipelines and prove challenging to clean (Venkatakrisnan et al., 2019). Long-term consumption of high-hardness domestic water poses serious risks to cardiovascular (Oğuz, 2021), nervous, urinary (Esmail et al., 2020), and hematopoietic systems. Within the treatment process of industrial wastewater in aerobic tanks, activated sludge with higher Ca<sup>2+</sup> levels will destabilize its bacterial micelle structure, thereby reducing microbial activity. Of the calcium-containing wastewater we discuss, some are directly derived from manufacturing, such as wastewater from light and heavy industry (e.g., steel, cement, ceramic, soda, textiles, leather, paper, mining, electroplating, and printing), whereas others are indirectly produced, such as leachate of solid wastes (Wang et al., 2024b), as

**Table 1** Sources of alkaline wastewater and CO<sub>2</sub>, as well as efficiencies of CO<sub>2</sub> fixation

Source of wastewater	Wastewater characteristics	Source of CO <sub>2</sub> from exhaust	CO <sub>2</sub> concentration	Efficiency of CO <sub>2</sub> fixation	Ref.
Wastewater from wastewater treatment plants	36 ± 2 mg/L NH <sub>4</sub> <sup>+</sup> 12 ± 1 mg/L PO <sub>4</sub> <sup>3-</sup> 230 ± 20 mg CaCO <sub>3</sub> /L alkalinity	Exhausted gas of biogas combustion	20.00 vol.% CO <sub>2</sub>	83%	Isimone et al., 2017
Feed synthetic wastewater and electroplating wastewater	pH = 11.1–11.2	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	–	Bardeeniz et al., 2025
Filter wastewater of steel slag from Arcelor Mittal	pH = 11.5–12.0 300 mg/L COD <sup>a)</sup> , TOC <sup>b)</sup> , Ca <sup>2+</sup> , Na <sup>+</sup> , TP <sup>c)</sup> , and DIC <sup>d)</sup>	CO <sub>2</sub> -enriched air from a bioprocess of septic tank wastewater	0.20 vol.%–0.50 vol.% CO <sub>2</sub>	300 mg CO <sub>2</sub> /L of bio-transformable COD provided CO <sub>2</sub> for neutralization	Bove et al., 2018
Distiller waste from a Chinese soda ash plant	pH = 11.4 Na <sup>+</sup> , Ca <sup>2+</sup> , and NH <sub>4</sub> <sup>+</sup>	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	638 mg CO <sub>2</sub> /L distiller waste	Zhang et al., 2021a; Xu et al., 2022
Wastewater of concrete from a field construction waste treatment plant (CWTP) in Incheon, Republic of Korea	330 mg/L Ca <sup>2+</sup> pH = 12.2	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	80%–100% 182 mg/L wastewater	Yoo et al., 2017
Wastewater of ceramic industry from north India	pH = 12.5 21 wt.% NaOH 22 wt.% NaOH·H <sub>2</sub> O	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	–	Dabas et al., 2019
Alkaline leachates derived from cement kiln dust, spray-dryer absorber ash, or circulating dry-scrubber ash	Ca, Al, Fe, and Mg elements	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	77%–93%	Noack et al., 2014

Notes: a) COD is the abbreviation of chemical oxygen demand. b) TOC is the abbreviation of total organic carbon. c) TP is the abbreviation of total phosphorus. d) DIC is the abbreviation of dissolved inorganic carbon.



**Fig. 3** Experimental set-up of mutual remediation of brewery industrial wastewater and CO<sub>2</sub> in biogas and subsequent processing (Rao et al., 2007; Bardeeniz et al., 2025), Copyright from Elsevier.

detailed in Table 2.

Various techniques have emerged for the treatment of Ca-containing wastewater, including ion exchange (Salces et al., 2024), membrane separation (Warsi Khan et al., 2024), polymer-chelating agents, and carbonate precipitation (Lin et al., 2016). However, the practical applications of ion exchange and membrane separation are limited due to high costs and material losses (Warsi Khan et al., 2024). Polymer-chelating reagent locks

Ca<sup>2+</sup> into a stable chelating precipitate, posing challenges in disposal and potentially resulting in secondary pollution (Nagandran et al., 2020). Traditional carbonate decalcification process, using Na<sub>2</sub>CO<sub>3</sub> as a precipitator, converts Ca<sup>2+</sup> ions from industrial wastewater to CaCO<sub>3</sub> precipitation. However, the application of this method is constrained by its inability to decrease overall salt content and its reliance on costly raw materials (Wang et al., 2018b).

Although using CO<sub>2</sub> to treat Ca-containing wastewater may not offer the same decalcification efficiency as other methods, it presents several advantages (Xu et al., 2022). Notably, it introduces no additional ions, causes no secondary pollution, and represents a more environmentally friendly method (Kumar et al., 2024). As illustrated in Table 2, this method effectively facilitates carbon sequestration, with the potential to directly absorb atmospheric CO<sub>2</sub>, positively affecting the treatment of calcium-containing wastewater.

When it comes to the mechanism of mutual treatment of carbon dioxide and calcium-containing industrial wastewater, current study trends primarily focus on the properties of solid waste dissolving in leachate and the three-phase response process within complicated systems. Recent advancements in reaction kinetics and equilibrium studies have revealed several key findings:

1) Kinetic studies indicate the precipitation reaction,

**Table 2** Sources of Ca<sup>2+</sup>-containing wastewater and CO<sub>2</sub>, as well as the ionic compositions and absorption efficiency

Source of wastewater	Wastewater characteristics	Source of CO <sub>2</sub> from exhaust	CO <sub>2</sub> concentration	Efficiency of CO <sub>2</sub> fixation	Ref.
Filter wastewater of steel slag from Arcelor Mittal	pH = 10.5–11.5 300 mg COD/L, TOC, Ca, Na, TP, and DIC	CO <sub>2</sub> -enriched air from a bioprocess of septic tank wastewater	0.20 vol.%–0.50 vol.% CO <sub>2</sub>	–	Bove et al., 2018
Produced water from oil and gas extraction	4.0 < pH < 7.0 pH (is increased using regenerable ion-exchange materials) Ca <sup>2+</sup> , Na <sup>+</sup> , and Cl <sup>-</sup>	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	58.5 g CO <sub>2</sub> /L wastewater	Bustillos et al., 2020
Seawater-based wastewater	Ca <sup>2+</sup> , Mg <sup>2+</sup> , Na <sup>+</sup> , and K <sup>+</sup> CO <sub>2</sub> absorbent (additional)	Flue gas	15.00 vol.% CO <sub>2</sub>	120.2 g CO <sub>2</sub> /L wastewater 33%–55%	Kang et al., 2018; Yoo et al., 2018; Kim et al., 2020
Waste liquid from the tanning process	2.5 wt.%, 5 wt.%, and 7.5 wt.% CaO in solid waste	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	–	Venkatakrishnan et al., 2019
Wastewater of concrete from a field construction waste treatment plant (CWTP) in Incheon, Republic of Korea	330 mg/L Ca <sup>2+</sup> pH = 12.2	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	80%–100% 182 mg CO <sub>2</sub> /L wastewater	Yoo et al., 2017
Distiller waste from a Chinese soda ash plant	pH = 11.0 Ca <sup>2+</sup> , Cl <sup>-</sup> , Na <sup>+</sup> , Mg <sup>2+</sup> , and SO <sub>4</sub> <sup>2-</sup>	Fuel gas	5.00 vol.%–20.00 vol.% CO <sub>2</sub>	–	Alamdari et al., 2014
	800 mg/L Ca(OH) <sub>2</sub> 100 g/L CaCl <sub>2</sub> 50 g/L NaCl	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	638 mg CO <sub>2</sub> /L distiller waste	Zhang et al., 2021a; Xu et al., 2022
Pulp mill wastewater	Ca <sup>2+</sup> , Mg <sup>2+</sup> , Na <sup>+</sup> , and K <sup>+</sup>	Waste gas from pulp mill	6.00 vol.% CO <sub>2</sub>	98.2%	Lee et al., 2022
Mining processing wastewater	Ca, Na, Al, and Fe elements	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	53 g CO <sub>2</sub> /kg waste	Yadav et al., 2010
Leachates derived from steel slag, ladle furnace (LF) slag, blast furnace slag, converter slag, stainless steel slag, or basic oxygen furnace (BOF) slag	Solid: CaO and MgO leaching solution (additional)	CO <sub>2</sub> cylinder or fuel gas	13.00 vol.%, 15.00 vol.%, and 100.00 vol.% CO <sub>2</sub>	44% 187 g CO <sub>2</sub> /kg slag 93.5% 289 g CO <sub>2</sub> /kg slag	Chang et al., 2011a; Chang et al., 2011b; Chang et al., 2012
Leachates derived from Municipal solid waste incineration (MSWI) fly ash, coal fly ash, and brine from coal-burning power plants in the Mpumalanga province of South Africa, or fly ash from a power plant in China	Solid: SiO <sub>2</sub> , CaO, Al <sub>2</sub> O <sub>3</sub> , Fe <sub>2</sub> O <sub>3</sub> , MgO, Na <sub>2</sub> O, and K <sub>2</sub> O leaching solution (additional)	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	86.4% 72 g CO <sub>2</sub> /kg ash	Nyambura et al., 2011; Wang and Maroto-Valer, 2011
Leachates derived from air pollution control (APC) residues or MSWI APC from Sardinia Italian	Ca and Mg elements	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	67% 250 g CO <sub>2</sub> /kg APC	Cappai et al., 2012
Leachates derived from Phosphogypsum	Solid: 50.2 wt.% SO <sub>3</sub> , 44.7 wt.% CaO, 1.16 wt.% Na <sub>2</sub> O, and soda solution (additional)	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	200 g CO <sub>2</sub> /kg phosphogypsum	Cárdenas-Escudero et al., 2011
Suspension of flue gas desulfurization (FGD) gypsum from Taiyuan Iron&Steel (group) Co., Ltd.	415 g/L CaSO <sub>4</sub> ·2H <sub>2</sub> O, and 10 wt.% NH <sub>3</sub> ·H <sub>2</sub> O (additional)	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	–	Wang et al., 2019
Alkaline leachates derived from cement kiln dust, spray-dryer absorber ash, or circulating dry-scrubber ash	Ca, Al, Fe, and Mg elements	CO <sub>2</sub> cylinder	100.00 vol.% CO <sub>2</sub>	77%–93%	Noack et al., 2014

calcium dissolution, and the conversion of dissolved CO<sub>2</sub> into carbonate are second-order, zero-order, and first-order reactions, respectively (as shown in Fig. 4

(a)). Thus, dissolution equilibrium and precipitation reaction of CO<sub>2</sub> serve as rate-limiting steps in the gas absorption process (Sheng et al., 2019), offering

theoretical support for process optimization.

2) Gas-liquid contact time is the primary factor determining the rate of the carbonation reaction, with the type of reactor adjustable through bubble size regulation, reaction temperature, and fluid dynamics (Fletcher, 2017; Hurlley and Smith, 2019). Recent equipment improvements have validated this finding (Abdolhosseini Qomi et al., 2022).

3) Recent studies have discovered appropriate leaching agents can alter the thermodynamic limit of the reaction and disrupt the initial gas-solid reaction equilibrium (as shown in Fig. 4(b)), thereby facilitating enhanced mutual treatment between CO<sub>2</sub> and industrial wastewater. Such leaching agents include ammonia solution (Wang et al., 2019) and ammonium salt solution (Chuaijiw et al., 2013).

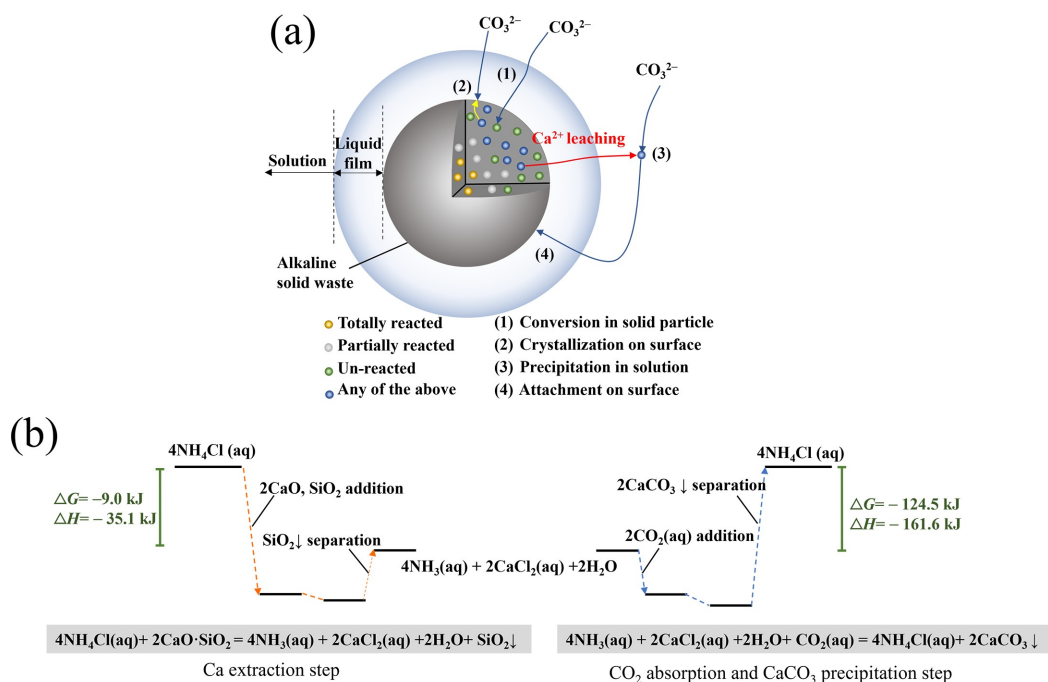
In summary, the core mechanism of CO<sub>2</sub> absorption by alkaline and calcium-rich industrial wastewater can be attributed to multi-stage chemical synergies and mineralization reactions, as illustrated in Fig. 1(b). For the industrial application of this technology, the current technical bottleneck, from a mechanistic perspective, lies in balancing reaction kinetics and energy input. Consequently, future research hotspots may focus on expanding novel energy input pathways, exploring synergistic transformation mechanisms of multiple

pollutants in complex wastewater systems (Ge et al., 2024), and advancing closed-loop technology integration for “carbon capture-valorization-industrial chain” systems. Recent advancements in nanomaterials have provided promising solutions for high-energy and high-power energy storage (Pomerantseva et al., 2019). By utilizing catalysts (Zhang et al., 2021b) to establish efficient mass transfer channels at gas-liquid interfaces, enhancing CO<sub>2</sub> dissolution and diffusion capabilities, and leveraging calcium ion confinement effects, treatment efficiency could be significantly improved. Additionally, AI-assisted reactor design, based on gas-liquid reaction mechanisms, is emerging as a critical tool for optimizing process parameters and enabling large-scale implementation (Bardeeniz et al., 2025).

In practice, the three-phase reaction device is suitable for absorbing CO<sub>2</sub> from Ca-containing industrial wastewater (Chaiwang et al., 2019; Tirapanichayakul et al., 2020). The representative devices in different specification are shown in Fig. 5, and their parameters are shown in Table 3.

### 3.3 CO<sub>2</sub> absorption by microbologically transformable wastewater

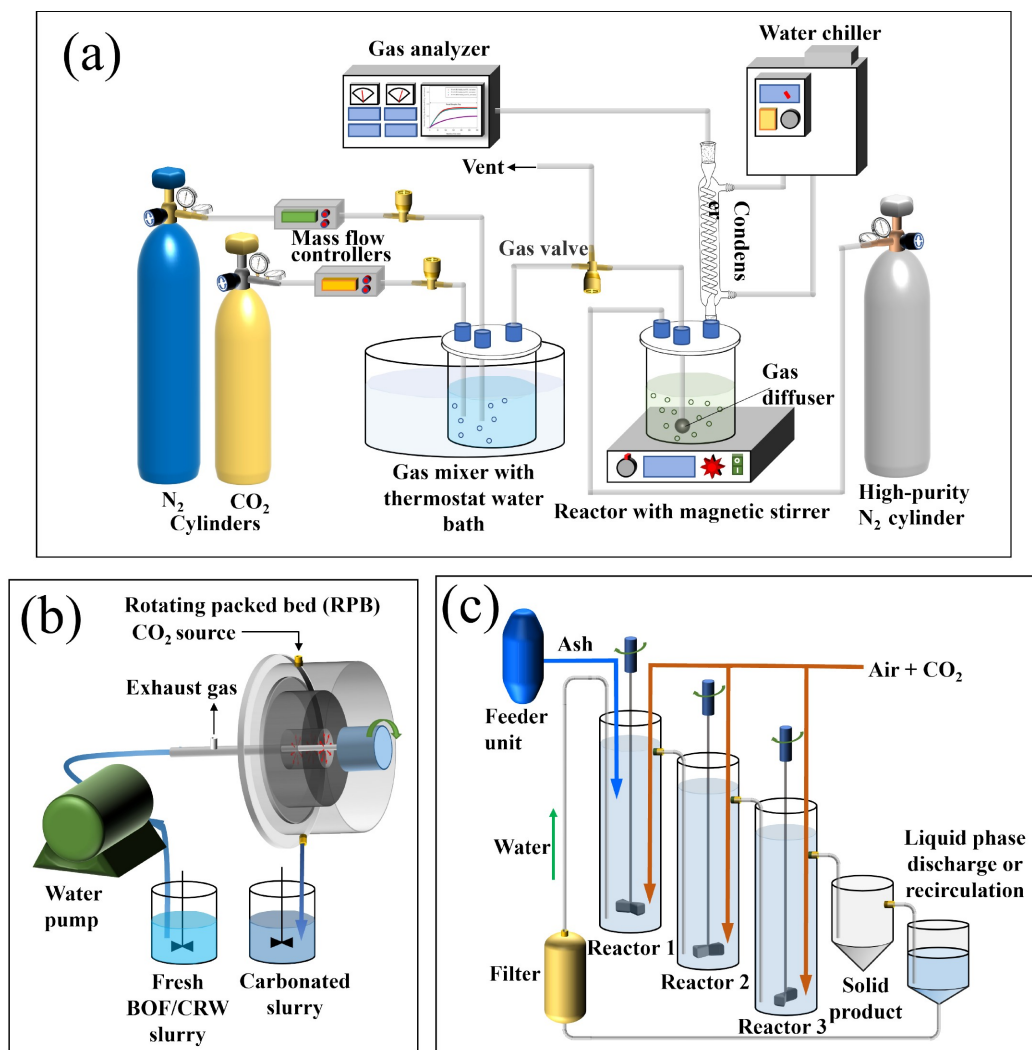
Microalgae can purify industrial wastewater effectively



**Fig. 4** (a) Mechanism of the carbonation reaction of alkaline solid wastes occurs in four routes during the absorption of CO<sub>2</sub> by leachate (Pan et al., 2012), Copyright from Taiwan Association for Aerosol Research; (b) change in enthalpy and the equations associated with Ca extraction, CO<sub>2</sub> absorption, and CaCO<sub>3</sub> precipitation steps at 80 °C (Kodama et al., 2008), Copyright from Elsevier.

by converting nutrients, such as N and P, into ester compounds upon exposure to sunlight (Saranya and Shanthakumar, 2019). Low-concentration CO<sub>2</sub> from the air can be directly absorbed and converted into organic compounds via photoreaction on chloroplasts and electron transport between chloroplasts in microalgae cells. Microalgae can, therefore, be a great choice for the selective removal of some contaminants from secondary and tertiary wastewater (Yadav et al., 2021). Notably, CO<sub>2</sub> plays a pivotal role in liquid pH regulation, affecting microalgae growth, wastewater treatment efficiency, and biomass yield. While excessive CO<sub>2</sub> concentration can lead to acidification, inadequate concentrations fail to provide a sufficient

carbon source, with most microalgae exhibiting optimal growth at CO<sub>2</sub> concentrations ranging between 5 vol.% and 10 vol.% (Razzak et al., 2017). For instance, flue gas has been shown to be a good CO<sub>2</sub> source (Zheng et al., 2016). Studies demonstrated 1.0 kg of dry algal biomass consumes approximately 1.9 kg of CO<sub>2</sub> (Singh and Ahluwalia, 2013; Singh et al., 2014). The use of wastewater for the absorption of low-concentration CO<sub>2</sub> by microalgae holds considerable promise for regions with limited industrial infrastructure due to its minimal nutrient and CO<sub>2</sub> requirements, low energy consumption, and operational costs (Judd et al., 2015). Table 4 illustrates instances of industrial wastewater and CO<sub>2</sub> conversion by various microalgae species.



**Fig. 5** Schematic of (a) the experimental apparatus and procedures of mutual remediation of seawater-based concentrated wastewater and 9.2 vol.% CO<sub>2</sub> (Kang et al., 2017), Copyright from Elsevier; (b) rotating packed bed applied in mutual remediation of CO<sub>2</sub> and a mixture of basic oxygen furnace slag and cold-rolling wastewater (Pan et al., 2013), Copyright from ACS Publications; (c) one batch pilot-scale reactor for mutual remediation of fly ash leachate and low-concentration CO<sub>2</sub> (Uibu and Kuusik, 2009), Copyright from Estonian Academy Publishers.

**Table 3** Device and classification of fixing CO<sub>2</sub> in calcium-containing wastewater

Reaction scale	Controllable parameters	Device	Reactor size/ performance	Ref.
Laboratory scale	Temperature, stirring, gas pressure, and flow rate, etc.	–	500 mL. Mass of carbonate salt: 14.35 g salt/mol amine CO <sub>2</sub> . Conversion yield: 43.2%	Kodama et al., 2008; Huntzinger et al., 2009; Nyambura et al., 2011; Poletti et al., 2016; Kang et al., 2017; Yoo et al., 2017; Wang et al., 2018a; Yoo et al., 2018; Venkatakrishnan et al., 2019; Wang et al., 2019; Kim et al., 2020)
	Temperature, gas pressure and flow rate, etc.	–	1 L 1.7 mol of CO <sub>2</sub> /L wastewater	Yang et al., 2007; Gaur et al., 2009; Sun et al., 2011
Small-scale	Gas flow rate, slurry flow rate, L/S ratio, and the flow type of BOF slag slurry, etc.	Rotating packed bed	5 kg CO <sub>2</sub> capture efficiency: <98.5% pH of cold-rolling wastewater (CRW) neutralized from 12 to 7 f-CaO in BOF slag eliminated from ~5% to 0%	Ferreira Filho and Chui, 2006; Pan et al., 2013
Pilot-scale	Temperatures, ash flow rate, water flow rate, CO <sub>2</sub> flow rate, mechanic stirrer, etc.	Continuous-flow reactor system	30 t/h (ash flow); 300 m <sup>2</sup> /h (susp. flow) pH neutralized from 13 to ~7 Fly ash carbonation ratio: 70%–100%	Arickx et al., 2006; Uibu and Kuusik, 2009; Hussain et al., 2014; Iasimone et al., 2017; Bove et al., 2018

Among them, CO<sub>2</sub> can serve as an indirect carbon source for microalgae, as shown in Fig. 6. NaHCO<sub>3</sub> (aq) was formed by introducing 10% CO<sub>2</sub>-enriched air into diluted dairy wastewater (in scrubber) and was

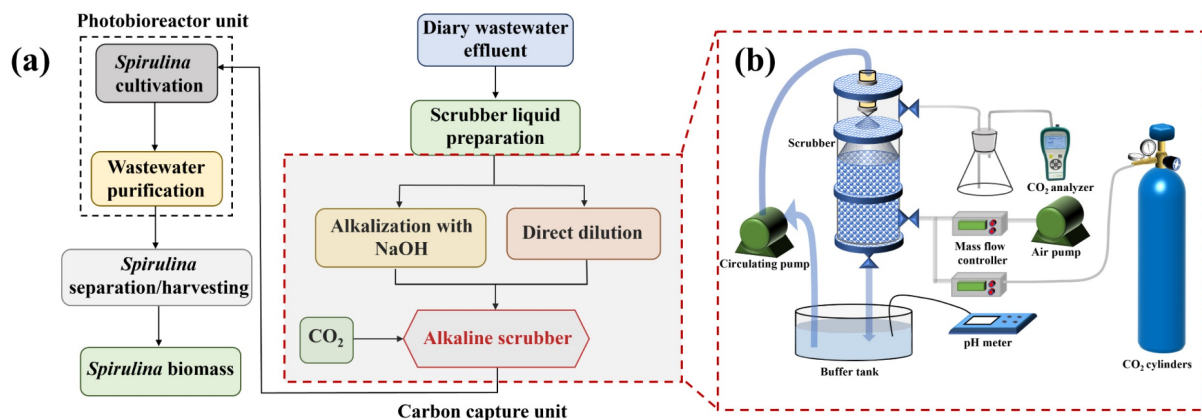
used as a direct carbon source for microalgae.

Recent studies have expanded the scope of microalgae remediation methods by identifying new algae species suitable for mutual remediation processes.

**Table 4** Sources of industrial wastewater and CO<sub>2</sub>, as well as the efficiencies of CO<sub>2</sub> absorption

Source of wastewater	Wastewater characteristics	Microorganism	Source of CO <sub>2</sub>	CO <sub>2</sub> concentration	Efficiency of CO <sub>2</sub> fixation	Ref.
Brewery wastewater	pH = 6.8 2100 mg/L COD, 45 mg/L TN <sup>a</sup> , 7 mg/L TDS <sup>b</sup> , and 23 mg/L NH <sub>3</sub> -N	<i>Chlorella</i> sp. and <i>Scenedesmus</i> sp.	CO <sub>2</sub> cylinder	15.00 vol.% CO <sub>2</sub>	–	Song et al., 2020
Brewery wastewater from the Sociedade Central de Cervejas e Bebidas (SCC) brewery at Vialonga, Portugal	TSS <sup>c</sup> , N-NH <sub>3</sub> , TKN <sup>d</sup> , PO <sub>4</sub> <sup>3-</sup> , P <sub>2</sub> O <sub>5</sub> , and COD	<i>Scenedesmus obliquus</i>	Air Air and brewery CO <sub>2</sub>	~0.04 vol.% CO <sub>2</sub> 10.00 vol.% CO <sub>2</sub>	– –	Ferreira et al., 2017; Ferreira et al., 2019
Distillery wastewater	80000–100000 mg/L COD and 40000–50000 mg/L BOD	<i>Spirulina</i> sp.	Air	~0.04 vol.% CO <sub>2</sub>	–	Krishnamoorthy et al., 2019
Raw dairy (milk processing) wastewater	4–40 g/L NaOH, COD, PO <sub>4</sub> <sup>-</sup> , and NH <sub>4</sub> <sup>+</sup>	<i>Spirulina maxima</i>	Air	~0.04 vol.% CO <sub>2</sub>	6 g CO <sub>2</sub> /L wastewater	Chang et al., 2013
Pharmaceutical wastewater from a pharmaceutical company in Haridwar, India	TSS, N-NH <sub>3</sub> , TKN, and TOC	<i>Tetraselmis Indica</i> BDU 123	Air	~0.04 vol.% CO <sub>2</sub>	–	Amit et al., 2020
Tannery wastewater	pH = 6.6 1128 mg/L BOD and 13300 mg/L COD	<i>Spirogyra condensata</i>	Flue gas	9.50 vol.%–16.50 vol.% CO <sub>2</sub> , 2.00 vol.%–6.60 vol.% O <sub>2</sub> , and CO, 0.01 vol.%–0.03 vol.% NO <sub>x</sub> , and 0.28 vol.%–0.32 vol.% SO <sub>x</sub>	–	Kwak et al., 2015; Saranya and Shanthakumar, 2019
Textile wastewater from a textile factory located in Daegu, Republic of Korea	pH = 8.7 380.5 mg/L TN, 94 mg/L TP, 2200 mg/L COD, 3110 mg/L TS, and 2340 mg/L VS <sup>e</sup>	<i>Chlorella</i> sp. and <i>Scenedesmus</i> sp.	Air	~0.04 vol.% CO	–	Kumar et al., 2018
<i>N,N</i> -dimethylformamide (DMF)-containing wastewater	2000 mg/L DMF, 3000 mg/L COD, and 500 mg/L NH <sub>3</sub> -N	Microorganisms in an artificial mixture of anaerobic digested sludge and activated sludge	Biogas	50.00 vol.%–80.00 vol.% of CH <sub>4</sub> , 20.00 vol.%–40.00 vol.% of CO <sub>2</sub> , and 0.00 vol.%–5.00 vol.% of N <sub>2</sub>	1 g CO <sub>2</sub> /L wastewater (2 g/L of DMF)	Kong et al., 2022

Notes: a) TN is the abbreviation of total nitrogen. b) TDS is the abbreviation of total dissolved solids. c) TSS is the abbreviation of total suspended solid. d) TKN is the abbreviation of total Kjeldahl nitrogen. e) VS is the abbreviation of volatile solid.



**Fig. 6** (a) Schematic of the integrated two-stage process of CO<sub>2</sub> absorption by dairy wastewater via the transformation of microalgae; (b) schematic of carbon capture unit in (a) for CO<sub>2</sub> capture from the air (Chang et al., 2013), Copyright from ACS Publications.

Species, such as *Chlorella* sp., *Spirulina* sp., *Scenedesmus* sp., and *Diatoms* sp., exhibit efficacy in this regard. For example, *S. platensis*, *S. quadricauda* (Ergene et al., 2009), *Spirulina platensis* (Yusta-García et al., 2017), *C. pyrenoidosa* (Pathak et al., 2015), *C. vulgaris*, and *Chlorella tenuis* (Liu et al., 2019) have demonstrated effectiveness in degrading pollutants, such as dye, COD, heavy metals, N, P, and other contaminants in textile wastewater (Gao et al., 2022). Similarly, *A. dimorphus* (Chokshi et al., 2016), *S. quadricauda* (Daneshvar et al., 2018), *Scenedesmus* sp. (Hemalatha et al., 2019), and *Chlorella sorokiniana* (Guldhe et al., 2017) exhibit proficiency in removing COD, biochemical oxygen demand (BOD), N and P nutrients from dairy wastewater. Additionally, *Nannochloris* sp., *Chlorella sorokiniana*, *Nannochloris* sp., *Navicula* sp., and *S. obliquus* have capabilities to degrade trimethoprim sulfamethoxazole triclosan, diclofenac, carbamazepine ciprofloxacin, ibuprofen, and diclofenac in pharmaceutical wastewater, respectively (Sharma et al., 2022). However, maintaining comparatively stable populations of specific species is one of the difficulties in employing microalgae to treat industrial wastewater (Parsy et al., 2024). Therefore, it is essential to suppress competing organisms, optimize culture conditions, and continue routine monitoring and management throughout the treatment process. When required, physical and chemical pretreatment can also be employed.

The proposed mechanism elucidates the role of microalgae in remediating potentially toxic pollutants in industrial wastewater, as shown in Fig. 7(a). However, further research is warranted to elucidate the purifying mechanism of microalgae, focusing on the following details:

1) Adsorption: Surface functional groups, such as

amino (–NH<sub>2</sub>), carboxyl (–COOH), hydroxyl (–OH), phosphoryl (–PO<sub>3</sub><sup>2-</sup>), and sulfhydryl (–SH), on microalgae cells facilitate the binding of pollutant molecules through hydrogen bonds, electrostatic bonds, or hydrophobic interactions during the adsorption process (Sharma et al., 2022).

2) Accumulation: Microalgae take in contaminants from wastewater, storing them within intracellular compartments, where enzymatic breakdown occurs both within and outside the cell (Yadav et al., 2021).

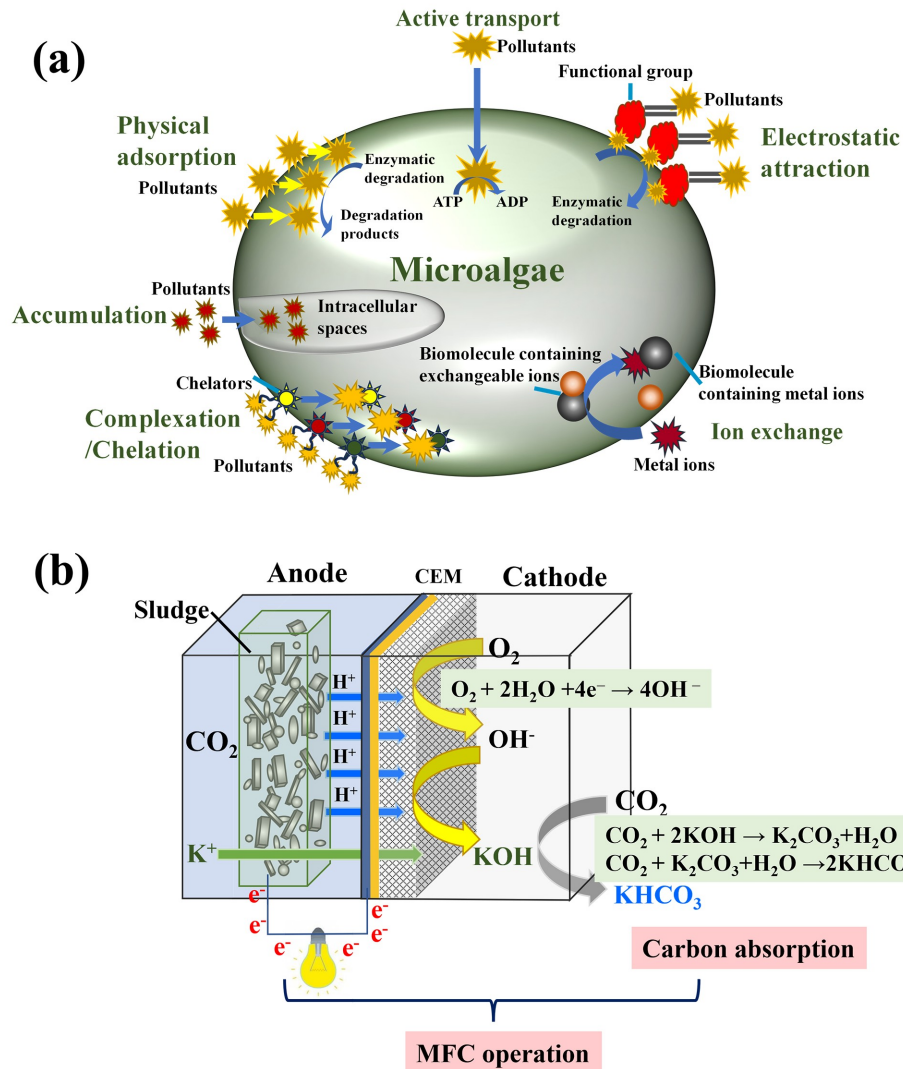
3) Immobilization: Cells or enzymes are enclosed in a matrix, gel, or porous support during immobilization. The porous structure allows wastewater infiltration into the microalgae confines, enabling toxin uptake and wastewater filtration (Yu et al., 2017).

In underdeveloped industrial regions, power generation mainly relies on fossil fuels. In this context, microbial fuel cells (MFCs) are effective systems to capture CO<sub>2</sub>, N, and P from wastewater, with a low risk of carbon emission while simultaneously generating power (Nagendranatha Reddy et al., 2019; Arun et al., 2020). In addition to microalgae, microorganisms, including bacteria and microalgae-bacteria consortia, can be used (Chen et al., 2013). Figure 7(b) shows a typical MFC (Gajda et al., 2016).

## 4 Environment benefits, economic effect, and application prospect

### 4.1 Environmental benefits

Although carbon capture plants have been established in several industrialized nations (Donnelly, 2021), their



**Fig. 7** (a) Diagram of the mechanisms involved in the remediation of pollutants in wastewater by microalgae (Sharma et al., 2022), Copyright from Elsevier; (b) schematic of the absorption of CO<sub>2</sub> by industrial wastewater containing K, based on the MFC reactor (Gajda et al., 2016), Copyright from Elsevier.

sophisticated technology and large investment requirements pose challenges for implementation in underdeveloped industrial areas. As an economical alternative, the mutual remediation method might effectively mitigate CO<sub>2</sub> emissions in underdeveloped industrial zones by reducing the CO<sub>2</sub> content in waste gas. As indicated by Tables 1, 2 and 4, micro-biologically transformable wastewater can absorb CO<sub>2</sub> at concentrations less than 20 vol.% in the exhaust gas, while alkaline and calcium-containing wastewater can absorb 60 vol.%–100 vol.% CO<sub>2</sub> from the exhaust gas.

The mutual remediation method provides additional environmental benefits by successfully lowering the alkalinity and calcium concentration of wastewater and

removing other contaminants to some extent. In a recent study, PO<sub>4</sub>-P from basic oxygen furnace slag was treated with lake water (Hussain et al., 2014), as outlined in Table 5. Moreover, elemental S in wastewater from refineries and CO<sub>2</sub> and H<sub>2</sub>S in the coal gas (Yang et al., 2007) were removed via mutual remediation, as outlined in Table 5. Notably, some heavy metal elements in wastewater can also be effectively removed using this method, such as Cu (Hunter et al., 2021), Pb (Aricx et al., 2006), Zn (Poletini et al., 2016), Cd, Th (Cárdenas-Escudero et al., 2011), Ba (Hunter et al., 2021), Sr, and Cr (Habibul et al., 2016). This approach could help reduce water pollution from heavy metals, as these elements

tend to accumulate in organisms, including humans, through the food chain.

Despite the demonstrated environmental benefits of heavy metal removal, the mechanistic pathways governing this process remain poorly understood (Zhang and Duan, 2020). Four hypotheses are proposed in Fig. 8(a): it is possible to hypothesize that in alkaline environments,  $\text{CO}_2$  combines with water to form  $\text{CO}_3^{2-}$ , which then breaks down into carbonate ions (Zhang et al., 2023). Similar to  $\text{Ca}^{2+}$ , these heavy metal ions could interact with  $\text{CO}_3^{2-}$  to create precipitates of insoluble carbonate. Another possibility is co-precipitation (Kim et al., 2023), in which some heavy metal ions, even if they do not react directly with the  $\text{CO}_3^{2-}$ , may precipitate with the  $\text{CaCO}_3$  particles that are created. Alternatively, adsorption (Jo et al., 2023) might be involved because the  $\text{CaCO}_3$  particles that were produced might have some adsorptive properties that enable them to absorb specific heavy metal ions. Furthermore, complexation (Hunter et al., 2021) might occur in some instances, where complexes may form on the surface of calcium carbonate, thereby immobilizing the heavy metal ions. Clarifying these mechanisms is critical to optimizing the environmental efficacy of mutual remediation systems, as enhanced metal removal directly translates to reduced ecological risks.

The environmental benefits of microalgae cultivation in wastewater include effective land use,  $\text{CO}_2$  sequestration, and wastewater purification, without triggering a food versus fuel feud (Lam and Lee, 2012). According to estimates, 1000  $\text{m}^2$  of land may generate 31.5 t of algae and remove 56.7 t of  $\text{CO}_2$  annually based on the daily production ratio of microalgae of 90  $\text{g}/\text{m}^2$

(Ye et al., 2018). Microalgae farming appears to be one of the most efficient methods for removing substantial amounts of atmospheric carbon. Ecological restoration of dispersed polluted areas is anticipated because of microalgae's capacity to degrade and transform pollutants (as indicated in Table 5). Figure 8(b) depicts a bioremediation circle of an ecological system (Salama et al., 2017).

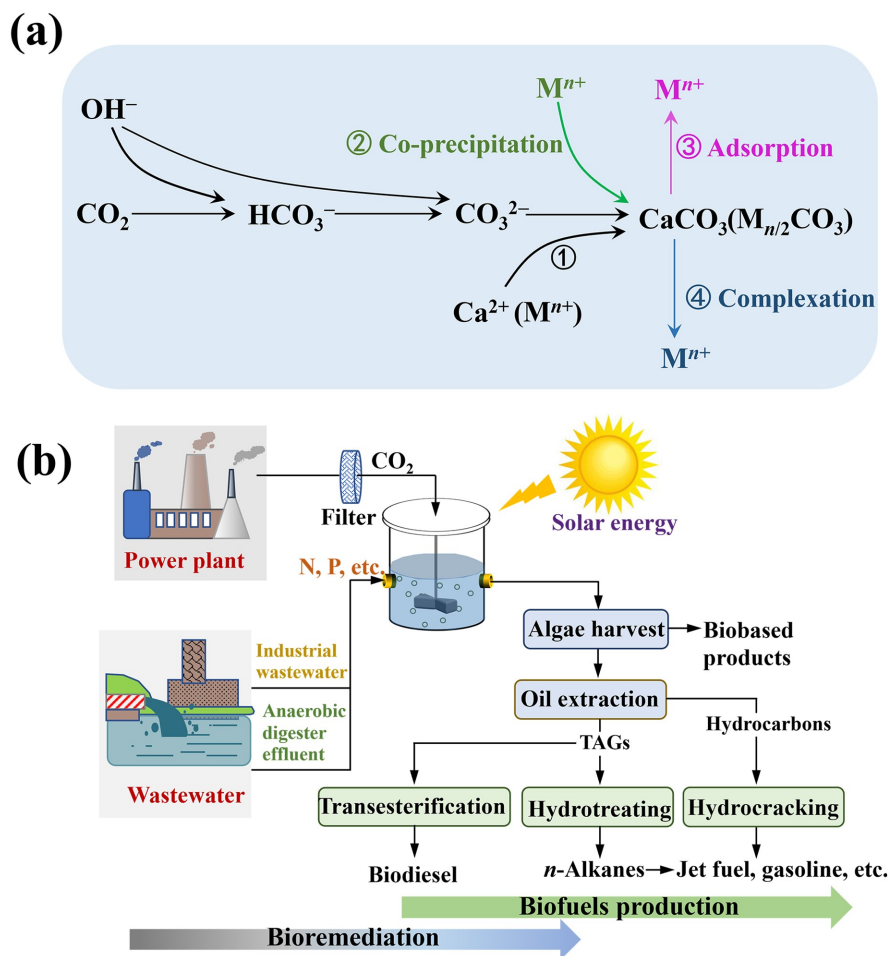
Regarding long-term global effects, this method might gradually alleviate the deepening pollution of soil, water, and air caused by industrial development, improving the frequency of global climate extremes and slowing the rate of global warming.

## 4.2 Economic effect

For a one million-ton landfill, the anticipated cost of constructing pipeline gas equipment using alkaline wastewater to absorb  $\text{CO}_2$  is USD640000, with pipeline gas priced at USD1.32 per ton, resulting in an 8% profit margin (Gaur et al., 2009). Various factors, including storage, transportation, energy consumption, and leach solution, contribute to the costs associated with solid waste. Notably, sulfuric acid and ammonium solution, serving as the leaching agent of red gypsum, constitute 82.86% of the total cost of fixing one ton of  $\text{CO}_2$  gas by red gypsum (Rahmani et al., 2014). The absorption of  $\text{CO}_2$  by red gypsum leachate resulted in a loss of USD66.82 per ton of  $\text{CO}_2$  absorbed, with the production of low-grade products. However, enhancing the value of the product may render the mutual remediation of red gypsum leachate and  $\text{CO}_2$  profitable. Thus, the product value is crucial in determining the

**Table 5** Removal of pollutants and toxins from wastewater via the mutual remediation method

System with impurities		Pollutants removed	Ref.
Alkaline wastewater	Seawater-based wastewater	6.2% $\text{Na}^+$ , 97.2% $\text{Ca}^{2+}$ , and 5.9% $\text{Mg}^{2+}$	Kim et al., 2020
	Basic oxygen furnace slag treated with lake water	96.1%–98.1% $\text{PO}_4\text{-P}$	Hussain et al., 2014
	Thermal desalination reject brine	59.0% $\text{Cl}^-$	Dindi et al., 2015
Ca-containing wastewater	Leachate of BOF slag	Most of Mg, Fe, Mn, and Zn	Polettini et al., 2016
	Leachate of phosphogypsum industrial waste	100.0% trace impurities (Cr, As, U, Ni, V, Se, Cd, Pb, Zn, and Th)	Escudero et al., 2011
Microbiologically transformable wastewater	Brewery wastewater ( <i>Scenedesmus obliquus</i> )	92.9% $\text{NH}_3$ , 88.5% TN, 40.8% P, and 61.9% COD	Ferreira et al., 2017
	Textile wastewater ( <i>Chlorella</i> sp. and <i>Scenedesmus</i> sp.)	95% TP, 70% TN, and 68%–72% color	Kumar et al., 2018
	Wastewater from sewage disposal plants ( <i>Scenedesmus</i> sp. and <i>Chlorella</i> sp.)	4.5 mg/L $\text{PO}_4^{3-}$ , 0.2 mg/L $\text{NO}_2^-$ , 0.8 mg/L $\text{NO}_3^-$ , and 13.7 mg/L $\text{NH}_4^+$	Iasimone et al., 2017
	Pharmaceutical wastewater ( <i>Tetraselmis Indica</i> BDU 123)	COD, TOC, nitrate, and phosphate in raw wastewater were 90.3%, 97.1%, 81.6%, and 94.9%, respectively	Amit et al., 2020
	MFC ( <i>Lolium perenne</i> )	99.0% Cr (VI)	Habibul et al., 2016



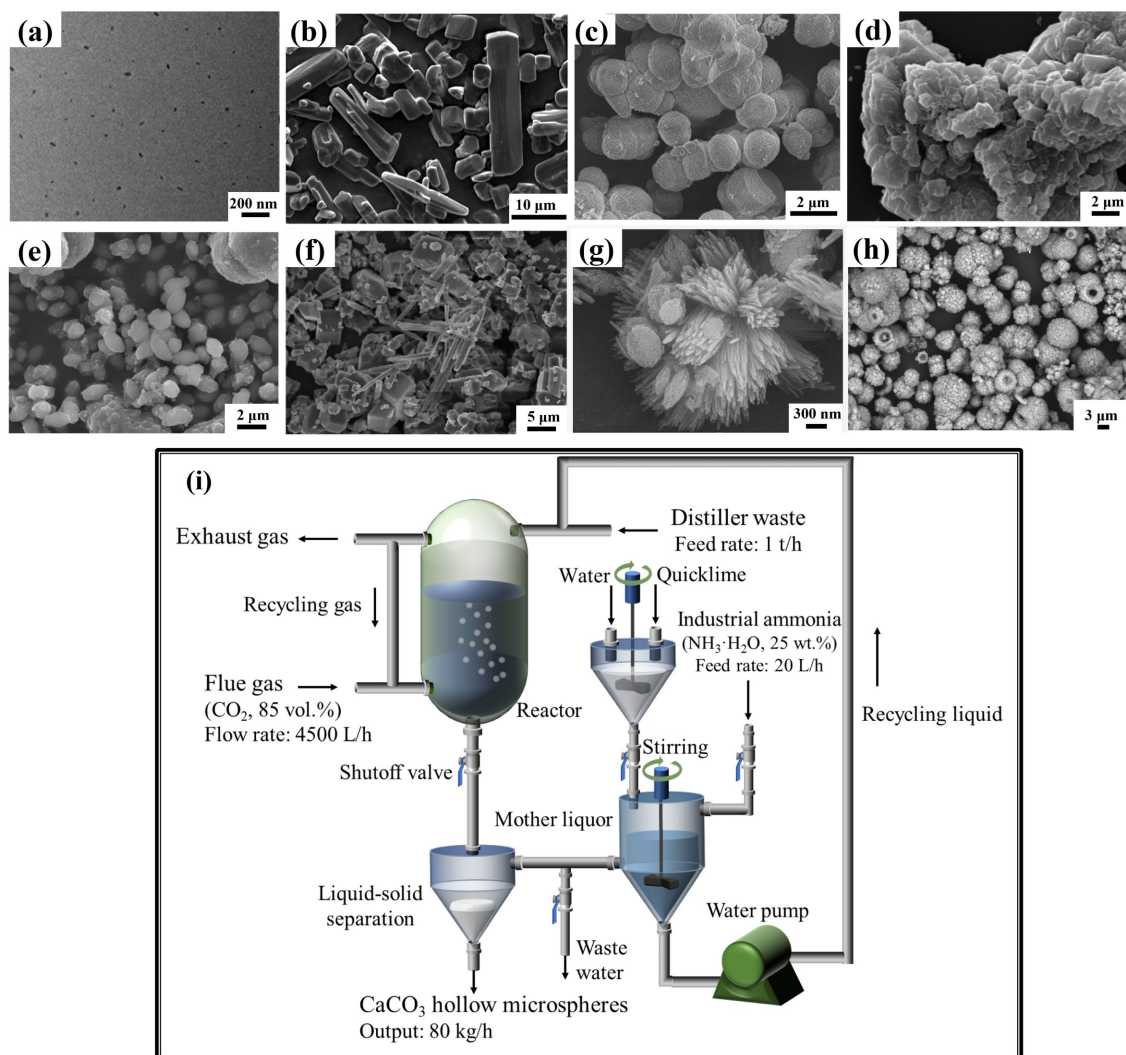
**Fig. 8** (a) Schematic of hypothesized mechanisms for the removal of heavy metals from industrial wastewater through the mutual remediation methods; (b) schematic of an integrated algal culture system for biofuel production and bioremediation of industrial wastewater and exhausted  $\text{CO}_2$ . TAG: triacylglycerol (Shen, 2014; Salama et al., 2017), Copyright from Elsevier.

economic feasibility of the method. The subsequent sections detail high-value products resulting from the mutual remediation of  $\text{CO}_2$  and three types of industrial wastewater.

Neutralizing alkaline wastewater can yield soluble carbonate, such as nano  $\text{Na}_2\text{CO}_3$  crystals (market price of approximately USD370.00 per ton), as shown in Fig. 9(a) (Dabas et al., 2019).  $\text{NaHCO}_3$  crystal is another product, as depicted in Fig. 9(b), and is a vital component in algal bio-fixation, urea production, and oil recovery (Dindi et al., 2015).  $\text{CaCO}_3$ , a product that may come in various morphologies (Wang et al., 2019), can be produced from the mutual remediation of Ca-containing wastewater and  $\text{CO}_2$ , as shown in Figs. 9(c)–9(h). Figure 9(c) depicts a mixture of vaterite and calcite, created from a desulfurized gypsum leachate (Wang et al., 2019).  $\text{CaCO}_3$  hollow microspheres (market price of approximately USD222.00 per ton), as shown in Fig. 9(h), were derived from distiller waste,

and Fig. 9(i) shows the flow diagram. The estimated operational profit per ton of distiller waste is USD5.91, owing to the high value of this product (Xu et al., 2022). Ordinary calcite powder from alkaline paper mill waste can be recycled for neutralizing acid mine drainage or as a raw material in the cement industry (Pérez-López et al., 2010). Furthermore,  $\text{CaCO}_3$  demonstrates effectiveness in absorbing hazardous components such as Pb in wastewater by heterogeneous nucleation and surface co-precipitation (Fiorito et al., 2022).

Microorganisms can transform wastewater into high-value biofuels, such as biohydrogen, biodiesel, and bioethanol (Costa and De Moraes, 2011; Huang et al., 2019). Despite the complexity and duration of biomass production processes, these biofuels offer green energy with high purity and calorific value (Feng et al., 2011). Notably, biodiesel derived from *Spirulina maxima*-treated wastewater exhibited 99.30% purity. The return



**Fig. 9** Carbonate products from the mutual remediation of industrial wastewater and low-concentration CO<sub>2</sub> in the literature. (a) Transmission electron microscopy (TEM) of nano anhydrous sodium carbonate (Dabas et al., 2019), Copyright from Elsevier. Scanning electron microscopy (SEM) image of (b) NaHCO<sub>3</sub> crystal (Dindi et al., 2015), Copyright from Elsevier; (c) vaterite (Wang et al., 2019), Copyright from Elsevier; (d) calcite powder (Pérez-López et al., 2010), Copyright from Elsevier; (e) calcite dropped with impurities (Al/Si/Fe oxide) (Sun et al., 2011), Copyright from Elsevier; (f) CaCO<sub>3</sub> samples in forms of calcite and aragonite (Kodama et al., 2008), Copyright from Elsevier; (g) aragonite (Kang et al., 2018), Copyright from John Wiley and Sons; and (h) CaCO<sub>3</sub> hollow microspheres (Xu et al., 2022), Copyright from Springer Nature. (i) Flow diagram of the production of CaCO<sub>3</sub> hollow microspheres in (h) (Xu et al., 2022), Copyright from Springer Nature.

on investment for biomass production can reach 86.92% by managing costs (Abdo et al., 2016). Microalgal species producing high-value products, including *Chlorella* sp., *Cryptocodinium* sp., *Haematococcus* sp., *Spirulina* sp., and *Nannochloropsis* sp., are gaining attention worldwide (Barsanti and Gualtieri, 2018). The global microalgae market, estimated at USD3.40 billion in 2020, is projected to reach USD4.60 billion by 2027 (Loke Show, 2022).

Based on this, a rough economic evaluation of the mutual remediation of industrial wastewater and CO<sub>2</sub>-

containing exhaust gas was performed, as shown in Tables 6–11. For alkaline wastewater and Ca-containing wastewater, an estimate of the total capital investment (TCI) for building a project to treat 10 t of industrial wastewater using the mutual remediation method came to roughly USD793190.60, as outlined in Table 6. Moreover, Table 7 details the daily manufacturing cost, which was estimated to be USD1395.00, with the total manufacturing cost (TMC) estimated at USD509175.00.

In a recent study, the industrial wastewater from pulp

mill processes absorbed CO<sub>2</sub> and SO<sub>x</sub> from flue gas (Lee et al., 2022). Ca<sup>2+</sup>, Mg<sup>2+</sup>, and K<sup>+</sup> in the wastewater were separated and transformed to CaCO<sub>3</sub>, MgCO<sub>3</sub>, and KOH, respectively, as depicted in Fig. 10. After this process, the pulp effluent met the requirement for wastewater treatment. Table 8 presents the favorable impacts of the process on the final product, with the economic evaluation outcomes displayed in Table 9. The mutual remediation technology used for recovering industrial wastewater and flue gas in this process demonstrates strong technical and economic viability.

For microbiologically transformable wastewater, the cost was estimated using the production of biofuel as a model, as delineated in Tables 10 and 11. Table 10 provides a detailed breakdown of the direct and indirect manufacturing costs for *Spirulina Maxima*, while Table 11 presents the net profit calculation for its production, based on the data from Table 10. To produce biodiesel from wastewater, Abdo et al. (2016) conducted a technical and economic analysis of the usage of *Spirulina maxima*. The process simulation was performed using specialized software, and *Spirulina maxima* emerged as the predominant species of microalgae in samples collected from the Matrouh wastewater treatment plant. Assuming a required biodiesel production rate of 10000 t/yr, the return on investment for *Spirulina maxima* was 14.82%. Therefore, the economic feasibility of biofuel

production from *Spirulina maxima* cultivated in wastewater treatment plants is evident.

Microalgae that have been separated and purified from natural sources often show poor purification effectiveness and are not suitable for treating wastewater with large toxic pollutant concentrations (Wang et al., 2023). Therefore, to create microalgal strains appropriate for engineering applications, advancements must be made through selective breeding, genetic engineering, and breeding for mutations (Raghuraman Rengarajan et al., 2024). Growing microalgae using nutrients from nearby wastewater and waste gas can reduce raw material costs and encourage resource recycling in undeveloped industrial areas. Despite the potentially high initial investment, microalgae can be used to produce electricity and reduce pollution by leveraging regulatory assistance and making sensible use of local resources. Government grants and assistance from academic institutions can also help overcome the technological and financial obstacles in these fields.

### 4.3 Application prospect

Mutual remediation can offer significant benefits to underdeveloped industrial areas in this regard. First, this method can efficiently reduce environmental pollution by capturing carbon dioxide from emissions

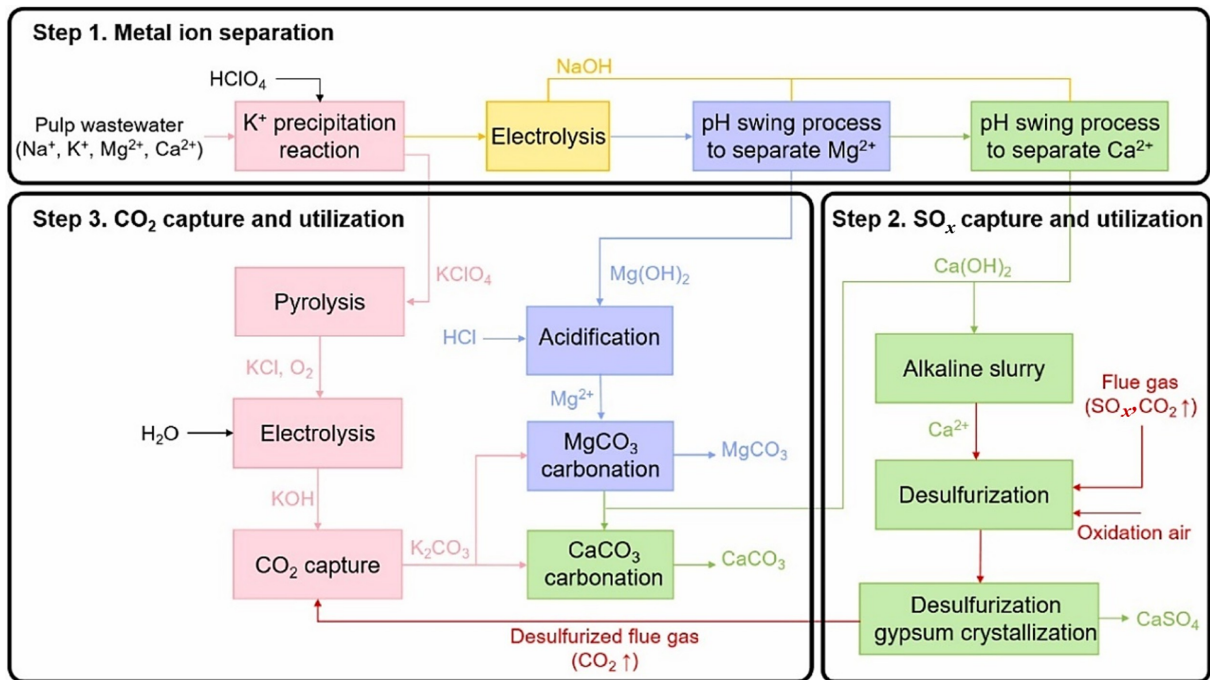
**Table 6** Analysis of the cost of investment in the construction of a facility to treat 10 t of industrial wastewater using mutual remediation

Items	Details	Estimated cost (USD)
Infrastructure and installation	Simple plant construction and installations	125471.47
Equipment	Reaction tanks, pumps, and liquid storage made of stainless steel	527357.37
Instruments and apparatus	Monitoring equipment of gas and wastewater	106980.98
Safety facilities	Including fire equipment and protective device	14547.15
Remaining investment		18833.63
Total capital investment (TCI)		793190.60

**Table 7** Cost analysis of treating 10 t of industrial wastewater per day using mutual remediation

Items	Details	Estimated cost (USD)
Raw material cost	CO <sub>2</sub> , wastewater, solid waste, and leaching solution	720.00
Transportation	Short-distance transport of raw materials	200.00
Energy consumption <sup>a)</sup>	Aeration, stirring, lighting, and other electrical energy consumption	100.00
Cost of labor	Five workers   USD750.00/month each (the average worker's wage in China)	125.00
Maintenance of equipment	Infrastructure and testing equipment maintenance	150.00
Remaining cost		100.00
Daily manufacturing cost		1395.00

Notes: a) Approximately 70% of the overall energy usage is accounted for by the power loss caused by aeration in the energy cost (Sun et al., 2016).



**Fig. 10** Illustration of capture and utilization of  $\text{SO}_x$  and  $\text{CO}_2$  using pulp mill wastewater (Lee et al., 2022), Copyright from Elsevier.

**Table 8** Annual profit of each product of the proposed mutual remediation of flue gas and pulp mill wastewater

Classification	Product (t/yr)	Price (USD/t)	Profit (USD/yr)
$\text{CaCO}_3$	57.00	300.00	17000.00
$\text{MgCO}_3$	20.00	700.00	14000.00
KOH	132.00	1350.00	179000.00
$\text{SO}_x$ emission treatment	0.23	307.00	69.00

Notes: Based on calculations, the annual profit can reach USD210000.00 per year.

and exposing it to chemical reactions with hazardous compounds in industrial wastewater, resulting in the production of low-toxicity or harmless byproducts. Second, by using these generated byproducts in industries like building materials and soil conditioners, this remediation process not only solves waste disposal

problems but also generates new economic value, providing industrially underdeveloped nations with a pathway to sustainable and green development. By implementing these policies, underdeveloped industrial areas can address environmental issues and move closer to achieving diversified and sustainable development.

This strategy can be considered for application in regions with low industrial activity, including non-industrial areas and post-war regions such as the South Pole, parts of Africa, and Asia. These areas often face challenges such as low productivity and a lack of modern industries, leading to limited discretionary income for the population (Roose et al., 2022). For instance, in Afghanistan, factories primarily focus on labor-intensive manufacturing, with over half the population suffering from severe hunger, especially women and children (Ahmad and Mohammad, 2022).

**Table 9** Cost evaluation of preparation of  $\text{CaCO}_3$  hollow microspheres from distiller waste (based on the treatment wastewater of 10 t/d)

Item	Cost (USD)
Total capital investment (TCI)	793190.60
Total manufacturing cost (TMC) = Daily manufacturing cost $\times$ 365 <sup>a)</sup>	117123.91
Product income	210000.00
Total revenue = Product income + savings on wastewater treatment at sewage treatment plants	211592.91
Annual profit	94469.00

Notes: a) TMC includes the yearly costs of materials, labor, and manufacturing. Based on calculations, the return on investment (ROI) is 11.91%, and the pay-back period is 8.40 years.

**Table 10** Total manufactured cost calculated for the biodiesel production from *Spirulina maxima*

Item	Cost (USD)
<b>Direct manufacturing cost (DMC)</b>	
Raw materials	
Methanal	500000.00
H <sub>2</sub> SO <sub>4</sub>	100000.00
Water	1.00
CaO	50000.00
Hexane	200000.00
Utilities	
Electricity	500000.00
Sensors	20000000.00
Cooling water	70000.00
Labor	500000.00
Maintenance = 0.06 × FCI	1256152.68
Supervision = 0.15 × labor	75000.00
Operation supplies = 0.15 × Maintenance	188422.90
Laboratory charges = 0.15 × labor	75000.00
Royalties = 0.03 × TMC	1358445.61
Subtotal	24873022.19
<b>Indirect manufacturing cost (IDMC)</b>	
Overhead, packaging, & storage = 0.6 × labor + supervision + maintenance	1094178.24
Local taxes = 0.015 × FCI	314038.17
Insurance = 0.005 × FCI	104679.39
Depreciation = 0.005 × FCI	1046793.90
Subtotal	2559689.70
<b>General expenses</b>	
Administrative costs = 0.25 × overhead	273544.56
Distribution & selling cost = 0.1 × TMC	4528152.03
Research and development = 0.05 × TMC	2264076.01
Subtotal	7065722.60

Notes: FCI: Fixed capital investment. Based on calculations, the total manufacturing cost (TMC) is USD34498434.49.

Additionally, regions heavily reliant on oil exports, such as parts of the Middle East, Latin America, and Africa, continue to struggle with low productivity, and a majority of the population earns a living through cheap labor (Escobar, 2019; Zanjani et al., 2021). Addressing these issues and improving economic systems, regional production, and quality of life in these regions are currently top priorities (Kahia et al., 2017). This method may also be used to mitigate pollution on islands and in coastal waters. In the Polynesian and Melanesia Islands, where the total population is 7.5

**Table 11** Cost evaluation of biodiesel produced from *Spirulina maxima*

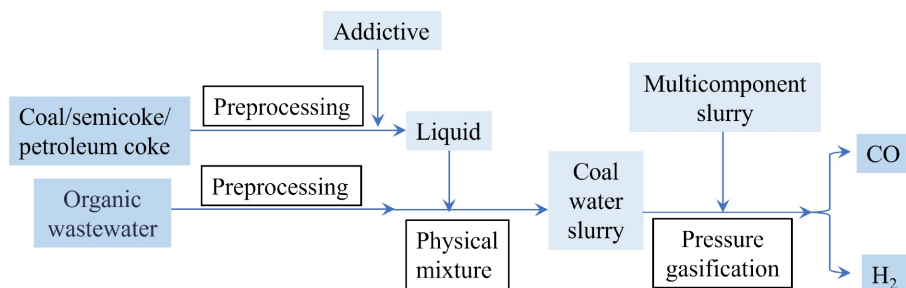
Item	Cost
Total capital investment (TCI) (USD)	24076260.00
Total manufacturing cost (TMC) (USD)	34498434.49
Biodiesel (USD/t)	12350000.00
Cake (USD/t)	53750023.00
Glycerol (USD/t)	1155840.00
Total selling cost (USD)	46848434.49

Notes: Based on calculations, the return on investment (ROI) is 14.82%, and the pay-back period is 6.75 years.

million (Zhu et al., 2021), small-scale factories are the backbone of manufacturing, but unmanaged wastes threaten the South Pacific environment and ecology. Persistent organic pollutants (Polidoro et al., 2017), radioactive substances, and heavy metals (Diarra and Prasad, 2021) in coastal waters and air pollution result in fish malformation, death, and even extinction, posing a serious threat to human health through the food chain and environmental exposure (Athey et al., 2020). The application of this method in South Pacific Island nations could address these waste problems and reduce pollution by covering 550000 km<sup>2</sup> of land (Mohee et al., 2015).

In fact, this mutual remediation method can be extended to the co-treatment of two or more waste streams. For instance, Fengdeng Environmental Protection Plant in Zhejiang, China, co-processes 30%–45% organic wastewater with 55%–70% pulverized coal in a coal-water slurry gasifier, converting them into syngas (primarily CO and H<sub>2</sub>) through reduction atmosphere, high-temperature melting, and rapid quenching (Fig. 11). This operational technology demonstrates coal/water savings and environmental benefits compared to conventional methods. Additionally, research shows metallurgical slags (steel (Gao et al., 2023), copper (Gao et al., 2021a), zinc (Duan et al., 2021), electrolytic manganese (Li et al., 2015) slags, and red mud (Li et al., 2024)) can be modified as catalysts for refractory organic pollutant removal via advanced oxidation processes. For example, steel converter slag achieved 98.8% removal of  $\alpha$ -nitroso- $\beta$ -naphthol from flotation reagents (Li et al., 2024).

The mutual treatment of wastes from fossil energy mining could alleviate severe pollution in regions with a single industrial and ecological structure (Yusta-García et al., 2017; Ahad et al., 2021). By integrating resources and planning land use more efficiently to reduce waste space occupation, small factories in these regions can expand, facilitating long-term



**Fig. 11** Schematic diagram illustrating the integrated process for mutual remediation of organic wastewater and pulverized coal, as implemented by Fengdeng Environmental Protection Co., Ltd. (Zhejiang, China), for synthetic raw gas production.

industrialization (Dorninger et al., 2021). In summary, the mutual remediation method represents a feasible strategy for reconciling industrial development with environmental sustainability across the globe.

## 5 Challenges and future work

### 5.1 Challenges and solutions

The large-scale implementation of mutual remediation methods faces several challenges. The technology for high-volume, low-cost applications is still in its infancy, primarily due to the low efficacy of wastewater in absorbing CO<sub>2</sub>. To tackle this issue, increasing the volume of industrial wastewater feed or reducing the bubble size can augment the total fixed CO<sub>2</sub> by expanding the gas-liquid mass transfer area. Aeration is essential for proper wastewater and CO<sub>2</sub> contact and reaction, but it consumes significant energy, accounting for 70%–80% of energy consumption in wastewater treatment processes and 40%–60% in biological tanks (Xiao et al., 2014; Sun et al., 2016). In remote areas, this energy demand can be met directly through local wind or solar power generation, mitigating energy costs.

Waste-derived products always contain residual contaminants, diminishing their value and complicating purification efforts. For example, various contaminants such as Cr, As, U, Ni, V, Se, Cd, Pb, Zn, and Th in the leachate of phosphogypsum industrial waste are transferred to products such as CaCO<sub>3</sub> (Cárdenas-Escudero et al., 2011). Such subpar goods can be indirectly used for flue gas desulfurization as limestone slurry. In addition, mixing two types of wastewater before CO<sub>2</sub> absorption is suggested for potential co-processing. Adjusting the pH of fly ash slurry by adding waste brine could aid in separating calcium/magnesium and other metal ions, thereby optimizing the quality of inorganic metal carbonate

products (Nyambura et al., 2011). Furthermore, exploring the mechanism of pollutant removal by CaCO<sub>3</sub> may promote its recycled usage in follow-up wastewater treatment, enhancing the technical and economic viability of mutual remediation methods.

Most microorganisms will not survive in the highly toxic environment of wastewater (Mohamed Najib et al., 2016); therefore, a combination of methods is needed to treat wastewater via microorganisms. For example, coking wastewater is refractory due to biological toxicity and complex composition (Wu et al., 2018). A new integrated bio-electrocatalytic process effectively degraded total nitrogen and COD in coking wastewater (Wu et al., 2021). Prior to this, some toxic organics are typically eliminated through processes such as flocculation sedimentation, activated carbon adsorption, and membrane separation. Moreover, the conversion and purification of microalgal bioproducts involve a complex production line, including transesterification, hydrotreating, hydrocracking, extraction, and distillation (Nitsos et al., 2020). The high processing cost and technical requirements of this line currently prevent the large-scale application of microalgae to produce biomass energy (Nitsos et al., 2020). Therefore, in developing regions, after purifying industrial wastewater and absorbing CO<sub>2</sub>, microalgae can be directly used without subsequent processing, such as soil amendments (Ahn et al., 2022). Alternatively, cultivating dominant species, such as *Spirulina maxima*, for biofuel production in sewage treatment plants proves economically feasible, with an 86.92% return on investment (Abdo et al., 2016).

A proposed treatment plan combines multiple approaches to address the inefficiency of industrial wastewater treatment. Taking the example of CO<sub>2</sub> absorption by leachate from solid wastes, the treatment process involves several stages, as illustrated in Fig. 12. Preliminary treatment mainly comprises the physical removal of the solid phase. The primary treatment involves chemical treatment based on CO<sub>2</sub> absorption

by industrial wastewater, neutralizing leachate alkalinity, removing Ca and some heavy metal elements to produce  $\text{CaCO}_3$ , and further eliminating suspended solids and organic matter through flocculation and other methods. During secondary treatment, microalgae, bacteria, and other microorganisms convert the leachate and  $\text{CO}_2$  into biomass products, effectively transforming most organic contaminants into biomass products.

One of the key challenges in practice is the cost. Hence, it becomes necessary to obtain a certain quantity of high-value products to offset these expenses. The quality of carbonate products produced from alkaline and calcium-containing wastewater requires further optimization based on detailed mechanism exploration. Understanding the reaction mechanisms and products generated is crucial for optimizing product quality throughout the  $\text{CO}_2$  absorption process (Baena-Moreno et al., 2022). Moreover, the composition, yield, and purity of biomass products produced by microorganisms are pivotal factors influencing the overall value of the final products. Therefore, choosing strains and algae species with high yield and conversion ratios is crucial for increasing profitability.

A major challenge for the mutual remediation method is that small factories or workshops produce and discharge independently, meaning they are disconnected from one another and do not exchange material flow and energy flow. This results in nonregulated and dispersed pollution in the absence of supervision. Therefore, it is advised that waste be handled on-site to reduce the expense of waste collection and transportation. In practice, many factories generate both wastewater and  $\text{CO}_2$ . Boilers are extensively used across heavy and light industries, such as steel, cement, soda, textiles, leather, and printing. Most of these operations produce  $\text{CO}_2$  emissions, which

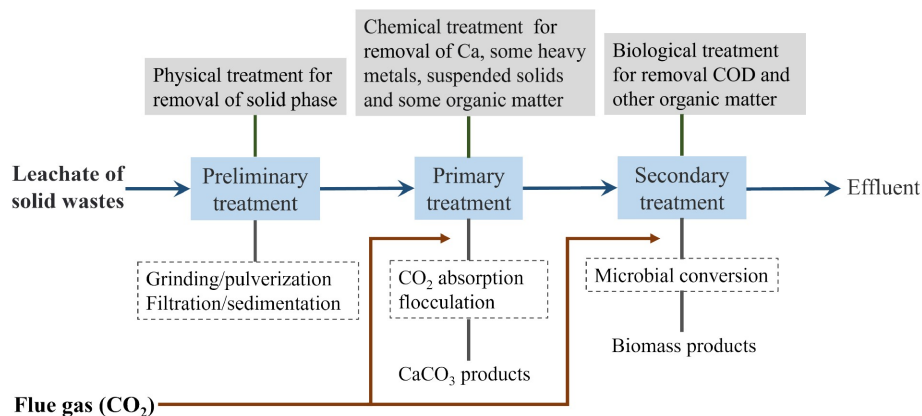
can be absorbed by the wastewater from the same factory. For instance, in Changzhou, China, wastewater from a printing and dyeing facility can directly absorb  $\text{CO}_2$  from boiler exhaust, lowering its pH from above 12 to around 7. Furthermore, this concept of waste-to-waste reactions can be applied to solid waste (Gao et al., 2021b; Wu et al., 2022) and other forms of liquid and gaseous waste (Guérin et al., 2022).

The application of the mutual remediation method might bring about a small local impact, as it is challenging to attract the attention of small factories and locals. However, the potential global impact is much more significant, regarding the ability to address broader environmental issues on a large scale.

## 5.2 Small-scale low-carbon industrial parks

In certain scenarios, wastewater and  $\text{CO}_2$  emissions originate from different factories often situated in remote locales, where waste collection and transportation prove prohibitively costly and impractical (Riedmann et al., 2014). The small city of Kalundborg in Denmark is addressing this challenge (Jacobsen, 2008). Notably, the Statoil refinery channels its wastewater to the adjacent Asnaes power station, reducing reliance on natural water bodies. Furthermore, the flue gas desulfurization byproducts from power plants are fed into the Gyproc drywall plant to serve as a raw material. This example demonstrates the need and feasibility of establishing industrial parks in underdeveloped industrial areas for recycling of wastes.

Beyond the Kalundborg model, exemplars of low-carbon industrial parks, such as the Debert Air Industrial Park in Nova Scotia, Canada (Côté and Liu, 2016), and Masdar City in the UAE (Griffiths and Sovacool, 2020), underscore the efficacy of combating climate change through energy innovation while



**Fig. 12** Treatment process of leachate and  $\text{CO}_2$ .

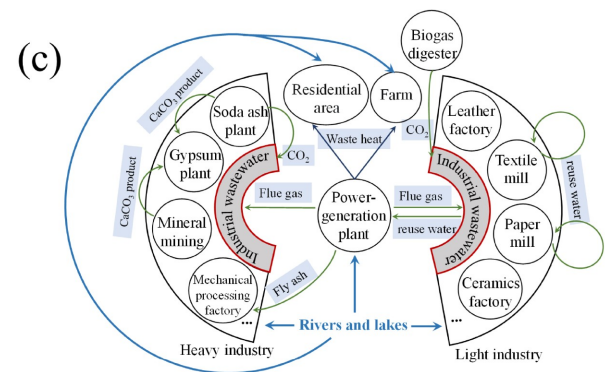
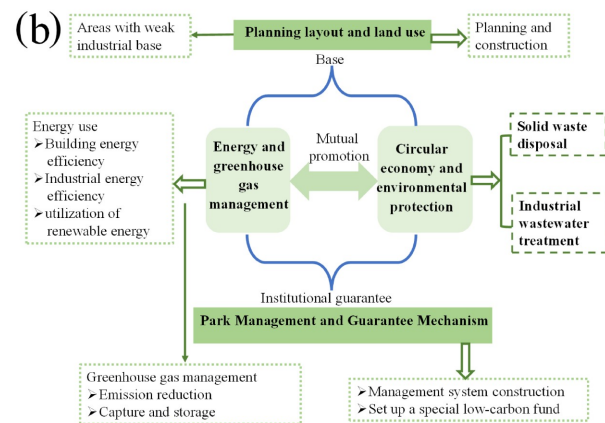
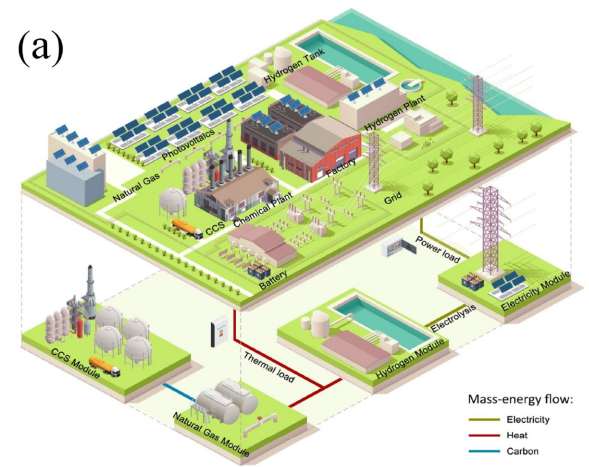
enhancing the environmental performance of industrial complexes (Feng et al., 2018). Figure 13(a) illustrates a near-zero carbon industrial park model (Wei et al., 2022). Nonetheless, direct replication of such comprehensive low-carbon industrial parks in underserved industrial zones proves impractical (Boix et al., 2015). Instead, the concept of establishing small-scale, primary, and resource-recycling industrial parks emerges as an alternative, offering a more versatile structural framework and broader operational scope (Wei et al., 2022), illustrated in Fig. 13(b).

Within this evolving context of industrial park development, zero-carbon and low-carbon industrial parks, where environmental protection and energy conservation are primary objectives, present particularly favorable conditions for implementing mutual remediation of waste streams (Ma et al., 2024). Under the global dual-carbon targets and with the continuous advancement of artificial intelligence in recent years, the next decade is expected to witness exponential growth in the development of zero-carbon and low-carbon industrial parks worldwide (Genc et al., 2019; Wu et al., 2024). Consequently, mutual waste remediation within these industrial parks will emerge as a crucial approach for internal waste management, presenting vast prospects for future development.

This promising outlook for waste remediation is further supported by the comprehensive development trajectory of these parks, which entails meticulous planning, land layout optimization, and green energy use to achieve efficient energy and greenhouse gas management. The development trajectory of these parks entails meticulous planning, land layout optimization, and green energy use to achieve efficient energy and greenhouse gas management (Andiappan et al., 2016). Moreover, embracing circular economy principles and waste treatment technologies facilitates environmental stewardship and resource reuse (Li et al., 2023). Additionally, instituting a tailored management system, possibly through the creation of a low-carbon special fund, ensures the prudent construction and operation of the park (Wu et al., 2023). To further advance these efforts, the following policy recommendations are proposed to promote the adoption and implementation of mutual remediation technologies for waste treatment:

1) Policy Framework: Propose establishing a supportive policy framework, including financial incentives, tax reductions, and subsidies, to encourage enterprises to adopt this green technology.

2) R&D Investment: Advocate for increased investment in research and development of mutual remediation technologies, fostering collaboration between academia and industry to drive further



**Fig. 13** (a) A model near-zero carbon industrial park (Wei et al., 2022), Copyright from Elsevier; (b) development approach of small low-carbon industrial parks; (c) a simplified diagram of a symbiotic network of a small-scale low-carbon industrial park.

innovation and application.

3) Standards and Regulations: Recommend developing industry standards and technical guidelines to ensure the safety and effectiveness of mutual remediation processes, providing a reliable basis for implementation.

4) Public Awareness and Education: Emphasize the

importance of raising public awareness and acceptance of mutual remediation technologies. Suggest that governments and relevant organizations conduct promotional campaigns to enhance societal understanding and support for green technologies.

5) **Regional Collaboration Mechanisms:** Propose establishing regional collaboration mechanisms to encourage cooperation and knowledge-sharing among different regions in the research and application of mutual remediation technologies, promoting widespread adoption.

These recommendations aim to create an enabling environment for the successful integration and scaling of mutual remediation technologies, ultimately contributing to sustainable development and environmental preservation.

Figure 13(c) depicts an example of a small-scale low-carbon industrial park. This park is centered around water bodies, and a power plant acts as the main source of CO<sub>2</sub> in the flue gas. Varied industrial wastewaters are harnessed to absorb CO<sub>2</sub> emissions from workshops, factories, neighboring industrial facilities, power plants, or biogas digesters. Robust pipeline infrastructure facilitates fluid exchange between CO<sub>2</sub> and wastewater streams, with consideration to power consumption and waste scale. Within this integrated ecosystem, energy and material exchanges among factories foster resource sharing within a confined geographical area, effectively reconciling environmental conservation with production imperatives.

## 6 Conclusions

This review assimilates insights from nearly two decades of relevant literature, investigating the efficacy and practicality of mutual remediation of industrial wastewater and CO<sub>2</sub>-containing exhaust gas. Through meticulous exploration, this review has illuminated the feasibility and application prospects of this method, particularly in underdeveloped regions, offering a potential remedy for the treatment of pollution generated by small-scale factories. Additionally, by conducting an economic viability assessment, this review underscores the economic feasibility of this approach.

The literature findings demonstrate the potential of this approach to address dual environmental challenges while also extrapolating its scalability and adaptability, especially in regions with limited industrial infrastructure. Furthermore, it offers a potential solution

for mitigating the adverse ecological impacts of industrial activities. However, it is imperative to acknowledge the need for further research to refine and optimize the methodologies discussed herein, as well as to evaluate their long-term ecological ramifications comprehensively.

**Conflict of Interests** 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.

**Acknowledgements** This work was supported by the Scientific and Technological Innovation Programs of Higher Education Institutions in Shanxi, China (No. 2024L363) and the Taiyuan Institute of Technology Scientific Research Initial Funding, China (No. 2024LJ007). We thank LetPub for linguistic assistance and pre-submission expert review.

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