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Review Article

Valorization of large-scale supply of carbonated water: A review

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ABSTRACT

While the use of carbonated water in enhanced oil recovery (EOR) within the petroleum sector is well-documented, its applications in other fields remain relatively unexplored. This review aims to shed light on the versatile utility of carbonated water across various sectors, with the objective of stimulating further research to address sustainability challenges. Carbonated water can benefit industrial, agricultural, and domestic contexts by offering a sustainable method for utilizing waste CO_2. This review examines the diverse applications of carbonated water, including its role in enhancing oil recovery, aiding medical and healthcare research, reducing carbon footprint in construction, influencing biofuel production and green chemistry, and contributing to the agricultural sector, household, and cleaning domains. The findings suggest that carbonated water could serve as a viable source for CO_2 utilization, presenting significant advantages across various fields. Despite initial costs and infrastructure requirements, integrating carbonated water into existing practices - especially in agriculture and food production - offers clear benefits for offsetting carbon emissions. Continued research and development are essential to advance these technologies and promote sustainable and environmentally responsible practices. We assert that ongoing research and innovation are crucial to unlocking the full potential of carbonated water in various emerging applications.

1. Introduction

Greenhouse gas emissions are widely recognized as a major contributor to the severity of climate change [1,2]. In response to this critical environmental issue, recent years have seen increased exploration of carbon utilization and conversion techniques [3–7]. Among these strategies, carbonated water has emerged as a versatile resource with applications in multiple areas - industrial, agricultural and domestic sectors. This paper reviews the utilization of carbonated water across these distinct sectors, aiming to provide an understanding of its applications and potential benefits.

Carbonated water, generally recognized as sparkling water or soda water, is water in which CO_2 gas has been dissolved under elevated pressure [8]. One of the primary applications of Carbonated Water Injection (CWI) is in Enhanced Oil Recovery (EOR) within the oil and gas sector [9,10]. EOR techniques are employed to increase crude oil extraction from mature reservoirs where conventional primary and secondary recovery methods have reached their limits. CWI involves injecting carbonated water into the oil reservoir to enhance EOR. The dissolved CO_2 in the carbonated water diffuses into the crude oil, reducing its viscosity and altering the interfacial tension between oil and water, thus increasing the oil's mobility. This viscosity reduction facilitates the flow of crude oil toward production wells, leading to improved recovery rates [9,11]. Additionally, the injected CO_2 can interact with the reservoir rock, changing wettability and capillary forces to further enhance oil displacement and recovery [8,12]. Recent advancements in

Abbreviations: ACWI, Active Carbonated Water Injection; APW, Accessible porosity for water; CBI, Carbonated Brine Injection; CSWI, Carbonated Smart Water Injection; CWI, Carbonated Water Injection; CEOR, Chemically Enhanced Oil Recovery; CA, Contact Angle; DBD, Dry Bulk Density; EOR, Enhanced Oil Recovery; FMD, Flow-mediated dilation; GERD, Gastroesophageal reflux disease; IFT, Interfacial tensions; IoT, Internet of Things; LABSA, Linear Alkylbenzene Sulfonate; LCA, Life Cycle Assessment; LSCW, Low Salinity Carbonated Water; MNB, Micro-nano Bubble; NA, Natural Aggregate; PA, Popliteal Artery; RMA, Recycled Masonry Aggregate; RED, reverse electrodialysis; TEA, Techno-economic Assessment; VOC, Volatile Organic Compound.

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CWI technology have focused on optimizing the injection parameters, such as CO_2 concentration, injection rates, and reservoir characteristics, to maximize both oil recovery and CO_2 storage potential [11,13–16]. Furthermore, numerical simulations and laboratory experiments have been conducted to understand the complex interactions between carbonated water, crude oil, and reservoir rock, providing valuable insights for field-scale implementation [17,18].

In this review paper, we explore the further application of carbonated water in the medical and healthcare field, including swallowing behavior [19], medical imaging [20], dental care [21], cardiovascular health [22–24], and physiological research [25]. For instance, research has highlighted carbonated water's effectiveness in enhancing dental implant biofilm removal through intensified cavitation, which could potentially transform dental cleaning methods [21]. It has also been investigated for improving dentin debris removal during root canal treatments, thanks to its enhanced bubble formation during ultrasonic activation, leading to better cleaning outcomes [26]. In medical imaging, carbonated water has shown potential as a medium for Doppler ultrasound imaging, offering clearer flow information and improved signal sensitivity [20]. Additionally, consuming carbonated water alongside medication may facilitate faster and more consistent drug absorption, presenting therapeutic possibilities [25].

Within the industrial sector, carbonated water has merit for construction materials, particularly cement-based products [8,12]. By replacing normal mixing water with carbonated water, the carbon sequestration capacity of porous cement-based materials is enhanced, reducing their carbon footprint [12]. Additionally, carbonated water facilitates accelerated carbonation, which naturally occurs slowly. This is crucial for industries aiming to reduce environmental impact and promote circular economy principles by incorporating waste materials, such as recycled aggregates, into production processes [8].

In the agricultural sector, studies have demonstrated that carbonated water can enhance plant growth and yield by improving nutrient uptake, pH regulation, enhanced photosynthesis, and potential hormonal effects [27]. In addition, research has highlighted the benefits of carbonated water for plant productivity, emphasizing its positive effects on soil quality, CO_2 enrichment, and various growth factors [28]. Recently, utilizing CO_2-enriched micro-nano bubble (MNB) technology to enhance Amaranth growth has shown promising potential for vegetable cultivation [29].

To our knowledge, most literature reviews have focused on the application of carbonated water injection in the petroleum sector, particularly for EOR [30–38]. However, there has not yet been a comprehensive review on the use of carbonated water in the industrial and agricultural sectors. Therefore, our examination of these diverse applications aims to provide a holistic understanding of carbonated water's versatility and practical utility. We aim to provide valuable insights that are applicable across various contexts and to inspire further research in the industrial, agricultural, and domestic sectors.

2. Methods

To explore the literature on the application of carbonated water in industrial and agricultural domains, we conducted a comprehensive search using reputable academic platforms. We utilized Elsevier's ScienceDirect [39] for research journals, the Web of Science platform for the SCIE Science Citation Index Abstracts database [40], as well as other commonly employed databases such as Scopus [41], Google Scholar [42] and ResearchGate [43]. Our search focused on keywords such as "Carbonated Water Applications", "CO_2 Saturated Water", "Sparkling Water" and "Soda Water". To detail the searches, we also applied the following key phrases: "Carbonated Water in Oil/Petroleum industry", "Carbonated Water in the construction sector", "Carbonated Water and construction materials" and "Carbonated Water and health care", "Carbonated Water and Biofuel/Chemistry/Energy", "Carbonated Water in Agriculture". We identified and reviewed a total of 110 papers (as illustrated in Fig. 1) using the PRISMA (Preferred reporting items for systematic review and meta-analysis protocols) [44,45] method, which helped us screen and exclude literature based on inclusion criteria to ensure relevance [44,45]. Our review concentrated on the two primary application fields: industrial and agricultural. In Section 3, we discussed the primary role of carbonated water in the petroleum industry, particularly in Enhanced Oil Recovery (EOR). While EOR research is the most extensive, there is also significant literature on the use of carbonated water in health and medical fields, construction materials, and chemical industries. This review aims to cover these diverse applications comprehensively. The use of carbonated water in agriculture is analyzed in Section 4, based on two comprehensive review articles. Additionally, the practical uses of carbonated water in everyday life, such as in cleaning, are discussed in Section 5 as adjunct applications.

3. Industrial use of carbonated water

3.1. Carbonated water in the oil industry

3.1.1. Carbonated Water Injection (CWI) technology

This section explores the potential of Carbonated Water Injection (CWI) as an Enhanced Oil Recovery (EOR) method, evaluating its effectiveness, adaptations, and the use of nanoparticles to enhance CO_2 solubility. Additionally, it examines modeling simulations for practical CWI applications.

Reservoirs often lack the natural pressure required for effective oil extraction [36,46,47]. Common methods like gas injection or water flooding are used to enhance recovery [30], but gas injection alone faces limitations such as efficiency issues, pressure drops, corrosion, gravity override, reservoir compatibility, gas availability, miscibility, and potential environmental risks [15,48,49]. These challenges have led to research into alternatives like carbonated water injection [35,36,46,47]. In CWI, CO_2 from industrial processes or natural gas fields is combined with water to create carbonated water, which is then injected into reservoirs via dedicated wells [9,31,32,38]. Carbonated water acts as a key transport medium for CO_2 [50], which, when released into the reservoir, leads to oil swelling, viscosity reduction, and decreased surface tension of oil droplets, facilitating their coalescence [32,46,51]. Additionally, changes in water layer thickness or reduced distances between oil droplets can promote contact and merge between them. The coalescence of trapped oil ganglia, therefore, can reduce the number of small oil droplets and increase the size of larger oil masses, making them easier to be carried out of the porous medium and thus enhancing oil recovery efficiency [52].

Local flow diversion in CWI occurs when certain pores become less permeable due to oil blockage, variations in water layer thickness, emulsions, or uneven gas pressure distribution [53,54]. Consequently, the fluid (including water and dissolved CO_2) seeks out more permeable pathways, bypassing the obstructed areas. The flow diversion can contribute to the redistribution of fluid towards previously unaffected regions, thereby increasing the contact area with oil and enhancing oil recovery efficiency [53,54]. Research has confirmed the effectiveness of CWI in enhancing oil recovery and contributing to CO_2 sequestration [13,18,33,37,55]. Key operational parameters such as CO_2 concentration and injection flow rates, critically impact CWI performance and oil recovery rates [56].

Ahmadi et al. emphasized the importance of flow rates and CO_2 concentrations in CWI, achieving final recovery rates between 32.3 % and 40.6 % [57]. This outperformed conventional water flooding, which achieved only 30 % in-situ crude oil recovery after 60 years. Esene et al. [51] conducted a sensitivity analysis revealing that changes in injection rate and pressure significantly affected oil recovery. Higher injection rates could increase recovery by 6 % while raising injection pressure improved CWI performance by up to 16 %. The advantages of CWI are evident in the secondary and tertiary oil recovery stages. Mahzari et al. [11] found that secondary CWI recovered 26 % more oil than

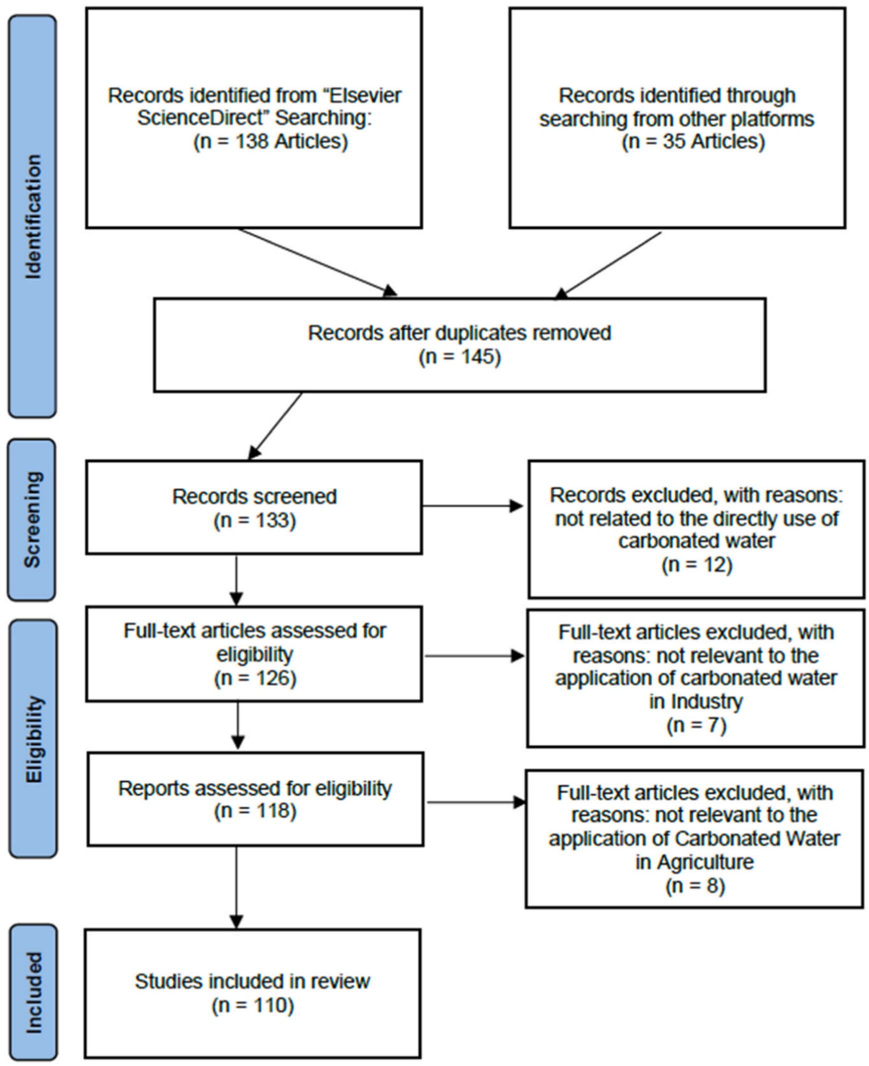

Fig. 1. The process of collecting application of carbonated water literature by the PRISMA method.

conventional seawater injection, due to CO_2 transfer from carbonated water to oil, leading to oil swelling and reduced residual oil saturation [31]. Tertiary injection following secondary injection resulted in a 12.5 % increase in oil recovery, as reported by Mosavat et al. [56], significantly enhancing oil recovery compared to conventional water flooding. The operational conditions and their effects are summarized in Table 1.

3.1.2. Carbonated Water Injection and adaptations

Several investigations have illuminated the utility of CWI and its various adaptations, such as Carbonated Brine Injection (CBI), Carbonated Smart Water Injection (CSWI), and Active Carbonated Water Injection (ACWI) [59–62]. These methods incorporate saline ions (sodium, chloride, calcium), modify specific ions (calcium, magnesium, sulfate), or apply surfactants to lower contact angles (CA), thereby improving the wettability of reservoir rock and enhancing oil displacement [59–61, 63]. Some techniques also reduce interfacial tensions (IFT) between oil and carbonated water, aiding oil expulsion [64–67].

Nowrouzi et al. [61] reviewed CSWI and found it significantly boosted oil recovery in carbonate reservoirs. Their work demonstrated a notable reduction of CA to 18.75° (for Gachsaran oil as shown in Fig. 2A). This wettability enhancement translated into a remarkable 78 % increase in oil recovery. Manshad et al. [59] explored the impact of water-soluble ions and dissolved CO_2 on wettability and oil production, showing that smart water injection alone could boost oil production by up to 33 %. Combining it with CO_2 further enhanced recovery due to altered carbonate rock wettability. Jia's study [18] proposed methods for measuring CO_2 solubility and CA in brine, highlighting CWI as a promising alternative to conventional CO_2 flooding, especially for high-salinity carbonate reservoirs. Given the positive effect of low-salinity EOR [68], Rahimi et al. [69] evaluated the influence of Low Salinity Carbonated Water (LSCW) on IFT. Surprisingly, their study found that combining low-salinity water with carbonated water could significantly reduce the IFT between oil and brine, with reductions of up to 51.8 %. These studies collectively shed light on the potential of CSWI and related techniques to enhance oil recovery in carbonate reservoirs, offering valuable insights for the industry.

Furthermore, utilizing surfactants in carbonated water can also achieve efficient oil recovery and perform well in ultra-low permeable reservoirs. One inspiring work conducted by Du et al. optimized the concentrations of surfactants Linear Alkylbenzene Sulfonate (LABSA) and Cetyltrimethylammonium Bromide (CTAB) at 300 ppm and 350 ppm respectively [70]. Moreover, a CO_2 concentration of 750 mg/L yielded the highest oil recovery. Therefore, the adjustment above led to a notable oil recovery increase of around 34 % [70]. In another laboratory study, Chen and colleagues investigated the potential of ACWI to enhance oil recovery in low-permeable reservoirs [63]. The study used various injectivity scenarios and surfactant concentrations. They

Table 1
Operational conditions and enhanced recovery mechanisms for carbonated water injection in oil fields.

Category	Process/ Mechanisms	Effect/Description	References
Operational Conditions	Higher pressure and lower water salinity	Enhance recovery effectiveness.	[35,36,46,47]
	Co-solvents like methanol and acetone; Temperature-pressure effects	Boost CO_2 dissolution.	[32,46,58]
	Lower injection rates	Improve oil recovery.	[13,18,33,37,55]
Enhanced Recovery Mechanisms	Carbonated water swells oil due to mass transfer	Reduce viscosity and promote interconnection; Decrease interfacial tension between water and oil.	[32,46,58]
	Alters wettability to water-wet	From oil-wet to water-wet.	[13,18,33,37,55]
	Carbonated water forms a new gas phase	Block paths and increase production.	[51,56]
	Coalescence of trapped oil ganglia	Oil droplets coalesce, forming larger droplets and facilitating easier recovery.	[52]
	Local flow diversion	Directs oil droplets toward collection points.	[53,54]

ultimately identified 0.6 PV of LABSA as the optimum surfactant concentration. One of the most striking results was that ACWI could boost the oil recovery factor by 64 %. This outcome highlights the efficacy of combining surfactants with CWI in challenging reservoir conditions. However, since its scope was limited to laboratory conditions, further research is needed to validate these results in real low-permeable reservoir applications.

In addition, the CWI combined activating solution gas drive method can enhance oil recovery [71,72]. Shakiba et al. [71] showed that CWI improved oil recovery efficiency and following a solution gas drive can further enhance recovery. The results are compelling: more than 25 % of the original oil in place was recovered after secondary CWI tests, and over 18 % was recovered after tertiary CWI tests. Alqam et al. [73] combined pendant drop tests and molecular dynamics simulations to understand how adding carbon dioxide affects these interactions. They found that carbonated water shifts wettability from weakly oil-wet to intermediate to water-wet. Molecular simulations reveal that these changes were due to altered IFT and asphaltene swelling driven by interactions with carbon dioxide. This research highlights carbonated water's potential for enhanced oil recovery and offers insights into the mechanisms behind this wettability shift.

3.1.3. Nanoparticles

Nanomaterials can enhance CO_2 solubility in carbonated water [74], impacting EOR and CO_2 sequestration [75,76]. Sun et al. discovered that SiO_2-enhanced carbonated water increased CO_2 solubility by an impressive 17 % and displayed superior stability [76], although its applicability was limited at elevated temperatures. Nowrouzi et al. examined the influence of TiO_2, MgO, and γ-Al_2O_3's on CO_2 solubility, highlighting their role in reducing IFT in Chemically Enhanced Oil Recovery (CEOR) [75]. Their research suggests combining nanoparticles with carbonated water could enhance oil recovery and significantly reduce IFT, with variables such as temperature, salinity, nanoparticle concentration, and pressure affecting the outcomes. In a pioneering effort, Chaturvedi and Sharma [14] investigated the innovative use of polymeric nanoparticle suspensions in carbonated water to enhance oil recovery from sandstone reservoirs, improving CO_2 absorption and oil recovery. Salt in water reduces CO_2 loading and oil recovery efficiency, while higher temperatures negatively affect CO_2 absorption, as demonstrated in Fig. 2B. This introduces carbonated polymeric nanoparticle suspensions as a promising approach for EOR in sandstone reservoirs [14].

3.1.4. Modeling and simulations

Modeling and simulations of CWI offer valuable insights for practical operations [17,34,64]. Esene et al. [17] utilized a novel 3D heterogeneous reservoir model to assess factors, such as oil recovery, fluid distribution, operational parameters, and well placement. Their work highlighted CWI's merits in EOR with high sweep efficiency and CO_2 storage benefits. Injection pressure and well orientation are emphasized for improved performance, prompting further investigation into displacement mechanisms. Motie and Assareh [77] presented a modeling strategy to assess CWI for EOR and CO_2 sequestration in naturally fractured reservoirs, particularly during tertiary production. Their research reported a 10.6 % incremental oil recovery and highlighted the potential of trapping 3000 mol of CO_2 in the matrix. These outcomes address concerns about CO_2 emissions and the role of geological CO_2 storage as a solution, with a call for validation in different reservoir types and conditions. Mahzari et al. [10] proposed a method for simulating CWI in carbonated rocks, emphasizing short CWI cycles and geochemical intricacies. CWI's worth in EOR suggests future enhancements, including water preparation, CO_2 solubility, and reservoir selection, while geological research identifies suitable reservoirs. According to their study, oil recovery profiles from simulations show that tertiary injection with carbonated water offered a 6.2 % increase in oil recovery over regular water. In short, carbonated water injection cycles can achieve the same benefit while mitigating rock dissolution risks near the injection well, as depicted in Fig. 2C. Table 2 summarizes findings across different aspects of CWI for EOR, such as the efficacy of CWI, parameter analysis, wettability improvement, nanotechnology applications, and modeling simulations, and so on.

3.2. Application of carbonated water in health and medical fields

Carbonated water has diverse applications in healthcare and medical field, offering benefits in areas such as dental care [21], swallowing behavior, intestinal motility [26,78], pharmacokinetics [79–81], medical imaging [82], cardiovascular health [22–24], and psychological well-being [20].

3.2.1. Dentistry - removing biofilm from dental implants

The potential application of cavitation to enhance biofilm cleaning has attracted considerable interest within the research community. Currently, a lack of effective methods for the specific removal of biofilms from dental implants presents a significant challenge. Vyas et al. explored using carbonated water with an ultrasonic dental scaler to enhance biofilm removal in dental implants [21]. They found that cavitation, which aids in biofilm removal, significantly increased when the scaler operated in carbonated water, as shown in Fig. 3 A. Carbonated water facilitates earlier cavitation inception and generates a greater number of cavitation bubbles around the tip of the ultrasonic scaler. When these bubbles collapse, they exert shear forces on the surface to increase the cleaning effect. The collapse of bubbles could create microjets or acoustic streaming around oscillating bubbles, both of which contribute to surface cleaning. Furthermore, the use of carbonated water can increase the number of inertial collapsing bubbles on the surface, indicating that the increased level of carbonation enhances the ability to remove biofilm [21].

3.2.2. Enhancing dentin debris removal

Van der Sluis et al. [26] conducted a study to evaluate the

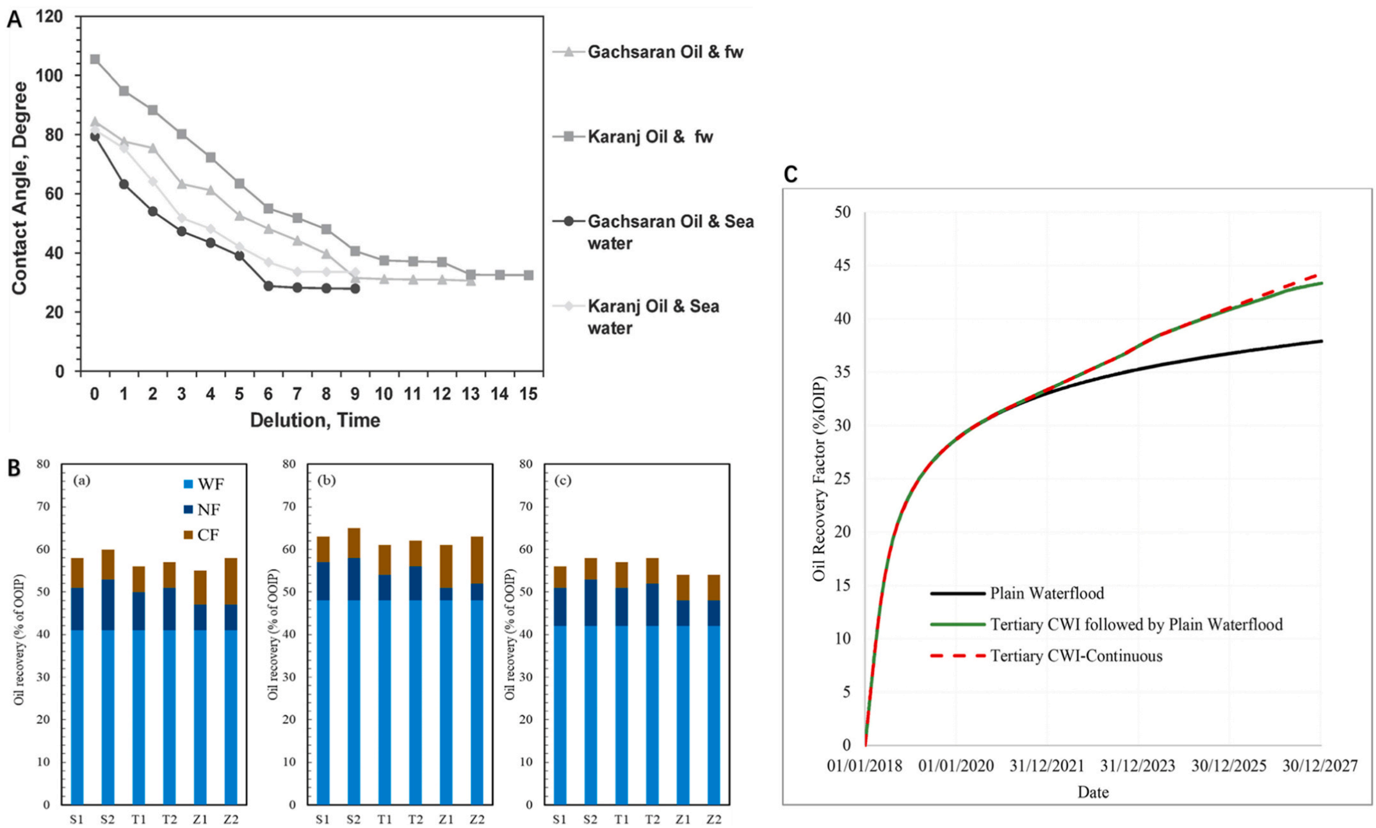

Fig. 2. (A) Carbonated water injection: the changes in contact angles of two droplets of oil on sections aged in different samples of saline water with different dilutions and aqueous bulk. Adapted with permission from Nowrouzi, et al. Copyright 2019 Elsevier. (B) The image compares oil extraction percentages for each injection phase under different conditions: (a) at 328 K with water-filled sand packs, (b) at 353 K with similar packs, and (c) from sand packs impregnated with 3% NaCl solution at 328 K. The abbreviations WF, NF, and CF indicate the methods used: water flooding, nanofluid flooding, and carbonated fluid flooding, respectively. Adapted with permission from Raghav, et al. Copyright 2020 Elsevier. (C) Profiles of oil recovery for three simulation cases. Tertiary carbonated water injection would lead to 6.2% additional oil recovery. Adapted with permission from Mahzari, et al. Copyright 2019 Elsevier.

effectiveness of ultrasonic activation in removing dentin debris from root canals using various irrigants, including 2 % and 10 % sodium hypochlorite, carbonated water, and distilled water. The study employed three refreshment/activation cycles utilizing the intermittent flush technique, specifically targeting root canals contaminated with dentin debris. The results reveal a cumulative benefit of ultrasonic activation coupled with intermittent flushing for three cycles. Despite the similarity in fluidic properties among the irrigants, which results in comparable flow characteristics, acoustic cavitation is a crucial factor. Notably, sodium hypochlorite proves to be significantly more effective in removing dentin debris compared to carbonated water, which in turn performs better than distilled water. The study further supports the observation that carbonated water exhibits accelerated bubble formation under ultrasonic activation, potentially enhancing its cleaning capabilities. However, further research is needed to investigate these mechanisms.

3.2.3. Doppler ultrasound imaging

Carbonated water shows merits in Doppler ultrasound imaging, offering clear and quantifiable flow information. Lee et al. conducted a study comparing carbonated water to traditional media for producing blood-like responses in ultrasound images [20]. They found that carbonated water delivered clear flow in Doppler ultrasound images, making it a viable medium for medical ultrasonic applications as clearly indicated in Fig. 3B. The application mechanisms of carbonated water in Doppler ultrasound technology lay in the fact that the bubbles contained in it can act as scatterers to effectively simulate the scattering effect of red blood cells in the blood. When carbonated water is introduced into Doppler ultrasound scanning, these bubbles scatter under the action of ultrasonic waves, thus enhancing the sensitivity of Doppler signals. This principle makes carbonated water a simple and efficient material that can be used in Doppler ultrasound phantom design to simulate and evaluate blood flow conditions. Although the specific effects of carbonated water on solubility, bubble size, and blood flow simulation effects still need further study, this research initially confirms its significant advantages in Doppler ultrasound, providing a valuable reference for future related research and applications. Moreover, compared to other materials such as sugar water, saline, starch, and cooking oil, carbonated water can produce clearer and stronger scattering signals to make blood flow simulation more accurate and reliable [20].

3.2.4. Paracetamol absorption

Van Den Abeele et al. conducted a crossover investigation [81] to address variability in systemic drug exposure after oral administration. They studied the effects of consuming sparkling water alongside conventional paracetamol tablets in a fast state, using healthy volunteers. The study monitored antroduodenal motility and drug disposition over time, revealing transient pressure events in the upper gastrointestinal tract following the ingestion of sparkling water, as shown in Fig. 3C. When the drug was taken along with sparkling water, brief fluctuations in pressure were observable in the stomach and the upper section of the duodenum. However, when the drug was consumed with tap water, no such pressure changes were detected, as can be seen in Fig. 3C (a) for tap water and (b) for sparkling water. The study supports that co-administering paracetamol with sparkling water leads to faster and more consistent absorption due to direct effects on tablet dissolution and

Table 2
Summary of studies on Carbonated Water Injection (CWI) and its variants in Enhanced Oil Recovery (EOR).

Category		Key Findings	Reference
Efficacy of CWI	Overall effectiveness	Final recovery rates between 32.3 % and 40.6 %, outperforming conventional water flooding.	[57]
	Secondary CWI	Secondary CWI recovers 26 % more oil than conventional seawater injection.	[11]
	Tertiary CWI	Tertiary injection with carbonated water offers a 6.2 % increase in oil recovery over regular water.	[10]
	CWI + Gas drive	More than 25 % of original oil recovered after secondary CWI tests, and over 18 % after tertiary CWI tests.	[71]
Wettability Improvement	CO_2 and water interaction	Carbonated water shifts wettability from oil-wet to water-wet, aiding in oil recovery.	[73]
	CSWI in carbonates	18.75° reduction in contact angle, 78 % increase in oil recovery.	[61]
	Ions and CO_2 Interaction	Smart water injection boosts oil production by 33 %; with CO_2, it enhances recovery further.	[59]
	LSCW Impact	LSCW can significantly reduce the IFT between oil and brine.	[69]
Other Parameter Analysis	Sensitivity analysis	Injection rate and pressure changes significantly affect oil recovery.	[51]
	Surfactant optimization	Optimization of surfactant concentrations for better oil recovery.	[70]
Nanotechnology	CO_2 solubility	SiO_2-enhanced carbonated water increases CO_2 solubility by 17 %.	[76]
	IFT reduction	The combination of nanoparticles and carbonated water can significantly reduce IFT and enhance oil recovery.	[75]
	Sandstone reservoirs	Carbonated polymeric nanoparticle suspensions enhance CO_2 absorption and oil recovery.	[14]
Modeling and Simulation	Reservoir modeling	The 3D reservoir model highlights the high sweep efficiency and CO_2 storage benefits of CWI.	[17]
	Fractured reservoirs	Incremental oil recovery and potential CO_2 trapping in fractured reservoirs.	[77]

indirect impacts on gastrointestinal motility.

3.2.5. Drinking water and swallowing behavior

In studies concerning the swallowing behavior of patients, carbonated beverages have been demonstrated as a useful tool [19,78,83]. They notably reduce the duration of swallowing sounds, particularly in the later phases of the pharyngeal stage, potentially offering a solution for addressing swallowing difficulties in the aging population [19,78]. Morishita et al. investigated the impact of carbonated beverages on the swallowing behavior of elderly inpatients without dysphagia by employing cervical auscultation recordings [78]. They noted a decrease in swallowing sound duration after consuming carbonated drinks, especially in the late pharyngeal phase. This study implies that carbonated beverages have a real impact on the swallowing behavior of this patient population, revealing how sensory stimulation, like carbonation, affects swallowing in older individuals.

Kubota et al. [84] aimed to explore the effects of drinking cold or carbonated water on blood pressure in both young and older adults. The results show that consuming cold carbonated water leads to a more significant increase in blood pressure compared to room temperature water in both age groups. The pressure response persisted during the recovery period and was more pronounced in older individuals. These findings suggest that even small amounts of cold and carbonated water can effectively raise blood pressure, making it a potential first-aid approach for certain types of acute hypotension. In addition, carbonated water has been found to enhance cerebral blood flow and improve emotional states [85]. Fujii et al. [23] conducted a study on the effects of carbonated water on cerebral blood flow and mood states in humans exposed to ambient heat stress [25]. They measured middle cerebral artery blood velocity and found that carbonated water increases cerebral blood flow. Participants reported reduced sleepiness, increased motivation, and exhilaration, and a blood pressure rise. A control group drank non-carbonated water at 4 °C for comparison. These findings suggest carbonated water can impact physiological parameters, including cerebral blood flow and blood pressure, and influence psychological states, especially under heat stress.

However, it is important to note that frequent consumption of carbonated water, despite its perceived health benefits, can harm dental health due to its acidic nature, potentially leading to enamel erosion, and compromising dental treatment adhesives [86]. Carbon dioxide, essential for bodily functions like regulating pH balance, respiration, and circulation is mostly lost during consumption, with a small portion absorbed in the digestive system. The association between carbonated beverages and Gastroesophageal reflux disease (GERD) is uncertain, with conflicting study results. These drinks can affect the stomach differently, potentially causing delayed emptying or increased belching. Furthermore, carbon dioxide absorption influences hydrochloric acid formation, which, when consumed excessively, can lead to stomach issues such as ulcers and gastritis [87].

3.2.6. Cardiovascular health

Endothelial dysfunction, which is linked to increased cardiovascular mortality, can be ameliorated by therapies that enhance blood flow and shear stress [24]. Nishimura et al. [24] examined the impact of repeated artificial CO_2 (1000 ppm) bathing on various physiological parameters in six healthy males. Participants immersed themselves in CO_2-rich water at 34 °C for 20 minutes daily over five days. The study found that tympanic temperature significantly decreased and cutaneous blood flow in the immersed skin significantly increased during CO_2 bathing ($P < 0.05$). Subjects also reported a warm sensation during the baths, with thermal sensation scores decreasing with repeated exposure.

Building on this foundation, a study by Ogoh et al. [23] hypothesized that CO_2-rich water could enhance endothelium-mediated vasodilation with reduced heat stress. In this investigation, 12 subjects underwent acute lower legs and feet immersion in mildly warm (38 °C) normal or CO_2-rich tap water (1000 ppm) for 20 minutes. The results indicated that CO_2-rich water immersion significantly increased flow-mediated dilation (FMD) ($P < 0.01$), while normal water did not affect FMD. The increase in FMD was positively correlated with changes in skin blood flow ($P < 0.01$), suggesting that enhanced skin blood flow improves endothelial function. Notably, normal tap water required heating to approximately 43 °C to achieve the same skin blood flow level as CO_2-rich water at 38 °C. A subsequent study by Ogoh et al. [22] further investigated the effects of carbonated water on vascular function. In this study, 10 men immersed their lower legs in either tap or carbonated water at 38 °C. The results show that immersion in carbonated water, but not tap water, significantly elevated popliteal artery (PA) blood flow (from 38 ± 14 to 83 ± 31 mL/min; $P < 0.001$) and skin blood flow (by 779 ± 312 %; $P < 0.001$). However, carbonation did not significantly affect gastrocnemius muscle oxyhemoglobin concentration or tissue

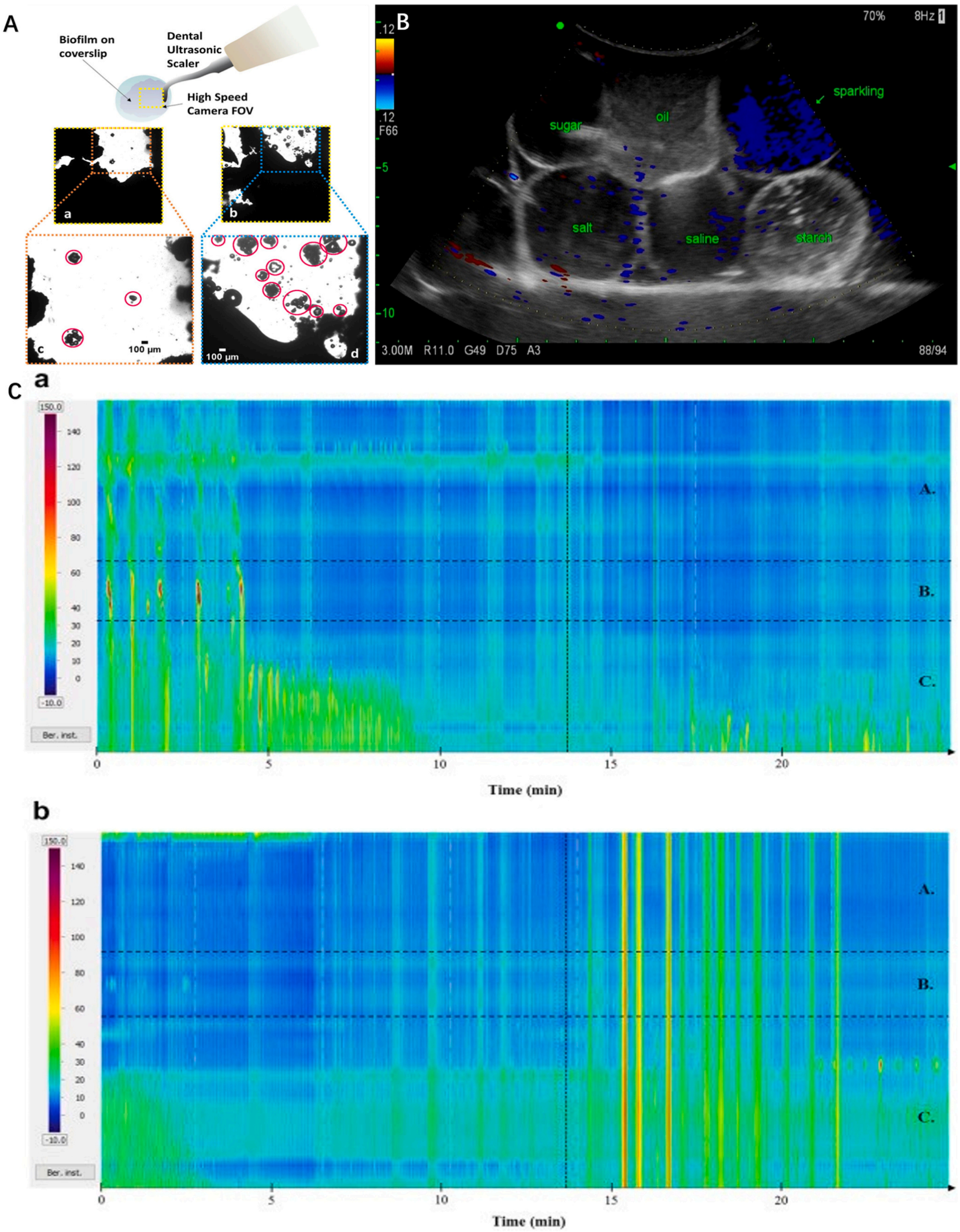

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Fig. 3. (A) High-speed video captures show biofilm removal. Images reveal biofilm cleared by ultrasonic cavitation in still water (a, c) and carbonated water (b, d). Larger cavitating bubbles over 100 μm are marked in red, indicating increased bubble activity at the biofilm surface in carbonated water. Adapted with permission from Vyas et al. Copyright 2021 Elsevier. (B) Doppler was observed in carbonated water (sparkling), sugar water (sugar), cooking oil (oil), salt water (salt), distilled water (saline), and starch (starch) after setting the gain to 66. Adapted with permission from Lee et al. Copyright 2020 Elsevier. (C) Typical examples of high-resolution manometry recordings, which were captured after a healthy volunteer consumed one tablet of Dafalgan® (containing 500 mg of paracetamol) with either 330 mL of plain tap water (in example a) or 330 mL of sparkling water (in example b). Region A stands for the proximal part of the stomach (corpus), B for the distal part of the stomach (antrum), and C for the proximal duodenum. Colors indicate pressure amplitude (mm Hg). Adapted with permission from Van Den Abeele et al. Copyright 2017 Elsevier.

oxygenation index. The increase in PA blood flow was correlated with the increase in skin blood flow ($P = 0.005$), but not with oxyhemoglobin concentration ($P = 0.765$) or tissue oxygenation index ($P = 0.136$). These findings suggest that the increase in skin blood flow primarily drives the increase in PA blood flow due to carbonated water immersion. Collectively, these studies demonstrate that CO_2-rich water immersion can improve endothelial-mediated vasodilator function and reduce arterial stiffness with minimal heat stress. This suggests potential therapeutic benefits for patients with cardiovascular disease. Key findings of carbonated water applications in medical and healthcare fields are summarized in Table 3.

3.3. Application of carbonated water in the construction industry

In recent years, the construction industry has sought innovative solutions to improve material properties, reduce carbon emissions, CO_2 sequestration, and recycle industrial waste. Although the use of carbonated water in construction materials is not yet widespread, pioneering studies have explored its potential applications [8,12].

Suescum-Morales et al. conducted a study assessing the use of carbonated water as a mixing solvent to enhance cement-based materials with recycled aggregates, as shown in Fig. 4A [8]. The study compared Natural Aggregate (NA) and Recycled Masonry Aggregate (RMA), finding that carbonated water improved mechanical properties and CO_2 sequestration by up to 181 %, especially with RMA compared to NA and regular water. No benefits were observed with NA after one-day curing. Still, this highlights carbonated water's potential to enhance performance and sustainability in cement-based materials with recycled aggregates, supporting sustainable construction goals.

Suescum-Morales et al. also explored using carbonated water as a mixing agent for incorporating recycled brick aggregates into porous cement-based materials [12]. They discovered that carbonated water effectively improved the mechanical properties and porosity of the materials by facilitating simultaneous hydration and carbonation. As demonstrated in Fig. 4B, across all mixtures examined, the use of carbonated water was found to enhance both the dry bulk density (DBD) and the accessible porosity for water (APW) of the mixtures. This was attributed to the carbonation reaction triggered by the carbonated water under controlled conditions. This reaction increased mechanical strength for both NA and RMA after seven days of curing. Additionally, a more intense presence of $CaCO_3$ peaks was observed in the X-ray diffraction analysis. During heating from 480 to 1000 °C, a greater weight loss was detected due to the decomposition of calcite, as can be found in the thermogravimetric analysis/differential thermal analysis (TGA/DTA) in Fig. 4 C.

For mixtures containing NA, normal water resulted in a 3.8 % mass loss, while carbonated water led to a 9.19 % mass loss within the 480–1000 °C range, suggesting greater $CaCO_3$ formation, as can be seen in Fig. 4C (A). For mixtures with RMA, as depicted in Fig. 4C (B), the mass loss was 5.5 % for normal water and 6.01 % for carbonated water in the same temperature range. The difference in calcium carbonate formation was less significant in the RMA mixture due to its complex composition and potential lower sensitivity to pH changes. The presence of impurities and variable particle sizes in RMA could also have influenced the carbonation process [12]. This research demonstrates the feasibility of using recycled brick aggregates and reinforces the potential of carbonated water to enhance construction materials.

Table 3
Key findings of applying carbonated water in the health and medical fields.

Category		Key Findings	Reference
Dentistry	Biofilm removal	Carbonated water with an ultrasonic dental scaler enhances biofilm removal from dental implants.	[21]
	Dentin debris removal	Carbonated water aids in dentin debris removal from root canals, outperforming distilled water but less effective than sodium hypochlorite.	[26]
Pharmacokinetics	Paracetamol absorption	Sparkling water consumption alongside paracetamol tablets leads to faster and more consistent drug absorption.	[81]
Swallowing Behavior	Impact on elderly	Carbonated beverages reduce swallowing sound duration in elderly patients, aiding in swallowing difficulties.	[78]
Blood Pressure	Effects of cold/ carbonated water	Consumption of cold and carbonated water increases blood pressure in young and older adults.	[84]
Psychological Well-being	Effects on mood and cerebral blood flow	Carbonated water enhances cerebral blood flow and improves mood states, especially under heat stress.	[25]
Medical Imaging	Doppler ultrasound imaging	Carbonated water provides clear flow in Doppler ultrasound images, proving its efficacy in medical imaging.	[20]
Cardiovascular Health	Vascular function	Repeated CO_2-rich water immersion increases cutaneous blood flow, lowers tympanic temperature. Lower leg immersion in 38 °C CO_2-rich water enhances flow-mediated dilation and skin blood flow, while also increasing popliteal artery blood flow, improving endothelial function, and reducing arterial stiffness.	[22–24]

3.4. Carbonated water application for biofuels

Recent studies have aimed to optimize the conversion of biomass materials into sugars for biofuel production, particularly focusing on bioethanol. These environmentally friendly approaches have shown potential in reducing costs and enhancing efficiency in biofuel

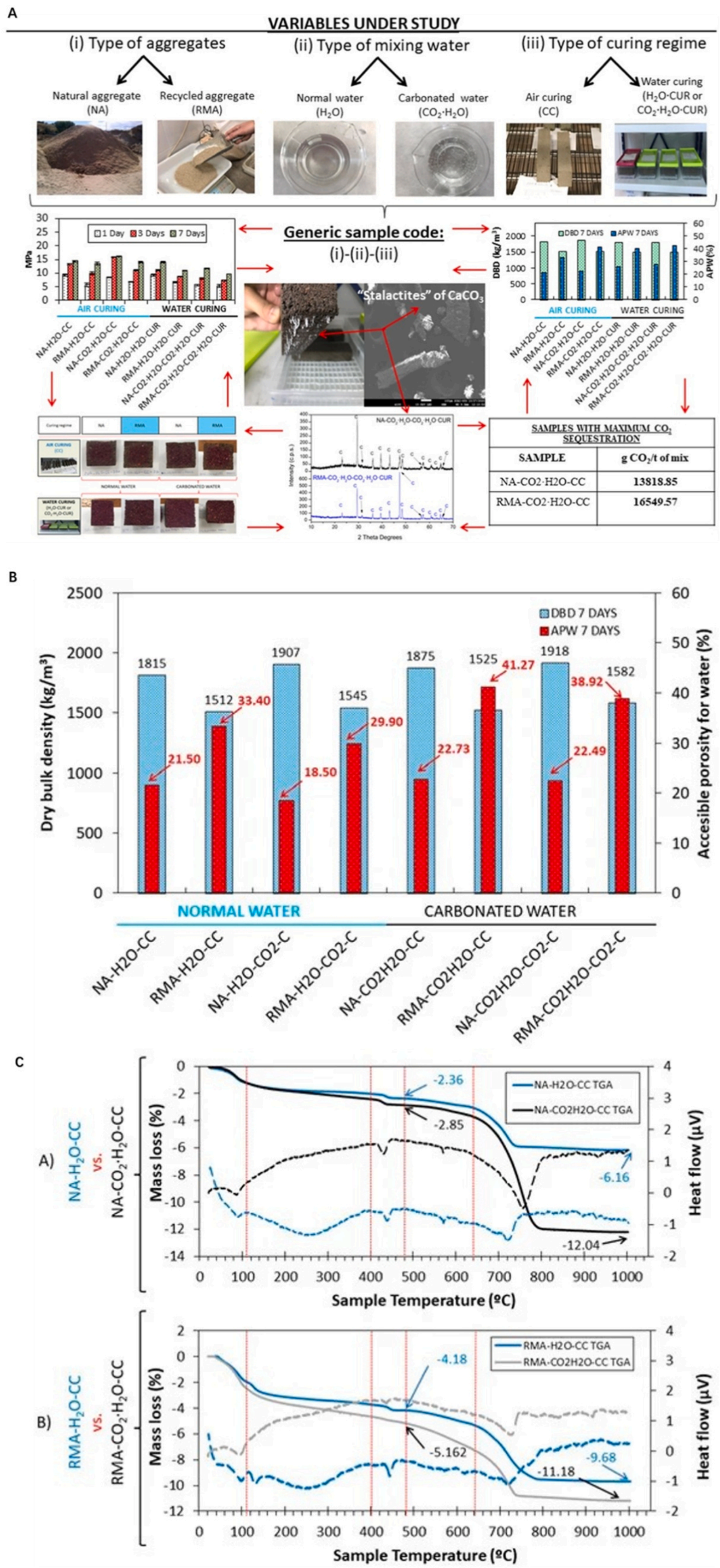

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Fig. 4. (A) Assessment of the use of carbonated water as a mixing solvent to enhance the properties of cement-based materials with recycled aggregates. Adapted with permission from Suescum-Morales et al. Copyright 2022 Elsevier. (B) The utilization of carbonated water was found to enhance both the dry bulk density (DBD) and the Accessible porosity for water (APW) of the mixtures for both NA and RMA after seven days of curing. (C) The TGA (solid lines) and DTA (dotted lines) curves are presented for two different mixtures: A) the mixture containing NA, and B) the mixture with RMA. In both cases, the curves compare the use of normal water with the use of carbonated water. Adapted from Suescum-Morales et al. 2022.

production.

King et al. [88] explored the utilization of supercritical carbon dioxide dissolved in water for the pretreatment and depolymerization of sugars in biomass such as corn stover and switchgrass. This process operated at temperatures ranging from 150 to 190 °C and pressures of 150–450 bar, adjusting parameters such as temperature, CO_2 pressure, treatment time, and particle size to optimize the conversion efficiency. The principle behind this method lies in the unique physical properties of supercritical carbon dioxide, which allowed it to form a uniform solution with water. This solution penetrated the biomass fibers, disrupting their structure and facilitating the depolymerization of cellulose and hemicellulose. Compared to traditional sulfuric acid pretreatment, this approach reduces the required enzyme quantities and eliminates the need to neutralize the acidic medium post-pretreatment.

Furthermore, the dissolution of carbon dioxide enabled in situ pH adjustment, which could optimize the conditions for enzymatic hydrolysis and eliminate the need for additional pH adjustment steps. Experimental results demonstrate that under optimal conditions, this supercritical carbon dioxide pretreatment and enzymatic saccharification process significantly reduces the amount of enzyme required, achieving a remarkable 33 % reduction in Depol 692 L enzyme usage compared to dilute sulfuric acid pretreatment, as can be seen in Fig. 5 [88]. Additionally, it exhibits promising potential in enhancing sugar yields from specific biomass substrates.

Yamagishi et al. [89] explored the effectiveness of using carbonated water to remove calcium from $Ca(OH)_2$-treated rice straw. They found that a washing sequence of two water washes followed by two carbonated water washes was more effective, removing 92.1 % of the calcium and recovering 49 % as CaO. This method not only improved calcium removal but also enhanced sugar extraction during enzymatic saccharification, likely due to the lower achieved pH. Under an unpressurized CO_2 atmosphere, this washing sequence released 78.5 % of glucose and 90.0 % of xylose. Putt et al. [90] identified the potential of high-rate algal ponds to yield 59 tons of dry biomass per hectare annually, with a specific productivity of 20 g/m^2/day. Traditional methods of introducing concentrated CO_2-air mixtures for algal growth are inefficient for gas transfer. An innovative approach using a carbonation column (CC) achieved an 83 % CO_2 transfer efficiency and established an air-to-pond mass transport coefficient of 0.0037 m/min enhancing algae production when used with CO_2-rich exhaust gas streams and raceways. The main

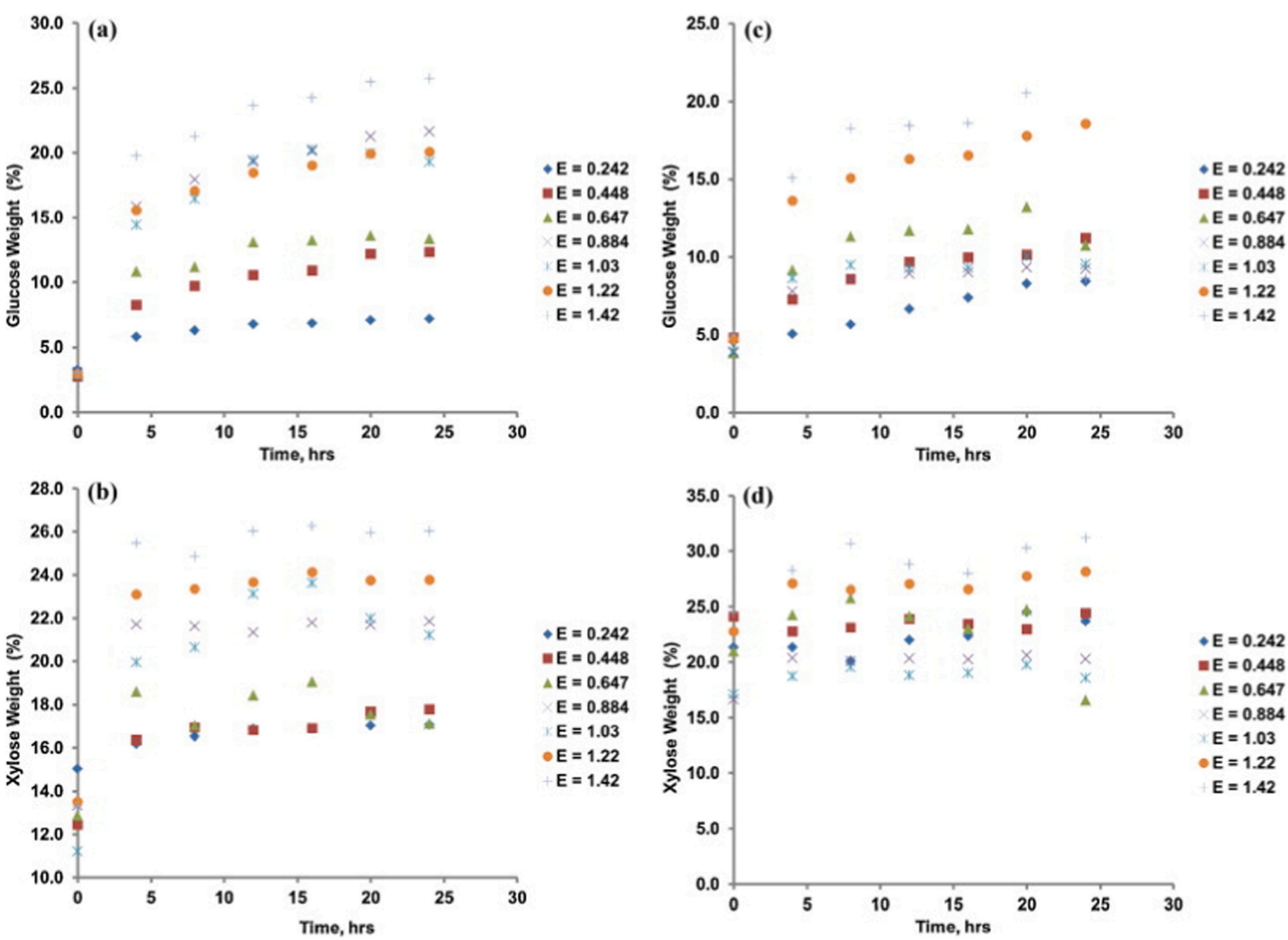

Fig. 5. The enzymatic hydrolysis of switchgrass hydrolysate pretreated with carbonated water (a, b) and dilute sulfuric acid (c, d) using Depol 692 L enzyme yielded glucose and xylose in weight percentages (E = enzyme loading in g-enzyme/g-biomass). Adapted with permission from King et al. Copyright 2012 Elsevier.

findings from this section are summarized in Table 4.

3.5. Green chemistry & renewable energy

Wang et al. [91] presented an innovative and sustainable approach to graphene manufacturing using carbonic acid-enabled electrochemical under-etching delamination. This process involves the electrochemical reduction of Cu_2O between the copper catalyst substrate and synthesized graphene. The process started with preparing a self-pressurized vessel containing the vertical mechanism for the gradual immersion and delamination of ethyl cellulose-coated graphene on copper foil into a carbonic acid solution. Ethyl cellulose (food-grade) was used as a thin film handle layer, replacing traditional polymers that rely on harsh solvents, thus improving the environmental sustainability of the process. The copper foil substrate served as the cathode and was biased at approximately 10 V in a two-terminal DC set-up, as illustrated in Fig. 6. This applied potential triggers the electrochemical reduction of Cu_2O to copper metal. The reduction occurred preferentially at the interface between the Cu_2O and the graphene, leading to the under-etching of the graphene layer from the copper.

The carbonic acid electrolyte was formed by dissolving carbon dioxide in deionized water and played a crucial role in maintaining the system's conductivity. The bicarbonate anions presented in the electrolyte facilitate the efficient electron transfer and uniform reduction of Cu_2O. This electrochemical delamination occurred gradually as the graphene-coated copper foil was immersed deeper into the carbonic acid solution. The outcome of this research is a residue-free and environmentally friendly method for transferring graphene, eliminating the need for harsh chemical etchants, and reducing water usage.

4. Agricultural use of carbonated water

In agriculture, carbonated water has shown the potential to enhance plant growth and crop yields. Enoch & Olesen [27] found that CO_2-enriched irrigation generally improved plant growth and increased yield, while Storlie & Heckman [28], however, observed variable effects of CO_2-rich water on different plant species. Despite these promising results, recent studies on this topic are limited. This emphasizes the need for ongoing research and reanalysis of historical findings to uncover new insights into using carbonated water in agriculture.

4.1. Plant irrigation with CO_2-enriched water

Enoch & Olsen's study on plant irrigation with CO_2-enriched water found more plant growth compared to normal water irrigation. This enhancement was attributed to improved nutrient uptake, pH changes aiding nutrient absorption, enhanced photosynthesis, and effects on plant hormones and pesticides [27]. Overall, their study highlighted the benefits of CO_2-enriched water for plant growth and food production. Despite the historical significance of such research, dating back to Mitscherlich's report [92], it had often been overlooked in later studies, making Enoch & Olesen's work important for revisiting the varying effects of CO_2-enriched water on plant growth and associated mechanisms [93].

Since the mid-19th century, researchers have studied plant carbon absorption. Early experiments [28] found that oat plants initially suffered from CO_2-enriched water but eventually thrived, sparking debates on root or leaf absorption. Later studies [94–97] suggested minimal root absorption. Mitscherlich's research [92] saw no yield improvement, suggesting excessive soil CO_2 limits impact. Subsequent studies [92,98,99] found elevated root zone CO_2 hinders growth. Livingston & Beall [100] confirmed atmospheric CO_2 assimilation, with the exception of Stylites Andicola, which primarily absorbed through roots.

4.2. CO_2-enriched water mechanisms

Enoch & Olesen's experiments indicated a 2.9 % increase in plant yield with CO_2-enriched water in the tests [27]. CO_2-enriched water irrigation could alter soil-air composition, influenced by irrigation methods and timing. Controlled environments with constant CO_2 additions exhibit more pronounced changes [101]. Additionally, CO_2 dissolving in irrigation water raised air CO_2 levels in enclosed spaces like greenhouses, briefly benefiting plant growth, with outcomes dependent on greenhouse size, air exchange, and irrigation area [102–117]. Initially, CO_2 in irrigation water boosts nutrient availability in soil reactions, but prolonged exposure may lead to nutrient leaching and deficiencies, with effects varying based on plant, soil, and pH. Mycorrhiza in the soil also affects phosphorus nutrition [118–122]. Root-based CO_2 absorption for photosynthesis is generally minor, contributing less than 5 % and often less than 1 % of the total CO_2. Enoch & Olesen further observed that most CO_2 for photosynthesis came from the air, around 95–99 % [27]. Moreover, CO_2 potentially acts as a plant hormone, influencing root growth, tuberization, and hormonal regulation by modulating hormone levels, root development, and seed germination via interactions with ethylene, auxins, and cytokinins [102]. Lastly, pesticide and CO_2 interactions can affect soil nitrification and nitrogen availability. Under optimal CO_2 and recommended pesticide levels, nitrification remains unaffected. However, under CO_2 stress, pesticides inhibit NH_4-oxidation, and high pesticide concentrations reduce nitrogen production, making CO_2-enriched water less suitable for plant growth [118,123–125].

4.3. CO_2-enriched water for plant productivity

Carbonation affects soil conditions, enriches air with CO_2, and influences growth-promoting hormones and enzymes [28]. Storlie & Heckerman [28] emphasized the need for specific conditions to optimize plant growth with carbonated water. They examined optimal conditions for plant growth with carbonated irrigation water, highlighting the role of elevated pH for nutrient uptake. Drip irrigation and polyethylene mulch can boost CO_2 levels, especially useful in arid regions. However, the studies show inconsistent results, with some crops benefiting, especially when used with polyethylene mulch, while others show no significant gains. Thus, further research is essential for a comprehensive understanding of carbonated water's effects on plant productivity.

Khan et al. [29] enhanced Amaranth green (Amaranthus viridis) growth using CO_2-enriched micro-nano bubble (MNB) technology, with promising results for vegetable cultivation in regions such as China, Southeast Asia, and India. Three groups were studied over eight weeks: G1 (MNB + CO_2 water), G2 (MNB + air water), and G3 (simple water,

Table 4
Main findings of application of carbonated water in the biofuels field.

Category		Key Findings	Reference
Biofuel Production	Biomass conversion	High-pressure carbonated water process for breaking down materials like corn stover and switchgrass, yielding less sugar initially but requiring fewer enzymes for further breakdown compared to sulfuric acid treatment.	[88]
Calcium Removal	Enhancing sugar extraction	Carbonated water effectively removes calcium from rice straw treated with $Ca(OH)_2$, improving sugar extraction and recovery as CaO.	[89]
Algal Growth	CO_2 utilization	High-rate algal ponds with carbonation columns (CC) show high CO_2 transfer efficiency, improving algal productivity for biofuel production.	[90]

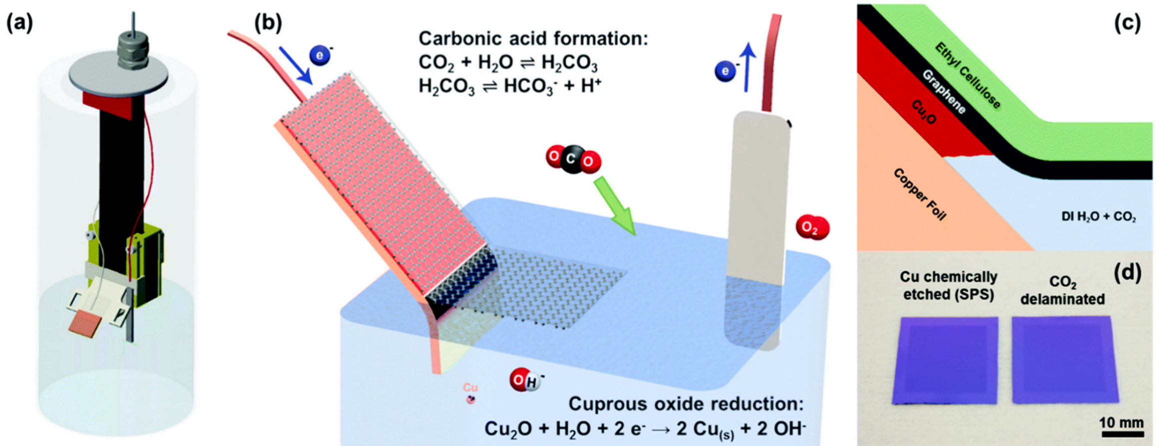

Fig. 6. (a) A self-pressurized vessel containing the necessary vertical setup was depicted. This setup facilitates the gradual immersion and delamination process in (b), where an ethyl cellulose-coated graphene layer on copper foil was submerged into the carbonic acid solution. This bias allowed for (c) the under-etching of the Cu_2O interlayer that exists between the graphene and the copper foil. Notably, (d) this setup enabled the transfer of inch-scale graphene without the need for chemical etchants and without the requirement for subsequent rinsing in deionized water. Adapted with permission from Wang et al. Copyright 2017. Royal Society of Chemistry.

controlled group). The study concluded that G1 had a more promising effect on nutrient content and growth levels than G2, including height, leaf size, root development, and various plant chemical parameters. Amino acids, α-amylase enzyme activity, vitamin C, soluble sugars, nitrogen, protein, and chlorophyll levels all showed positive effects. However, potential risks, such as excessive soil CO_2, can harm plants and soil health, as observed by He et al. [126]. This highlights the need for caution and sustainable practices when exploring using CO_2-enriched water in agriculture. We summarized the main findings of carbonated water in the agricultural section in Table 5.

5. Other uses of carbonated water

In this section, we explored other applications of carbonated water, focusing on its effectiveness in cleaning, its potential as a paint solvent, its positive role in extinguishers, and its contribution to culinary innovation.

Table 5
The application of carbonated water in the agricultural section.

Category		Key Findings	Reference
Agricultural Use	Plant growth enhancement	CO_2-enriched irrigation generally improves plant growth and yield, with 2–9 % greater plant growth compared to normal water.	[27]
	Soil conditions	CO_2-enriched water alters soil conditions, enriches air with CO_2, and influences growth-promoting hormones and enzymes; results show variable effects on different crops.	[28]
	CO_2 as a plant hormone	CO_2 could act as a plant hormone affecting root growth, tuberization, and hormonal regulation.	[102–117]
	CO_2-pesticide interaction	Interaction between CO_2 and pesticides can affect soil nitrification and nitrogen availability.	[118, 123–125]
	Micro-Nano bubble technology	CO_2-enriched micro-nano bubble water enhances Amaranth growth, affecting various chemical parameters and nutrient uptake.	[29]

5.1. Cleaning

Moreno et al.'s research [93] focused on addressing fouling issues in reverse electrodialysis (RED) stacks, a critical component in generating renewable energy from salinity gradients. Fouling, which leads to decreased power output and increased energy consumption, was a significant concern. The study explored using CO_2-saturated water as a cleaning method to tackle fouling issues in these RED stacks. During the experimental process, CO_2-saturated water was periodically injected into the RED stacks which simulated the real-world fouling conditions. The injection of this carbonated solution triggered a nucleation effect that led to the formation of tiny bubbles that effectively disrupted and removed fouling deposits, as can be seen in Fig. 7A. Simultaneously, the solution lowered the pH level of the feed water, further enhancing the cleaning effect. The findings indicate that using CO_2-saturated water allowed the RED stacks to maintain an average net power density of 0.18 W/m^2 under challenging fouling conditions, even at low temperatures. In contrast, using air sparging resulted in a significantly lower net power density of 0.04 W/m^2. The electrochemical impedance spectroscopy measurements reveal that air sparging increased stack resistance due to stagnant bubbles left inside the system after each cleaning cycle. The study shows the different impacts of various injection media on stack ohmic resistance and highlights operational and maintenance measures to optimize stack performance. For instance, injecting water/CO_2 (saturated) temporarily increases the stack ohmic resistance, but this increase is transient as CO_2 bubbles do not get trapped within the stack. In contrast, air bubbles in stacks with air sparging tend to remain and cause a permanent increase in ohmic resistance and, therefore, a reduction in the efficiency of the stack, as described in Fig. 7B.

In another research regarding carbonated water for cleaning, Abubakar et al. [127] investigated the cleaning efficiency of carbonated water compared to distilled water, emphasizing the significance of dust mitigation on surfaces, especially in the context of efficient energy devices. They proposed an economical self-cleaning approach inspired by nature, employing water droplets. The study focused on bubble formation and dust distribution within carbonated and distilled water droplets on hydrophobic surfaces. It was observed that carbonated water, containing dissolved compounds, generates more bubbles, leading to a 1.5–2.5 times greater concentration of dust particles than distilled

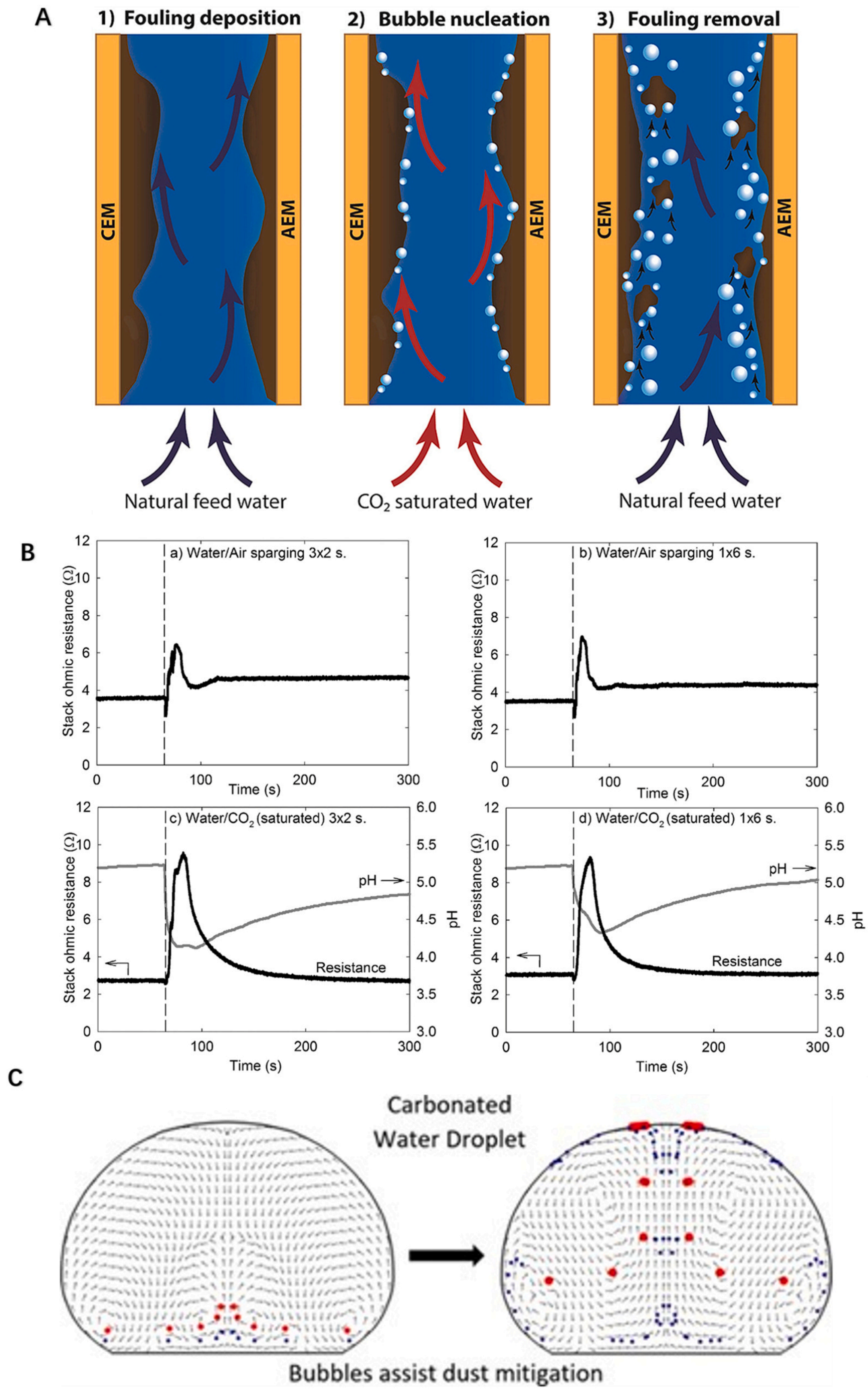

Fig. 7. (A) The RED stacks were periodically injected with CO_2-saturated water to simulate real-world fouling conditions. This injection of carbonated solution induced a bubble nucleation effect. These bubbles effectively disrupted and removed the fouling deposits, thereby improving the performance of the RED stacks. (B) The variation of stack ohmic resistance over time for different injection scenarios. In scenario a), water/air sparging injection was performed for a duration of 3×2 seconds, while in scenario b), the injection lasted for 1×6 s. Similarly, for scenarios c) and d), water/CO_2 (saturated) injection was applied, with durations of 3×2 s and 1×6 s, respectively. Both (A) and (B) were adapted from Moreno et al. Copyright 2017, Elsevier. (C) In a carbonated water droplet, dust can be mitigated by the CO_2 bubbles. Adapted with permission from Abubakar et al. Copyright 2022, American Chemical Society.

water. These bubbles played an important role in dust removal, enhancing the mobility of dust particles within the droplet and ultimately expediting the cleaning process.

Their further research [128] attributed the specific mechanisms underlying the enhanced cleaning performance of carbonated water. The effectiveness of carbonated water in removing dust from hydrophobic surfaces was attributed to the interaction between CO_2 bubbles and the flow structure within the droplets. This interaction accelerated the spread and infusion of carbonated water onto dust particles, resulting in superior dust removal compared to distilled water, as depicted in Fig. 7 C. Additionally, the presence of bubbles within the carbonated water droplets enhanced the overall efficiency of dust removal from the surface.

In a subsequent study by Abubakar et al. [129], the research examined CO_2 gas bubbles' behavior within carbonated water droplets, including their effects on spreading characteristics and rebounding ability. The study confirmed predictions related to droplet size and spreading speed through experimental data obtained via high-speed recording. It was found that CO_2 gas bubbles within the droplets undergo compression due to the total impact pressure of the droplets. This compression could lead to a slight reduction in bubble size. Under conditions of elevated pressure, smaller adjacent bubbles tend to merge, particularly toward the conclusion of the droplet's spreading and retraction phases. This increased pressure leads to a greater vertical height of the droplet, albeit with a slightly reduced contact diameter on the surface. The energy expended in compressing the CO_2 gas within the bubbles impacts the droplet's ability to rebound after the retraction phase.

In their study, Yilbas et al. [130] investigated the use of rolling liquid droplets for removing environmental dust from an inclined hydrophobic surface. They compared the movement of distilled and carbonated water droplets of varying volumes and the surface's inclination angle. The results highlighted a significant difference: carbonated water droplets moved notably faster on the dusty surface than distilled water. This enhanced motion was attributed to the formation of bubbles on the carbonated water droplets' surface, which reduced friction and enhanced speed. Additionally, the study explored the composition of environmental dust, revealing diverse components that could dissolve in water. Some components acted as sites for bubble formation within carbonated water droplets, further accelerating the dust's removal. The interaction between these bubbles and dust particles at the liquid-solid interface can greatly expedite dust removal. For smaller droplets (20 mL) and a low surface inclination angle ($d = 1^{\circ}$), both distilled and carbonated water droplets' rolling motion was observed to stop prematurely on the hydrophobic surface.

5.2. Solvent for paint

Ho et al. [131] discussed the issue of Volatile Organic Compound (VOC) emissions from solvent-based coatings and the desire to replace them with water-based coatings. However, traditional water-based coatings (latex) have limitations in hardness, durability, gloss, and cold-weather application due to the need for polymer particles to coalesce, which often leads to imperfections. The article proposed a solution using CO_2-responsive copolymers that can create a water-borne coating where the polymer fully dissolves before application and becomes water-resistant after application. These polymers dissolve in carbonated water but are insoluble in neutral water. The application of a carbonated polymer solution results in a clear, continuous, water-resistant coating without the need for particle coalescence, offering a VOC-free solution with improved coating quality.

5.3. Fire extinguishers

Recent developments in fire suppression technology have explored many innovative methods [132–135]. Kropotova et al. [132] assessed fire extinguishing agents based on CO_2 and water, specifically for forest fuel combustion. Their research highlighted a trade-off where cycling spraying resulted in a slight increase in CO and CO_2 emissions but used significantly less water, thus reducing the overall environmental impacts. The study found that the composition of the liquid played an essential role in determining gas concentrations and overall efficiency, which varied notably. Lv et al. [133] took a different approach by enhancing the effectiveness of water mist for gasoline fire suppression by adding KBr, Tween-80, and dissolved CO_2. These additives proved instrumental in reducing flame height and enhancing the overall efficiency of the water mist. They discovered that there was an extensive improvement over pure water mist. Gaidukova et al. [134] explored using CO_2 hydrate in the form of granules and tablets for suppressing fires in solid materials. Their findings suggest that CO_2 hydrate is more effective than traditional methods such as water spray, snow, and ice, especially in complex fire scenarios such as multi-tier crib fires. They identified optimal ratios of CO_2 hydrate for containment and found a significant reduction in emissions and enhanced efficiency across a range of combustible materials. Based on the above reviews and findings, it is validated that carbonated water is effective in acting as a good solution for fire suppression, especially in tackling liquid and gas fires or fires in which the dry chemical fire extinguisher cannot reach. Because it could form a protective layer over flames by CO_2 to cut off the oxygen supply and rapidly cool the burning area with water [132]. Importantly, unlike many chemical fire suppressants [135], carbonated water does not leave harmful residues and has a lower CO_2 emission profile, which makes it a more environmentally friendly option. However, the method still requires further research and validation to fully understand its performances, limitations, and potential environmental impacts in diverse fire suppression scenarios.

5.4. Culinary practice

In culinary practice, carbonated water is gaining popularity in batter recipes, such as those for fish or tempura, due to its ability to create a light and crispy texture. The effervescence of carbonated water adds aeration to the batter, making it lighter and fluffier, resulting in enhanced crispiness when frying. This effect also ensured a more uniform coating on various foods [136]. Moreover, carbonated water imparts a pleasant tangy flavor and prevents excessive oil absorption

Table 6
Applications of carbonated water in other fields.

Category		Key Findings	Reference
Cleaning	Dust removal	Carbonated water enhances dust removal efficiency on hydrophobic surfaces by increasing bubble formation.	[127–129]
		Carbonated water droplets move faster on dusty surfaces, reducing friction and enhancing speed in dust removal.	[130]
Paint Solvent	VOC-free coating	Carbonated water used with CO_2-responsive copolymers creates a clear, water-resistant coating without VOC emissions.	[131]
Fire Fighting	Fire extinguishers	Form a protective layer over flames by CO_2 to cut off the oxygen supply and rapidly cool the burning area with water; less environmental impact than other chemical fire suppressants.	[132–135]
Culinary Practice	Batter texture and flavor	Carbonated water adds aeration to the batter, resulting in a lighter, crispier texture and a pleasant tangy flavor while reducing oil absorption during frying.	[136]

during frying, enhancing both texture and flavor for an improved dining experience. Table 6 contains the main findings of this section.

6. Conclusion and outlook

In this paper, we reviewed the advantages of applying Carbonated Water Injection (CWI) for Enhanced Oil Recovery (EOR) and CO_2 sequestration [137]. Although CO_2 is commonly used in gaseous form in industry, its application as carbonated water is less prevalent due to cost and infrastructure requirements [138,139]. Future research could explore CWI's potential in diverse oil field scenarios and reservoir types, including carbonate rocks, shale oil fields, and offshore sites [140]. Additionally, exploring the effects of new surfactants and nanomaterials on CWI efficiency is crucial [16]. Understanding how different CO_2 concentrations impact fluid dynamics and oil-water interfacial tension (IFT) is essential for optimizing CWI, despite its advantages in reducing surfactant use [141].

Advancements in computational simulations offer deeper insights into multiphase flow dynamics in CO_2 and water mixing. The increasing use of artificial intelligence and machine learning could further optimize CWI [142]. The integration of the Internet of Things (IoT) and sensor technology allows for real-time data collection and analysis in oil fields, enabling machine learning algorithms to predict optimal water injection parameters and maximize output [143,144]. While CWI adjusts injection strategies in oil fields using CO_2 for recovery, environmental claims need validation. Challenges include ensuring the safe use of material, complying with green chemistry standards, ecosystem monitoring, etc.

Addressing practical issues such as wastewater treatment and managing minerals, organics, metals [145–147] to meet discharge standards involves technical challenges and costs [146,148]. Potential groundwater and soil contamination, along with ecological disruptions and increased greenhouse gas emissions, highlight the need for comprehensive environmental monitoring [149,150]. Additionally, the use of carbonated water should promote efficient resource cycling and waste reduction [151]. Techniques such as LCA [152,153] and TEA [154,155] could provide further insights into these aspects.

We also reviewed the diverse applications of carbonated water in sectors such as healthcare and medical, construction materials, biofuel production, green chemistry, and domestic uses. In addition, integrating carbonated water utilization into agriculture shows an advantage for offsetting carbon emissions and promoting sustainable farming practices. However, further research and cost reductions are essential to ensure their economic viability and sustainability across various applications. Therefore, this review also aims to inspire innovation in carbonated water production and distribution, encouraging the adoption of sustainable practices in industry, agriculture, and domestic sectors.

CRediT authorship contribution statement

Stefano Cucurachi: Conceptualization, Writing – review & editing. **Yasmina Dimitrova:** Writing – original draft. **Justin Z. Lian:** Writing – original draft. **Indraneel Sen:** Conceptualization, Writing – review & editing. **Matteo Fasano:** Writing – review & editing.

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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