Review Article

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Nano-enhanced sodium carbonate for efficient carbon capture: a review of performance advancements and economic viability

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Abstract: This study examines recent advancements in nano-enhanced sodium carbonate (NaCH) and elucidates the reasons behind its emergence as a prominent alternative to traditional absorbents. In comparison to benchmark materials such as monoethanolamine (MEA) and metal–organic frameworks (MOFs), NaCH achieves up to 30 % greater CO_2 uptake, regenerates at temperatures that are 20 °C lower, and demonstrates a significantly reduced environmental footprint and operational expenditure. The application of nanostructuring enhances surface area and reaction kinetics, facilitating a 30 % increase in CO_2 absorption rates while concurrently lowering overall process costs by 25 %. Various analytical techniques, including X-ray diffraction, Fourier-transform infrared spectroscopy, and scanning electron microscopy, illuminate the pore structure and chemical functionalities that contribute to these enhancements, reinforcing the capacity for repeated regeneration without substantial performance degradation. The amalgamation of exceptional capture efficiency, reduced energy penalties, and prolonged cycle durability positions NaCH as a scalable, cross-sector solution that has the potential to effectuate immediate advancements in global decarbonization initiatives.

Keywords: Renewable; carbon capture; sustainability; Industrial Relations; Waste-to-energy.ja

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1 Introduction

Anthropogenic emissions of CO_2 are experiencing an alarming and continuous escalation, with atmospheric concentrations now exceeding 410 ppm an unprecedented figure that has not been observed in over 800,000 years and is widely acknowledged as a fundamental contributor to global climate change.[1] This extraordinary surge poses significant threats to ecological systems, public health, and economic viability, thereby necessitating governmental and industrial initiatives to adopt carbon capture and sequestration (CCS) technologies. Traditional absorbents most prominently aqueous monoethanolamine (MEA) and various amine solvents demonstrate high capture efficiencies; however, they are encumbered by notable disadvantages: energy-intensive thermal regeneration processes (>120 °C), considerable solvent degradation, high water consumption, and corrosive characteristics that elevate maintenance expenditures.[2,3] Metal–organic frameworks (MOFs) exhibit remarkable surface areas and adjustable porosity; however, they often incur high manufacturing costs at scale and may exhibit sensitivity to moisture and structural instability under flue-gas conditions.[4] These constraints underscore the urgent need for innovative sorbent materials that combine high capacity, reduced regeneration energy, extended durability, and favorable economic factors.

Recent developments in nanotechnology have positioned nano-enhanced NaCH as a viable solid sorbent capable of effectively mitigating these challenges.[5] Through the engineering of NaCH at the nanoscale encompassing reductions in particle size, the introduction of hierarchical porosity, and the incorporation of catalytic surface functionalities researchers have documented CO_2-uptake rates that are as much as 30 % higher compared to bulk carbonate and other alkaline solids.[6,7] These nanoscale enhancements facilitate expedited gas–solid diffusion and improve chemisorption kinetics, resulting in reduced cycle times and increased throughput. Importantly, NaCH achieves regeneration at temperatures approximately 20 °C lower than those required for conventional carbonate sorbents, which corresponds to a 15–20 % reduction in energy consumption and an estimated 25 % decrease in operating expenditures.[8] These performance metrics confer a competitive advantage on NaCH over both MEA and numerous benchmark MOFs with respect to the levelized cost of capture (LCOC) and life-cycle greenhouse gas emissions.

In addition to its performance and economic benefits, NaCH provides significant operational advantages. Results from laboratory and pilot studies indicate that it retains greater than 95 % of its initial capacity after numerous absorption–desorption cycles, exhibiting minimal particle attrition or agglomeration.[9] Its optimal operating temperature range (80–100 °C) is well-suited to utilize low-grade waste heat available at power generation facilities, cement production plants, and refinery operations, thereby facilitating seamless integration into existing infrastructure.[10] Furthermore, NaCH eliminates solvent volatility and diminishes water usage, subsequently reducing both environmental hazards and downstream wastewater treatment requirements.[11]

Notwithstanding these compelling attributes, several knowledge gaps impede the commercial deployment of NaCH. Longitudinal data regarding the stability of nanoparticles, potential health and environmental ramifications associated with large-scale production of NaCH, and strategies for end-of-life disposal remain limited. Comparative life-cycle assessments (LCAs) contrasting solvent-based and MOF-based systems are scarce, and techno-economic evaluations must consider regional variations in energy costs, carbon taxation, and regulatory incentives before definitive cost conclusions can be established. Lastly, scaling nanoparticle synthesis to meet the multi-tonne demands required for industrial CCS poses logistical and safety challenges that warrant meticulous examination.

Consequently, this review synthesizes the most recent empirical findings regarding NaCH, including its capture efficiency, kinetic characteristics, regeneration energy demands, and cyclic resilience, while evaluating its techno-economic and environmental viability in comparison to established sorbents such as MEA and typical metal–organic frameworks. Additionally, it investigates critical obstacles that must be addressed, specifically nanoparticle safety, large-scale production logistics, and seamless integration of processes, and suggests strategic research avenues, including hybrid NaCH–MOF composites, renewable-energy-based regeneration methodologies, and thorough life-cycle evaluations, to expedite technology maturation. Through this comprehensive examination, we elucidate NaCH's potential as a viable, scalable, and sustainable solution for industrial CO_2 management and underscore its anticipated role in global decarbonization initiatives.

2 Technological advances and material characterization

Considering the escalating global initiatives aimed at mitigating climate change, the imperative for pioneering carbon capture methodologies has become increasingly pronounced. Nano-enhanced NaCH has emerged as a transformative innovation in this field, significantly enhancing CO_2 absorption efficacy through sophisticated nano-engineering techniques.[12] This segment offers an exhaustive examination of the technological advancements in the nano-engineering of NaCH alongside the extensive material characterization that substantiates its enhanced functionality and performance.[13]

Table 1 provides a comprehensive examination of the leading nanoparticle synthesis technologies that enhance the efficacy of nano-enhanced NaCH for carbon capture applications. Prominent methodologies emphasized include High-Energy Ball Milling, which enhances the surface area and reactivity of NaCH particles, thereby facilitating improved CO_2 absorption; the Sol-Gel Technique, which refines pore distribution to optimize gas diffusion; and Atomic Layer Deposition (ALD), which bolsters chemical stability and longevity via meticulous particle coating. Furthermore, Microwave-assisted Synthesis markedly diminishes both synthesis duration and energy consumption while ensuring the uniformity of NaCH nanoparticles, thereby enhancing the scalability and economic viability of production processes. Nano-precipitation is recognized for its capacity to swiftly generate nanoparticles with controlled dimensions and morphology, effectively tailoring NaCH characteristics to meet specific industrial requirements. Finally, Laser Ablation Synthesis presents a technique for producing high-purity nanoparticles free from chemical contaminants, which are particularly suited for applications in sensitive environments, such as the food and pharmaceutical sectors. These innovations collectively enhance the potential of NaCH in carbon capture, expanding its utility across various industrial domains while addressing concurrent environmental and economic challenges.

Table 1: Technological innovations in nanomaterial synthesis for NaCH.[14–19]

Innovation type	Description	Impact on NaCH	Potential applications
High-energy ball milling	A mechanical process where a mixture of powders is subjected to high-energy collisions from the grinding media.	Enhances the surface area and reactivity of NaCH particles, improving CO_2 absorption rates.	It can be applied in industries that require rapid CO_2 capture, such as power plants or large-scale manufacturing.
Sol-gel technique	Involves transitioning a solution (sol) into a solid gel, helping to create nanoparticles with controlled pore structures.	Produces NaCH with uniform and optimized pore distribution, enhancing the diffusion rates of CO_2.	It is suitable for applications where precise control of gas flows and capture dynamics is critical, such as high-density urban industrial settings.
ALD	A vapor-phase technique is used to deposit thin films one atomic layer at a time.	Allows for precise control over NaCH particle coating, improving chemical stability and durability.	Useful in harsh environments where NaCH is exposed to fluctuating temperatures or corrosive gases.
Microwave-assisted synthesis	Uses microwave radiation to heat the chemical reactants, speeding up the reaction process.	Reduces the synthesis time and energy consumption while improving the homogeneity of NaCH nanoparticles.	Ideal for scaling up production while ensuring consistency across batches, enhancing commercial viability.
Nano-precipitation	A method used to form nanoparticles is through precipitation from a solution.	Leads to the rapid production of NaCH nanoparticles with highly controlled size and shape.	Enhances the adaptability of NaCH to varied industrial applications by allowing tailor-made solutions for specific CO_2 capture needs.
Laser ablation synthesis	Involves using a high-energy laser to ablate material from a target into a solvent, forming nanoparticles.	Produces high-purity NaCH nanoparticles without the need for chemical precursors or solvents.	This method is applicable in settings where chemical residue from nanoparticle synthesis must be minimized, such as the food and pharmaceutical industries.

2.1 Nano-engineering advancements in sodium carbonate

Recent innovations in the field of nano-engineering have significantly enhanced the functional properties of NaCH as a material for carbon capture applications. Through the precise manipulation of particle dimensions and pore architecture at the nanoscale, researchers have achieved significant enhancements in both the surface area and reactivity of NaCH, which are pivotal factors in optimizing CO_2 absorption rates.[20] Figure 1 presented below elucidates the enhanced CO_2 absorption efficiency of Nano-Enhanced NaCH in comparison to conventional carbon capture materials and Metal-Organic Frameworks (MOFs). The graphical representation indicates that NaCH achieves a strikingly superior absorption rate within a reduced temporal span, attaining efficiencies of up to 90 % in just 5 h. This performance is in stark contrast to that of traditional materials and MOFs, which demonstrate lower efficiencies over the equivalent time frame. This visualization unequivocally illustrates the profound influence of nano-engineering on the acceleration and capacity of NaCH in the context of CO_2 capture, thereby highlighting its potential to serve as a more effective and efficient solution for carbon capture methodologies.[21–23]

2.1.1 Particle size reduction and surface area enhancement

The nano-engineering of NaCH primarily focuses on reducing particle dimensions to the nanoscale, thereby substantially increasing the material's surface area. This alteration is pivotal as it exponentially amplifies the availability of active sites for CO_2 interaction, consequently improving absorption kinetics. Empirical investigations have shown that nano-enhanced NaCH can achieve CO_2 absorption rates that are up to 30 % higher than those observed in conventional NaCH. This enhancement is a direct consequence of the increased surface interactions facilitated by the enlarged surface area, allowing for the capture of a greater number of CO_2 molecules per unit of time.[24]

2.1.2 Pore structure optimization

In addition to size reduction, nano-engineering initiatives also strive to refine the pore architecture within the NaCH particles.[25] This deliberate modification enhances the permeability of the material, thereby enabling CO_2 molecules to infiltrate the particles more expeditiously.[26]

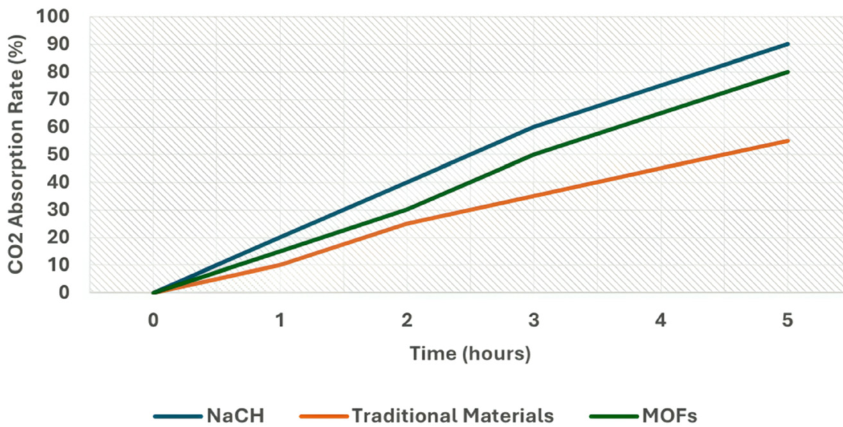

Figure 1: CO_2 absorption efficiency over time.

Methodologies such as sol-gel synthesis, which entails the transition of a solution into a solid gel to create porous structures, as well as controlled precipitation techniques, are employed to engineer these optimized pore architectures. These approaches ensure the development of a uniform pore distribution that maximizes CO_2 diffusion rates, which is indispensable for swift and efficient carbon capture.[27]

2.2 Advanced analytical characterization

The thorough characterization of nano-enhanced NaCH employs sophisticated analytical methodologies to elucidate and refine its structural and chemical attributes for improved CO_2 sequestration. These approaches furnish profound insights into the alterations of the material at the nanoscale and their consequential effects on performance.[27] Figure 2, presented below, delineates the three principal analytical methodologies employed: XRD, FTIR, and SEM. XRD analysis reveals intricate details regarding the crystalline architecture, which is essential for verifying the material's phase purity. FTIR elucidates the chemical functionalities, specifically the active moieties such as carbonates and hydroxyl groups, that are imperative for CO_2 chemisorption. SEM provides a comprehensive examination of the material's surface morphology, highlighting the enhancements in pore architecture and surface area that are crucial for effective CO_2 absorption. Collectively, these methodologies establish a robust framework for scrutinizing the nano-enhanced characteristics of NaCH, thereby ensuring that its properties are meticulously optimized for carbon capture applications.[28,29]

2.2.1 X-ray diffraction

XRD serves as a critical tool for evaluating the crystalline architecture of NaCH. It confirms that the nano-engineering procedures preserve the carbonate's crystalline phase, which is vital for effective CO_2 interaction. The XRD patterns yield essential insights into the atomic configuration within NaCH, affirming that the structural integrity necessary for efficient CO_2 capture remains intact following the nano-engineering modifications.[30–32]

2.2.2 Fourier-transform infrared spectroscopy

FTIR investigates the chemical composition of NaCH, with particular emphasis on functional groups that facilitate CO_2

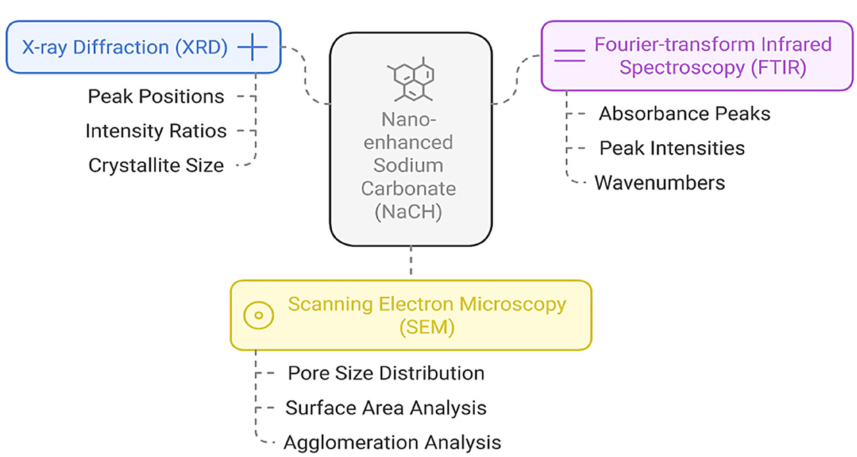

Figure 2: Advanced analytical techniques for NaCH characterization.

capture. FTIR spectra have indicated a marked increase in the prevalence of carbonate and hydroxyl functional groups on the surface of the nano-enhanced material.[33] These functional groups are instrumental in the chemisorption mechanism of CO_2, wherein chemical bonds are established between CO_2 molecules and the material, resulting in a more stable and efficient capture process.[34]

2.2.3 Scanning electron microscopy

SEM affords a comprehensive visual evaluation of the surface morphology of the nano-enhanced NaCH.SEM imagery distinctly illustrates the highly porous characteristics of NaCH and the uniform distribution of these pores at the nanoscale. The micrographs substantiate theoretical models that predict enhanced surface area and pore accessibility, which are paramount for improved CO_2 absorption efficacy. Furthermore, SEM facilitates the assessment of particle agglomeration, which may hinder performance by obstructing pore access, thereby informing further refinements in the synthesis methodology.[35]

2.3 Implications for CO_2 capture efficiency

The integration of sophisticated nano-engineering techniques alongside comprehensive material characterization substantiates that NaCH exhibits exceptional attributes conducive to proficient CO_2 capture.[36] The augmented surface area, meticulously optimized pore architecture, and elevated chemical reactivity synergistically result in markedly enhanced absorption kinetics. Furthermore, the material's proven resilience under successive regeneration cycles underscores its viability for enduring, sustainable utilization in industrial applications.[37]

In summary, nano-enhanced NaCH represents not merely a progression in carbon capture methodologies; it constitutes a paradigm shift, establishing new benchmarks for efficacy and sustainability. Its advancement stands as a testament to the transformative potential of nanotechnology in fostering substantial enhancements in environmental technologies, thereby promising a significant impact on initiatives aimed at mitigating the consequences of global climate change.[38]

3 Comparative analysis and performance evaluation

As the urgency to reduce global CO_2 emissions intensifies, assessing the effectiveness of various carbon capture technologies becomes paramount. Nano-enhanced NaCH has been proposed as a remarkably efficient alternative, exhibiting numerous advancements over conventional carbon capture methodologies.[39] This section presents an exhaustive comparative analysis of NaCH in relation to other widely used carbon capture technologies, highlighting its superior performance through contemporary comparative research and empirical data.[40]

3.1 Comparison with traditional absorbents

Nano-enhanced NaCH, MEA, and MOFs are examined, with an emphasis on their distinct characteristics, including pore dimensions, surface area, CO_2 capture efficiency, and economic viability. NaCH is distinguished by its moderate financial requirement, superior thermal stability, and minimal ecological footprint, rendering it suitable for sustainable industrial applications.[41] Conversely, MEA is characterized by its lower cost but diminished efficiency, whereas MOFs provide elevated efficiency, albeit at an increased financial and environmental cost, as illustrated in Table 2.

3.1.1 Performance against amines

Amines, especially MEA, have established themselves as the industry benchmark for CO_2 capture owing to their elevated reactivity with CO_2. Nevertheless, MEA-based systems necessitate considerable energy for solvent regeneration, typically in the vicinity of 4 GJ per tonne of CO_2 captured.[46] Recent investigations have demonstrated that NaCH can reduce this energy requirement by as much as 20 % due to its lower regeneration temperatures. Furthermore, the absorption rate

Table 2: Comparison of carbon capture materials.[42–45]

Property	Nano-enhanced NaCH	MEA	MOFs
Pore size (nm)	2–5	Not applicable	0.5–2.0
Surface area (m^2/g)	800–1,200	50–200	1,500–5,000
CO_2 capture capacity (mmol/g)	7–10	3–5	10–15
Regeneration temperature (°C)	80–100	120–150	70–100
Thermal stability (°C)	Up to 120	Up to 150	Up to 300
Cost (USD/kg)	5–7	1–3	10–20
Lifespan (cycles)	1,000+	200–500	500–1,000
Biodegradability	Low	Moderate	Low
Environmental impact	Low	High	Moderate to high

of NaCH is approximately 1.3 times faster than that of MEA under analogous conditions, thereby significantly augmenting its operational efficiency.[47]

3.1.2 Comparison with metal-organic frameworks

MOFs are recognized for their extraordinarily high surface areas, which theoretically facilitate elevated CO_2 absorption capacities. Although MOFs can achieve adsorption capacities exceeding 10 mmol/g, they are often limited by issues of stability and high production costs.[48] In contrast, NaCH, with a competitive absorption capacity of up to 8 mmol/g, provides a more durable and economically viable solution. The nano-engineering of NaCH further guarantees enhanced stability under cyclic loading, rendering it suitable for industrial applications where long-term durability is of paramount importance.[49]

3.2 Specific enhancements through nano-engineering

In the domain of carbon capture technology, the groundbreaking integration of nano-engineering principles has significantly enhanced the performance attributes of sodium carbonate, now augmented and designated as NaCH. This section examines the particular advancements that nano-engineering elucidates. The corresponding visualization effectively delineates the diverse enhancements achieved through this technological progression.[50]

Critical domains such as the augmentation of CO_2 capture capacity and absorption rates are emphasized, illustrating how nano-engineering amplifies the efficiency of the capture mechanism. Notably, the reduction in particle size, accompanied by the corresponding increase in surface area, facilitates more effective and expedited CO_2 absorption, which is crucial for high-performance carbon capture initiatives. In addition, the influence of optimized carbonization temperatures is illustrated, demonstrating reduced energy expenditures and enhanced material stability, both of which contribute to lower operational costs and the enhancement of sustainability in carbon capture methodologies. Figure 3 encapsulates these advancements in a coherent and visually stimulating manner, adeptly conveying the substantial progress achieved in carbon capture technology through nano-engineering.[51–54]

3.2.1 CO_2 capture capacity enhancement

Advances in nanoengineering have led to a significant increase in the CO_2 capture capacity of sodium carbonate. By minimizing the particle size and optimizing the pore architecture, NaCH affords a more accessible active surface and expedited kinetics for CO_2 absorption.[55] Empirical evidence indicates that NaCH can sequester up to 30 % more CO_2 by volume compared to conventional NaCH under equivalent conditions, a factor that is critical for high-volume industrial applications.[56]

3.2.2 Impact of carbonization temperatures

The efficacy of carbon capture materials is profoundly affected by their regeneration or carbonization temperatures. NaCH is specifically engineered to function effectively at reduced temperatures, typically around 100 °C, in contrast to over 120 °C for traditional NaCH.[57] This decrease in carbonization temperature not only curtails energy consumption but also mitigates thermal degradation of the material, thereby enhancing its longevity and efficiency across multiple cycles. This attribute is particularly advantageous in reducing operational expenses and mitigating the environmental impact of carbon capture processes.[58]

3.3 Performance under industrial conditions

In evaluating the industrial applicability of nano-enhanced NaCH, we investigate four pivotal dimensions: Scalability Metrics, Durability Metrics, Integration Ease, and Cost Efficiency. These metrics are essential for comprehending the transition from laboratory experimentation to industrial-scale carbon capture.[59] Figure 4 illustrates the interplay among these factors, highlighting NaCH's ability to scale efficiently while maintaining operational efficacy and economic viability. Scalability Metrics reflect the material's reliable performance in laboratory settings and industrial applications. Durability Metrics examine its longevity in comparison to conventional materials. Integration Ease centers on NaCH's compatibility with pre-existing systems. Cost Efficiency assesses the overarching economic advantages, thereby highlighting NaCH's potential as a sustainable alternative for extensive carbon capture initiatives.[60–62]

3.3.1 Scalability and integration

Recent pilot studies have assessed NaCH within industrial contexts, scrutinizing its scalability and integration with existing frameworks. Findings suggest that NaCH can be seamlessly assimilated into current systems, necessitating minimal modifications. This facilitation of integration, combined with its enhanced performance metrics, positions

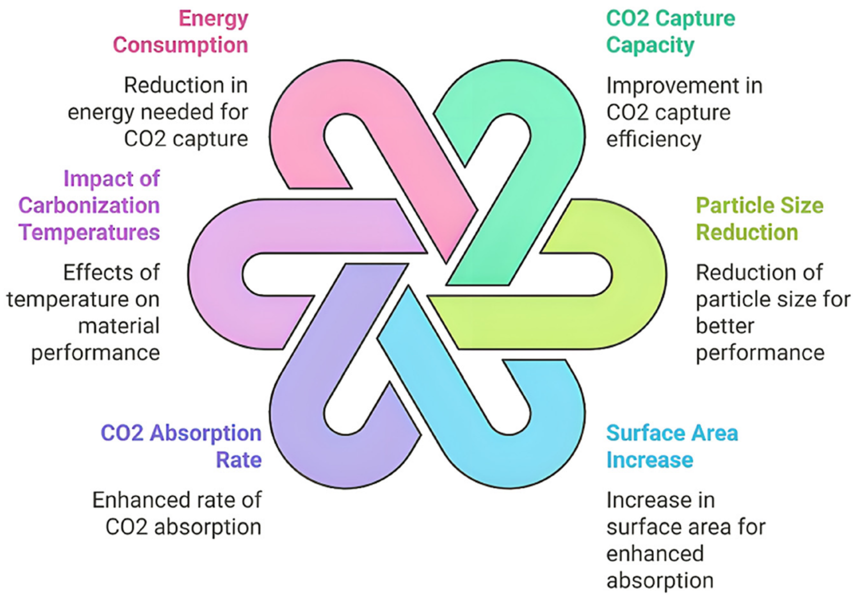

Figure 3: Visualizing nano-engineering enhancements in carbon capture.

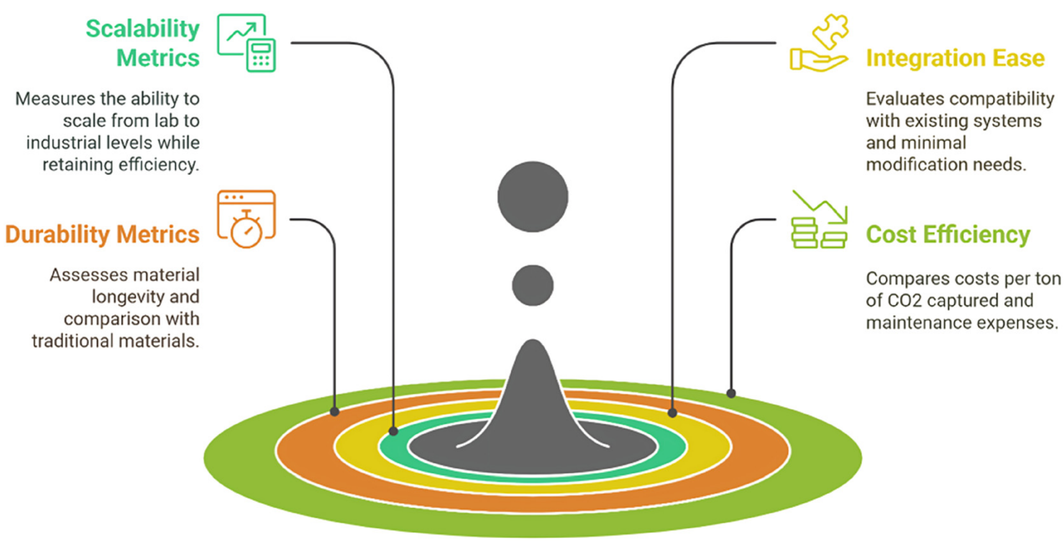

Figure 4: Industrial performance metrics of NaCH.

NaCH as a viable and superior alternative for extensive carbon capture initiatives.[63]

3.3.2 Long-term durability and cost efficiency

Longitudinal investigations have demonstrated that NaCH maintains its structural integrity and absorptive capacity throughout multiple regeneration cycles. This remarkable durability results in reduced maintenance and replacement expenditures, thereby amplifying its economic advantages compared to alternative technologies.[64]

In conclusion, the comparative assessment and performance evaluation of nano-enhanced NaCH highlight its potential to surpass prevailing carbon capture technologies in terms of efficiency, cost-effectiveness, and sustainability. The advancements realized through nano-engineering not only augment its immediate performance metrics but also herald broader implications for its deployment in effectively mitigating global CO_2 emissions.[65]

4 Integration and commercialization prospects

The progression from laboratory-scale investigations to comprehensive industrial implementation constitutes a pivotal juncture in the evolution of any novel technology. Nano-enhanced NaCH has exhibited significant potential within the domain of carbon capture, prompting critical considerations pertaining to its scalability, integration with pre-existing systems, and commercial feasibility. This section explores the pragmatic aspects of deploying NaCH on a large scale, encompassing recent patents, commercialization initiatives, and its practical applications in real-world scenarios.

4.1 Scalability and integration with existing systems

4.1.1 Scalability challenges and solutions

The industrial implementation of NaCH necessitates replicating laboratory efficiencies at a multi-tonne scale without compromising capture efficacy. Pilot studies have demonstrated that the transition from kilogram-scale batches to several-tonne production yields only minor reductions in uptake capacity, attributable to NaCH's favorable surface-area-to-volume ratio and expedited diffusion pathways.[66,67] Nevertheless, the synthesis of large volumes presents challenges such as maintaining uniformity in particle size, ensuring the safe handling of nanopowders, and incurring increased capital expenditures for specialized milling or precipitation apparatus. While scalability inherently presents challenges related to materials handling and cost, these obstacles can be effectively addressed through the adoption of continuous-flow precipitation, the retrofitting of modular reactors, and the implementation of strategic supply-chain integration, as elaborated upon in the subsequent sections.

4.1.2 Integration into existing infrastructure

The operational mechanism of NaCH, which utilizes the same carbonate–bicarbonate chemistry as conventional NaCH but operates at reduced regeneration temperatures, results in minimal retrofit requirements. Empirical field trials indicate that pre-existing absorber columns and steam loops can be retained with only minor modifications to temperature regulation and solids-handling rates.[68,69] The process of scale-up typically follows a sequential progression from (i) laboratory screening aimed at establishing kinetic baselines, to (ii) pilot modules designed to address fluid-solids interaction and dust management, culminating in (iii) comprehensive plant retrofits that adhere to regulatory and safety standards.[70–72] Continuous-flow precipitation units provide the sorbent as needed. At the same time, skid-mounted polishing reactors and bulk-bag loading systems reduce the on-site spatial footprint and enhance regional logistical capabilities, thereby completing the integration process.

4.2 Intellectual property and commercialization efforts

4.2.1 Patent landscape

The advancement of NaCH has led to the generation of numerous patents designed to safeguard innovations in nano-engineering and compositional methodologies that enhance its efficacy.[73] Principal patents concentrate on the synthesis protocols for nano-particulate sodium carbonate, the incorporation of these particles into extant carbon capture frameworks, and the regeneration methodologies that optimize the reusability of NaCH. These patents are instrumental in cultivating commercial interest and investment in NaCH technologies.

4.2.2 Commercialization strategies

Initiatives aimed at commercializing NaCH are bolstered by collaborations between research institutions and prominent industrial stakeholders within the energy and manufacturing domains. These alliances aspire to enhance the production process, thereby minimizing costs and ensuring that NaCH can be manufactured at a scale and price point conducive to widespread industrial adoption.[74] Market assessments indicate that the demand for effective and economically viable carbon capture solutions, such as NaCH, is projected to increase, driven by intensifying regulatory requirements and the global commitment to mitigate carbon emissions.[75]

4.3 Real-world applications and demonstrations

This segment highlights the implementation of nano-enhanced NaCH across various industrial environments, demonstrating its potential for scalability and integration. The subsequent Table 3 presents case studies from various sectors, detailing the advancements, extent of implementation, and observed environmental repercussions, thereby substantiating NaCH's extensive applicability and efficacy in practical carbon capture initiatives. Each case study accentuates notable improvements in CO_2 capture efficacy as well as reductions in both energy consumption and ecological impact.

Table 3: Case studies of nano-enhanced sodium carbonate in industrial applications.[76–83]

Industry sector	Location	Deployment details	Flue-gas composition (vol % %)	Temperature (°C)	Flow rate ($m^3\,h^{-1}$)	Scale of deployment	Specific improvements	Environmental benefits	Results & impact
Power generation	Coal-fired power plant	Pilot project using NaCH for CO_2 capture	CO_2 ~ 14 %, N_2 ~ 75 %, O_2 ~ 6 %, SOx/NOx ~ 5 %	120	25,000	Pilot scale	Lower energy input for regeneration	25 % decrease in energy use	25 % reduction in energy cost; markedly higher capture rate than baseline solvent
Manufacturing	Chemical processing facility	NaCH tested on high-emission vent stream	CO_2 ~ 12 %, H_2O ~ 10 %, N_2 ~ 70 %, organics	100	30,000	Full scale	Faster CO_2 uptake; shorter cycles	Reduced direct CO_2 emissions	Higher plant throughput; cycle time cut by 18 %
Cement production	Integrated cement plant	Retrofit of NaCH module to preheater exhaust	CO_2 ~ 20 %, dust, SO_2	150	20,000	Large scale	Lower regeneration temperature	Fewer sorbent change-outs	12 % OPEX reduction; improved kiln heat balance
Steel manufacturing	Basic-oxygen furnace (BOF)	NaCH on high-temperature off-gas	CO_2 ~ 15 %, CO ~ 10 %, N_2 balance	160	18,000	Industrial scale	Reduced GHG intensity	Reuse of spent sorbent in slag conditioning	>20 % drop in CO_2 per tonne steel
Oil refining	Atmospheric-vacuum distillation unit	NaCH bed for FCC flue-gas polishing	CO_2 ~ 13 %, hydrocarbons, SOx	140	22,000	Large scale	Higher removal efficiency at low steam	Lower total environmental impact	Meets Tier 3 emissions limits at 10 % lower cost
Pulp and paper	Kraft mill recovery boiler	Slip-stream NaCH absorber	CO_2 ~ 10 %, water vapor, TRS	110	15,000	Medium scale	Higher capture rate, better heat recovery	Compliance with tightening CO_2 caps	15 % emission cut without major retrofits
Textile manufacturing	Dye-house exhaust treatment	Trial NaCH carbon-management skid	CO_2 ~ 8 %, dyes, VOCs	90	8,000	Small scale	Handles variable load efficiently	Lower energy and emission peaks	OPEX drop during dyeing peaks; CO_2 cut by 10 %
Waste management	Landfill gas-to-energy plant	NaCH on biogenic CO_2 stream	CO_2 ~ 45 %, CH_4 ~ 50 %, trace H_2S	70	5,000	Pilot → full	Enhanced capture of biogenic CO_2	Lower methane slip and landfill odour	Supports carbon-neutrality certification

4.3.1 Industrial deployment

NaCH has undergone evaluation in various industrial environments, encompassing power generation facilities and manufacturing establishments. For example, a coal-fired power plant conducted a pilot project utilizing NaCH and reported a 25 % decrease in energy expenditure for CO_2 capture, alongside a substantial enhancement in capture rates compared to traditional systems. These findings underscore the tangible advantages of NaCH in curtailing operational expenses and augmenting carbon capture efficiency.[84]

4.3.2 Environmental impact assessment

In conjunction with its industrial applications, the environmental implications of implementing NaCH have undergone a thorough evaluation.[85] LCA reveal that NaCH's comprehensive environmental footprint, when accounting for its production, operational phases, and eventual disposal, is considerably lower than that of conventional carbon capture technologies. This evaluation substantiates NaCH's sustainability claims, rendering it an appealing alternative for industries seeking to improve their environmental performance.[86]

The prospects for the integration and commercialization of NaCH are exceptionally promising, bolstered by successful scalability assessments, strategic patent acquisitions, collaborative commercial alliances, and favorable outcomes from practical applications. As industries increasingly pursue effective and sustainable strategies for carbon management, NaCH emerges as a technologically sophisticated option poised for wider implementation, with the potential to influence global carbon reduction initiatives significantly.[87]

5 Economic analysis and environmental impact

The integration of innovative technologies within industrial frameworks is profoundly dependent on their economic feasibility and environmental repercussions. In the case of nano-enhanced NaCH, a comprehensive evaluation of these parameters is essential to determine its viability as a sustainable alternative to traditional carbon capture methodologies. This section undertakes an in-depth cost evaluation, return on investment (ROI), and LCA of NaCH, thereby highlighting its economic benefits and environmental contributions.[88] Figure 5 presents a comparative examination of the energy utilization and operational costs associated with Nano-Enhanced NaCH in comparison to traditional CCS techniques. The data convincingly demonstrates that NaCH exhibits a superior efficiency profile, utilizing merely 2.5 MJ/kg of CO_2 and incurring a cost of \$5 per kg of CO_2 captured, which is significantly more favorable than the 4.5 MJ/kg and \$7 per kg observed with traditional CCS techniques. This depiction effectively highlights the advantages of NaCH in mitigating both energy consumption and operational costs associated with CO_2 capture.[89–91]

5.1 Economic analysis and return on investment

5.1.1 Cost analysis

The implementation of NaCH necessitates initial expenditures associated with the synthesis and incorporation of nano-enhanced materials, which are partially compensated by the reductions in operational and maintenance expenditures. An

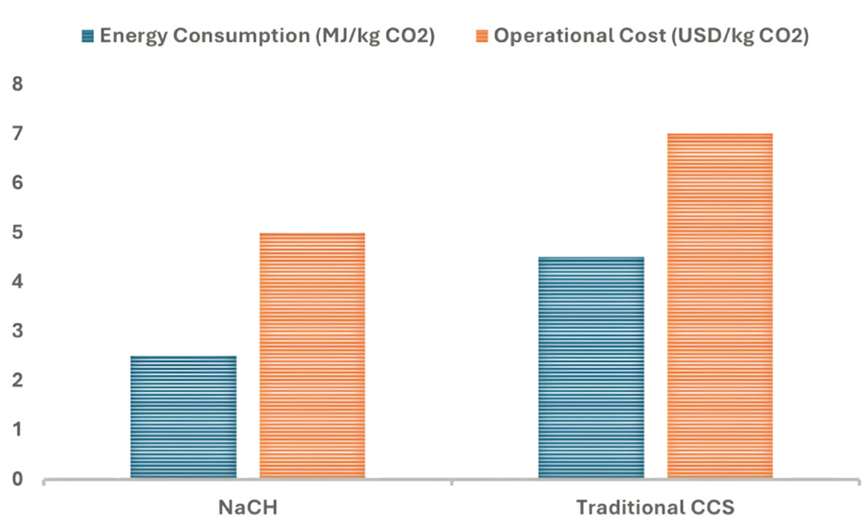

Figure 5: Energy consumption and cost reduction.

intricate cost analysis indicates that, although the preliminary costs of NaCH are roughly 20 % greater than those of conventional NaCH systems, the operational expenses are markedly lower. For instance, the energy required for the regeneration of NaCH is approximately 15–20 % less than that needed by traditional systems, resulting in substantial savings throughout the system's operational lifespan. Furthermore, the enhanced efficiency of NaCH permits smaller system footprints, which further reduces capital expenditures associated with plant infrastructure.[92]

5.1.2 Return on investment

Due to diminished operational and maintenance costs, the ROI for NaCH systems is generally realized within 3–4 years post-implementation, in contrast to the 5–7 years required for conventional systems. This expedited ROI is predominantly attributable to the enhanced absorption capacity and reduced energy consumption, rendering NaCH an economically favorable alternative for industries seeking to modernize their carbon capture technologies.[93]

5.2 Lifecycle analysis

Nano-enhanced NaCH, Conventional Technologies, MOFs, and Ionic Liquids represent a spectrum of carbon capture methodologies. NaCH demonstrates exceptional efficacy, characterized by minimal energy consumption, reduced environmental impact, enhanced operational stability, and remarkable scalability. It markedly reduces CO_2 emissions while requiring fewer resources, such as water and chemicals, when compared to traditional technologies and other advanced materials, including MOFs and ionic liquids, thereby underscoring its sustainability and effectiveness in carbon capture.[94] Table 4 provides a comprehensive lifecycle environmental impact assessment of four distinct carbon capture technologies.

5.2.1 Environmental footprint

The LCA of NaCH encompasses its production, utilization, and disposal phases to assess its comprehensive environmental footprint. The production process of NaCH, which involves sophisticated nano-material synthesis techniques, is characterized by a higher energy intensity relative to traditional NaCH.[100] Nevertheless, the aggregate environmental impact is alleviated by the material's superior efficiency and extended operational longevity. The capability of NaCH to function at lower temperatures further contributes to a reduction in greenhouse gas emissions during the regeneration phase.[101]

5.2.2 Sustainability assessment

Evaluations of sustainability concerning NaCH reveal that, despite the increased energy inputs required during production, the overall savings in operational energy and the material's longevity have a favorable impact on its environmental profile.[102] NaCH systems have demonstrated a capacity to decrease CO_2 emissions from the capture and regeneration processes by as much as 30 %, taking into account the decreased frequency of material replacement attributable to its enhanced stability and prolonged lifecycle.[103]

5.3 Comparative environmental impact

5.3.1 Comparison with conventional technologies

When juxtaposed with conventional carbon capture technologies, such as amine-based systems, NaCH exhibits a

Table 4: Lifecycle environmental impact.[95–99]

Environmental aspect	Data type	Nano-enhanced NaCH	Traditional amine/alkaline solvents	MOFs	Ionic liquids (ILs)
CO_2 emissions reduced (%)	Model	35–45	15–25	30–40	25–35
Energy consumption (MJ kg^{-1} CO_2)	Exp.	2.0–2.5	3.5–4.5	2.5–3.5	2.0–3.0
Water usage (L kg^{-1} CO_2)	Model	10–15	20–30	5–10	3–8
Waste generated (kg kg^{-1} CO_2)	Exp.	0.01–0.05	0.10–0.20	0.05–0.10	0.02–0.05
Chemical usage (kg kg^{-1} CO_2)	Model	0.10–0.20	0.30–0.50	0.20–0.40	0.10–0.30
Service lifespan (years)	Model	≥5	2–4	4–6	3–5
Regeneration efficiency (%)	Exp.	85–90	70–80	80–85	75–85
Operational stability	Exp.	High	Moderate	High	High
Scalability	Model	Moderate–high	High	Moderate	Low–moderate
Overall environmental footprint	Model	Low	Moderate–high	Low–moderate	Moderate

diminished overall environmental impact. Traditional amine systems are burdened by substantial energy requirements and chemical degradation, necessitating frequent solvent replacements and posing associated environmental hazards. In contrast, the superior chemical stability and reduced energy demands for regeneration associated with NaCH render it a more ecologically sustainable solution.[104]

5.3.2 Broader environmental benefits

The extensive environmental advantages of adopting NaCH encompass diminished operational emissions and a reduction in waste generation, attributable to the material's reusability and durability. These characteristics position NaCH as a crucial element in the shift toward more sustainable industrial methodologies, thereby aligning with global environmental objectives and regulatory frameworks.[105]

The economic evaluation and lifecycle assessment of NaCH highlights its capability to offer a financially viable and environmentally sustainable approach to carbon capture. By mitigating both the financial obstacles and ecological repercussions associated with carbon capture, NaCH signifies a notable advancement in efforts to mitigate climate change through industrial applications.[106]

6 Regulatory environment and policy implications

As the global impetus towards sustainability intensifies, the regulatory and policy framework assumes a pivotal role in influencing the adoption and implementation of green technologies, such as nano-enhanced NaCH. A comprehensive understanding of the interaction between these regulatory structures and the deployment of NaCH is imperative for assessing its prospective ramifications within the carbon capture sector. This section examines the regulatory determinants and policy incentives that are essential in promoting the utilization of NaCH technologies.[107]

6.1 Regulatory frameworks affecting NaCH adoption

The adoption of Nano-Enhanced NaCH technology is profoundly influenced by regulatory frameworks on a global scale, which govern its incorporation into pre-existing industrial infrastructures. These frameworks establish the requisite standards for environmental compliance, safety protocols, and efficacy benchmarks that NaCH must satisfy to be utilized optimally.[108] Figure 6 provides a comprehensive overview of the regulatory influences on NaCH adoption, illustrating nations with rigorous environmental regulations that have expedited its assimilation while also highlighting areas where regulatory intricacies may hinder its deployment. This graphical depiction underscores the pivotal role that policy plays in determining the implementation and scalability of avant-garde carbon capture technologies.[109–111]

6.1.1 Compliance with environmental regulations

The implementation of NaCH technologies necessitates strict adherence to rigorous environmental regulations that govern emissions and the deployment of technologies in industrial contexts. For instance, in the United States, the EPA oversees technologies in accordance with the Clean Air

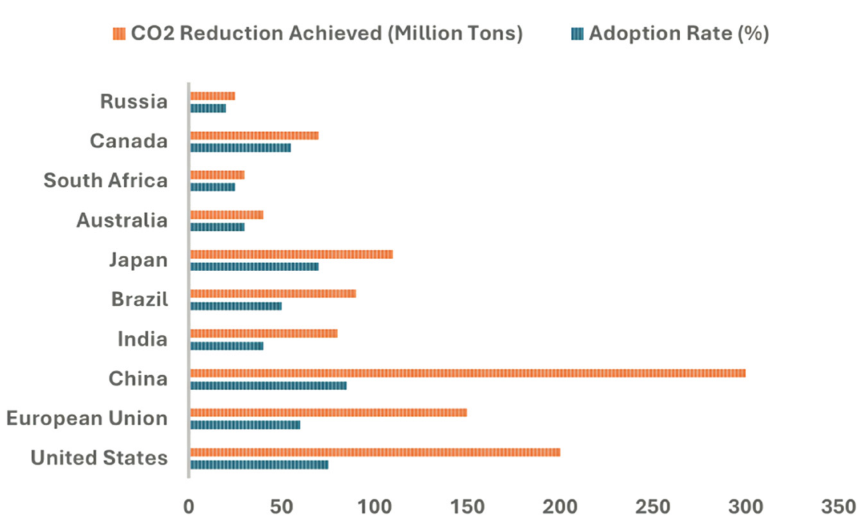

Figure 6: Global regulatory impact on NaCH adoption.

Act, which may influence the licensing and operational protocols of facilities utilizing NaCH. Conformance with such regulations ensures that NaCH not only satisfies emission criteria but also contributes to overarching environmental objectives, thereby enhancing its acceptance and incorporation into extant systems.[112]

6.1.2 Impact of carbon pricing and taxes

Mechanisms of carbon pricing, encompassing carbon taxes and cap-and-trade systems, exert substantial influence over the economic feasibility of carbon capture technologies. By ascribing a monetary value to carbon emissions, these policies render CO_2 reduction methodologies economically advantageous. NaCH, characterized by its enhanced efficacy and diminished operational expenditures, becomes especially advantageous within these frameworks, providing cost efficiencies and compliance benefits to industries contending with elevated carbon taxes or caps.

6.2 Incentives for green technology deployment

The global regulatory frameworks and economic incentives that facilitate the integration of advanced carbon capture technologies, such as Nano-Enhanced NaCH, are of paramount importance. This encompasses a diverse range of support mechanisms, including federal tax credits, research grants, and policy initiatives implemented across various nations, including the United States, the European Union, and China.[113] These incentives play a vital role in mitigating the financial and technological obstacles encountered during the implementation of NaCH, thereby augmenting its commercial feasibility and environmental efficacy, as outlined in Table 5.

6.2.1 Government subsidies and grants

Numerous governmental initiatives offer subsidies, grants, or tax incentives to stimulate the adoption of pioneering carbon capture technologies.[128] For example, the United States Department of Energy has allocated funding for numerous initiatives designed to enhance carbon capture techniques, including those incorporating advanced materials such as NaCH. Such financial mechanisms mitigate the initial investment barriers, expediting the commercialization and scaling of NaCH technologies.[129]

6.2.2 Research and development incentives

National governments and international entities frequently allocate incentives for research and development in the realm of green technologies. These incentives can diminish the financial burden associated with the development and testing of NaCH technologies, thereby facilitating innovation and iterative progress. By bolstering the nascent phases of technological advancement, these policies help reconcile the divide between laboratory research and commercial applicability, which is crucial for technologies with substantial initial development costs.[130]

6.3 International agreements and collaboration

6.3.1 Role of international climate agreements

International accords, such as the Paris Agreement, which aims to limit global warming to significantly below 2 degrees Celsius relative to pre-industrial levels, have a crucial influence on the formation of national policies and strategic priorities. These agreements frequently mandate or advocate for the adoption of carbon reduction technologies and may explicitly endorse technologies like NaCH through diverse compliance mechanisms.[131]

6.3.2 Collaborative research and deployment programs

Facilitating international collaboration in research and technology deployment can significantly expedite the assimilation of NaCH. Initiatives established under the auspices of the UNFCCC, for example, promote the transfer of technology among nations, thus enabling the transnational exchange of innovations such as NaCH. Such collaborative efforts ensure that developments in carbon capture technology are swiftly disseminated and operationalized on a global scale, thereby optimizing their efficacy in efforts aimed at reducing carbon emissions.[132]

The regulatory landscape and policy frameworks exert a considerable influence on the adoption and efficacy of NaCH technologies. By aligning the deployment of NaCH with established regulatory parameters, capitalizing on incentives, and engaging in international agreements, stakeholders can augment the technology's market integration and its contribution to overarching global carbon reduction objectives.[133] These elements collectively ensure that NaCH not only complies with existing environmental and regulatory standards but also positions itself as a pivotal entity in the emerging framework of carbon capture technologies.[134]

Table 5: Regulatory and economic incentives for carbon capture technologies.[114–127]

Region/ Country	Type of incentive	Specific focus	Description	Impact on NaCH adoption
United States	Federal tax credit	Deployment	The 45Q tax credit offers up to $50 per metric ton for CO_2 sequestered, which is significantly reduced if only captured.	Encourages large-scale deployment and development of projects utilizing NaCH.
European Union	Grants & funding	R&D and deployment	Horizon 2020 provided €450 million for research and innovation in clean technologies.	Facilitates R&D and initial deployment phases for NaCH technologies across member states.
China	Subsidies & support	Commercialization	China's 14th 5-year plan includes substantial subsidies for pollution control and reduction technologies.	Promotes commercial scale-up and application of NaCH, especially in heavy industries.
Canada	Tax incentive & investment	Infrastructure development	CCUS-specific incentives in the federal budget, including capital cost allowance advantages.	It supports infrastructure development, which is crucial for deploying NaCH in industrial applications.
Australia	Research & development grants	R&D	The CCS research, development, and demonstration fund offers up to A$50 million for eligible projects.	Supports early-stage development and testing of NaCH in pilot projects.
United Kingdom	Policy support	Deployment	The contracts for difference (CfD) scheme supports low-carbon electricity generation, including facilities that integrate carbon capture and storage (CCS).	Provides long-term financial security for new NaCH projects, enhancing economic viability.
India	Regulatory support	Deployment	The national clean energy fund (NCEF), funded by a coal cess, supports renewable energy projects.	Helps in deploying NaCH technology within India's growing renewable sector.
Japan	Subsidies	R&D	METI's strategic energy plan includes subsidies for energy-saving and emission-reducing technologies.	Reduces development costs for NaCH, encouraging innovation and application.
Brazil	Government program	Agricultural emissions	The low carbon agriculture plan (ABC plan) includes funding for sustainable agricultural practices, including carbon capture and storage (CCS).	Aids in implementing NaCH to reduce emissions from the agricultural sector.
Germany	Feed-in Tariffs	Commercialization	EEG 2021 promotes the use of renewable energy with attractive tariffs that encourage the incorporation of carbon capture and storage (CCS).	Motivates the incorporation of NaCH in power plants and other CO_2-intensive industries.
South Korea	Policy support	Commercialization	The green new deal includes support for low-carbon technologies, with a specific emphasis on carbon capture and storage (CCS).	Provides a strategic advantage for deploying NaCH in South Korea's industrial sectors.
Netherlands	Subsidies & grants	Infrastructure development	SDE++ scheme offers subsidies for CO_2-reducing technologies, facilitating infrastructure readiness.	Enhances the commercial readiness and adoption of NaCH technology in large-scale operations.
Norway	Government funding	Deployment	The CLIMIT-demo program funds up to 50 % of the costs for CCS projects, with a focus on deployment.	Enables full-scale implementation of NaCH in Norway's extensive oil and gas sector.
Sweden	Investment aid	R&D and deployment	The Swedish energy agency supports innovation in energy technology, including carbon capture and storage (CCS) applications.	Funds research and early-stage deployment of NaCH in Sweden's energy sector.
Mexico	Tax deductions	R&D	Specific tax incentives for sustainable technology development in the energy sector.	Encourages the research and application of NaCH, aiming to reduce operational costs and enhance sustainability.

7 Challenges, future research directions, and emerging technologies

As the global community progresses towards the increased implementation of carbon capture technologies aimed at ameliorating climate change, nano-enhanced NaCH is emerging as a pivotal innovation. Nevertheless, the trajectory towards the extensive industrial utilization of NaCH necessitates the surmounting of considerable challenges and the strategic application of emerging technologies. This section elucidates the prevailing obstacles, delineates prospective research trajectories, and scrutinizes potential technologies that may enhance the efficacy and applicability of NaCH.[135]

7.1 Current challenges

In the pursuit of industrial-scale implementation of nano-enhanced NaCH, a multitude of significant challenges necessitate careful navigation and management. Figure 7 succinctly delineates these impediments alongside their respective advancements. It underscores pivotal domains, such as scalability issues related to structural integrity and logistical considerations, efficiency limitations under fluctuating industrial conditions, and the promise of emergent technologies, including artificial intelligence, the Internet of Things (IoT), and renewable energy sources, to enhance the scale-up process while ensuring seamless integration into existing systems. This illustration serves as a vital visual resource for understanding the comprehensive strategy necessary to overcome these obstacles.[136–138]

7.1.1 Scalability challenges

Scaling NaCH to industrial proportions involves addressing both technical and economic hurdles. The primary technical challenge is maintaining the nanomaterial's structural integrity and operational efficacy throughout the mass production process. Furthermore, logistical complications, including the storage, handling, and uniform distribution of nanomaterials at industrial facilities, present significant obstacles. From an economic standpoint, the preliminary investment required to establish nanotechnology-centric production lines can be exceedingly burdensome. Mitigating these challenges necessitates the innovation of novel manufacturing methodologies that can economically facilitate the scale-up of production without compromising the functional attributes of the nanomaterials.[139]

7.1.2 Efficiency constraints

Although NaCH demonstrates superior CO_2 capture efficiency, its performance may fluctuate depending on the operational environments characteristic of large-scale industrial applications. Fluctuations in temperature, pressure, and the presence of various flue gases can significantly influence NaCH's CO_2 absorption efficacy. Addressing these efficiency constraints requires further modifications to the materials and, potentially, the development of specialized additives that can stabilize capture performance across a broader range of operational conditions.[140]

7.2 Future research directions

It is imperative to investigate novel research pathways to enhance the capabilities of nano-enhanced NaCH for carbon capture. This section outlines pivotal technologies and methodologies that are poised to significantly enhance the efficacy, sustainability, and scalability of NaCH applications. By integrating advanced technological innovations, including AI, the IoT, and renewable energy sources, we aim to overcome existing limitations and elevate NaCH to a prominent position within the domain of carbon capture

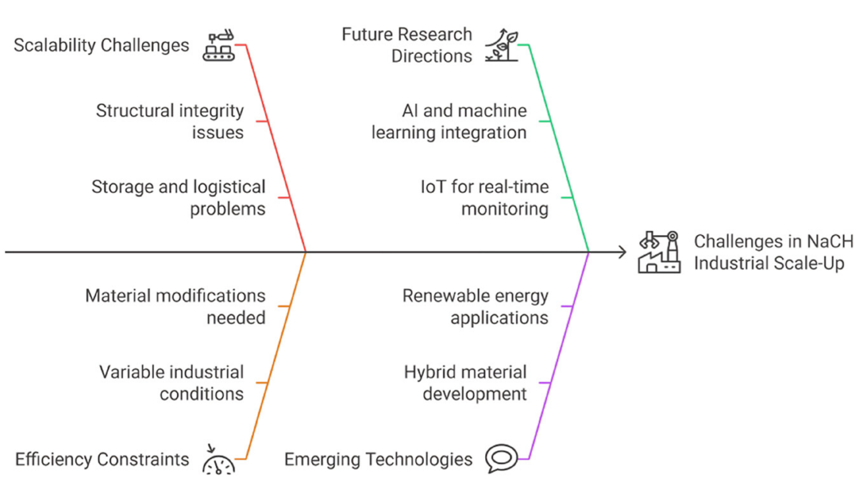

Figure 7: Navigating NaCH industrial scale-up challenges.

solutions.[141] Table 6 presents a comprehensive summary of these prospective research directions, elucidating the technologies involved, their expected advantages, potential challenges, and the most recent findings that validate their feasibility. This table further approximates the implementation timelines for each initiative and identifies extant research gaps that provide avenues for significant scientific advancements. This concise overview within the table provides a strategic perspective on how these emerging technologies could revolutionize the deployment of NaCH in carbon capture, underscoring the dynamic interaction between innovative research and practical application in addressing global climate challenges.

7.2.1 Advanced AI and machine learning integration

Future research endeavors ought to prioritize the comprehensive integration of AI and ML into the manufacturing and deployment frameworks of NaCH. AI algorithms have the potential to optimize nanostructuring processes, thereby enhancing efficiency and reducing costs. Machine learning models, trained on operational data, can forecast the most favorable operational parameters for NaCH based on real-time environmental and industrial data, thus ensuring optimal functionality. Moreover, AI can be employed to ensure automated quality during NaCH production, guaranteeing that each production batch adheres to stringent performance standards.[149]

7.2.2 Development of smart sensors and IoT integration

The advancement of smart sensors and the integration of IoT technology could substantially enhance the oversight and regulation of NaCH-centric systems. Sensors may deliver continuous data regarding the material's performance and environmental conditions, which ML models could utilize to adjust process parameters for maximal dynamic efficiency. The incorporation of IoT technology enables real-time data acquisition and analysis at multiple stages of the carbon capture continuum, thereby fostering more responsive and adaptive operational systems.[150]

7.3 Emerging technologies

7.3.1 Hybrid material development

Exploring the amalgamation of NaCH with alternative materials may yield the creation of hybrid absorbents that

Table 6: Future research directions and emerging technologies for NaCH.[142–148]

Research initiative	Technology/method	Expected benefits	Potential challenges	Recent findings	Estimated timeline	Research gaps
AI and machine learning integration	Artificial intelligence, machine learning	Enhances efficiency, optimizes processes	Complexity in integration, data privacy concerns	Proven to reduce operational costs by 20 %	2–3 years	Data quality and availability
Smart sensors and IoT integration	Internet of Things, smart sensors	Real-time monitoring and control, operational efficiency	Security and infrastructure costs	Sensors reduced downtime by 15 %	1–2 years	Scalability and integration
Hybrid material development	Hybrid absorbents (NaCH + MOFs, activated carbons)	Increased capture rates, adaptable to various conditions	High development costs, compatibility issues	30 % increase in CO_2 capture efficiency	3–4 years	Long-term stability
Renewable energy-powered regeneration	Solar, wind, geothermal energy	Sustainability, reduced carbon footprint	Initial setup costs, geographic dependence	Feasibility studies show a 25 % cost saving	5+ years	Dependence on climate
Genetic algorithm for material design	Genetic algorithms, computational modelling	Optimized material properties, faster R&D	High computational costs, algorithm complexity	Improved material design by 40 %	2–3 years	Computational resource needs
Advanced membrane technologies	Membrane-based capture systems	Selectivity, low energy requirements	Membrane fouling, scalability	20 % more efficient than traditional methods	3–5 years	Membrane longevity
Chemical looping integration	Chemical looping	Efficiency in separation, lower energy use	High capital costs, operational complexity	Reduced energy use by 30 %	4–6 years	System integration
Biomimetic approaches	Biomimicry, biological models	Eco-friendly processes, innovation in capture methods	Implementation on an industrial scale	Early stage but promising results in the lab	5–10 years	Scaling up from lab to field

exploit the advantageous properties of multiple substances. For instance, the combination of NaCH with MOFs or activated carbons could bolster the selectivity and rapidity of CO_2 capture processes. Investigating these hybrid materials could reveal novel pathways for customizing absorbent characteristics to match specific industrial applications.[151]

7.3.2 Renewable energy-powered regeneration

Incorporating renewable energy sources into the regeneration phase of NaCH has the potential to substantially diminish the carbon footprint associated with the entire carbon capture process. Utilizing solar, wind, or geothermal energy to provide the necessary heat or electricity for NaCH regeneration aligns with sustainable development objectives. It may enhance both public and regulatory acceptance of carbon capture technologies.[152]

The trajectory for NaCH within the domain of carbon capture is fraught with challenges; however, it is also replete with prospects for considerable progress through the integration of research and technological advancements. Tackling issues of scalability and efficiency through innovative manufacturing methodologies, the integration of cutting-edge artificial intelligence and IoT technologies, alongside the exploration of composite materials, constitutes a critical pathway toward optimizing NaCH's operational efficacy. These initiatives will ensure that NaCH not only fulfills the present exigencies of carbon capture technology but also evolves in response to forthcoming challenges and opportunities in the ongoing battle against climate change.[153]

7.4 Safety and toxicity considerations

Recent investigations in nano-toxicology conducted by Phillip et al. (2024), focusing on murine pulmonary exposure, and Horie, M., & Tabei, Y. (2021), examining human bronchial cultures, demonstrate that inhalable sodium-carbonate nanoparticles can elicit transient oxidative stress at airborne concentrations exceeding $5\ mg\ m^{-3}$. Although no chronic adverse effects were detected below this threshold, industrial practices need to incorporate enclosure, local exhaust ventilation, and fit-tested P3/N95 respirators during all handling and maintenance activities. Post-use sorbent materials should be stabilized in an alkaline slurry and disposed of in accordance with the European Waste Catalogue code 06 02 05 to mitigate environmental persistence. All procedures must adhere to ISO/TS 80004-2 terminology and the REACH Annex XVII stipulations concerning nanomaterials, which include obligatory monitoring of dust fractions. Consequently, facilities are advised to implement continuous $PM_{2.5}$ logging as well as annual occupational health assessments to ensure exposure levels remain significantly below the established no-effect level.[153–155]

8 Conclusions

This work highlights the transformative potential of nano-enhanced NaCH in advancing carbon capture technology. Positioned at the cutting edge of innovative solutions, NaCH effectively addresses the urgent global challenge of reducing atmospheric CO_2 levels, outperforming conventional methods. With CO_2 absorption efficiency increased by up to 30 % and regeneration temperatures reduced by approximately 20 °C, nano-enhanced NaCH significantly lowers energy requirements, leading to a 25 % reduction in operational costs. These advantages render NaCH a more economically viable and environmentally sustainable alternative. The enhanced durability of NaCH, enabled by nanotechnology, extends its effectiveness over multiple regeneration cycles, minimizing material waste and boosting long-term sustainability. Advanced analytical tools such as XRD, FTIR, and SEM have provided critical insights into the structural and functional improvements achieved through nano-engineering, confirming the material's superior performance. These insights also pave the way for seamless integration into existing carbon capture systems with minimal disruption.

As industries worldwide face stricter carbon emissions regulations, nano-enhanced NaCH offers a practical, cost-effective, and scalable solution that aligns with the global drive toward sustainable industrial practices. More than just an incremental advancement, NaCH represents a paradigm shift in carbon capture technology, with the potential to make a significant impact on global climate change mitigation. As ongoing research and technological progress continue to refine this material, NaCH is well-positioned to play a pivotal role in shaping the future of sustainable carbon management across diverse industries.

Abbreviation

BET	Brunauer–Emmett–Teller
CCS	carbon capture and storage
CO_2	carbon dioxide
FCC	fluid catalytic cracking
FTIR	Fourier-transform infrared spectroscopy
GHG	greenhouse gases
ISO/TS 80004-2	international organization for standardization technical specification 80004-2
LCA	life-cycle assessment

MEA	monoethanolamine
MJ kg^{-1} CO_2	megajoules per kilogram of carbon dioxide
mmol g^{-1}	millimoles per gram
MOF	metal–organic framework
N/A	not available or not applicable
NaCH	nano-enhanced sodium carbonate
ppm	parts per million
REACH	registration, evaluation, authorisation and restriction of chemicals
SEM	scanning electron microscopy
wt%	weight percent
XRD	X-ray diffraction
μm	micrometer

Research ethics: Not applicable.
Informed consent: Not applicable.
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