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Nanoparticle Applications in Carbon Capture: Emerging Opportunities in Climate Change Mitigation

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Abstract

General Background: The tourism sector increasingly relies on strategic alliances to address competitive challenges and share resources in dynamic markets. **Specific Background:** In this context, human resource management practices, particularly recruitment and training strategies, are central to building the competencies required for managing partnerships among tourism companies in Baghdad. **Knowledge Gap:** Despite the growing importance of alliances, many organizations emphasize legal and financial aspects while overlooking the role of qualified human capital in managing cooperative relationships. **Aims:** This study aims to analyze the relationship between recruitment and training strategies and the efficiency of strategic tourism alliances. **Results:** Using a descriptive-analytical approach and survey data from 93 respondents, the findings reveal a significant positive relationship between recruitment and training strategies and alliance efficiency, with a correlation coefficient of 0.800 and an explanatory power of 63%. Technical and behavioral training emerged as the most prominent dimension, while all dimensions showed statistically significant contributions. **Novelty:** The study integrates human resource management functions with strategic alliance performance in the tourism sector within the Baghdad context. **Implications:** The findings suggest that adopting competency-based recruitment and specialized training programs supports cooperation, reduces organizational conflicts, and contributes to achieving shared objectives in tourism alliances.

Highlights:
- Recruitment Practices Based on Competencies Support Alignment of Shared Goals
- Training Programs Strengthen Cooperation and Reduce Organizational Conflicts
- Technical and Behavioral Skills Show the Strongest Contribution to Alliance Performance

Keywords: Recruitment Strategies, Training Programs, Strategic Alliances, Tourism Companies, Human Resource Management.

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Introduction

Rapid growth in carbon dioxide emissions since the industrial revolution has been an important proposer for disruption of global warming and climate. Carbon capture and storage (CCS) technologies have attracted a lot of interest in their ability to counteract it by removing CO2 from the atmosphere [1]. The CCs traditionally capture CO2 produced from a large point-givash fuel power plant and industrial facilities, and either store it in geological structures or use it for favorable products. However, traditional carbon capture approaches have serious boundaries. In particular, amin (ie mono -daisted, etc.) is known for carrying out energy -intensive and expensive chemical absorption processes [2].

An important part of the production of the power plant (quoted to be about 20-30% of the power generated) can be used to reproduce AMIN solvents and compress CO2, resulting in "energy deed" which limits the future implementation on a large scale. In addition, traditional methods suffer from problems such as a decline in solvent, corrosion of equipment and efficiency with low catch over time [3, 4]. Zeolites or activated carbon (active carbons) provide an alternative using solid sorbents via physical adsorption, however these transfer materials also show very limited capacity at ambient conditions and are possibly demanding high regeneration temperatures for desorption. Recently, a shift in trend has been towards using nanotechnology in order to improve carbon capturing efficiency and overcome the challenges presented by traditional carbon capture techniques Nanostructured materials are able to provide a large surface area to enable high loading of active sites, with tunable surface chemistry and frequently show improved mass transfer, making nanomaterials ideal next- gen sorbents and catalysts for CO2 capture [5-7]. Nanomaterials such as carbon nanotubes (CNTs) and graphene sheets offer large surface areas and a porous structure, which can bind a large amount of gas molecules Similarly, ultra-porous nanomaterials such as metal–organic frameworks (MOFs) have reached CO2 storage capacities orders of magnitude higher than known conventional materials; one MOF (Mg-MOF-74) has been reported to adsorb ca 8 moll CO2 per gram under ambient conditions[8, 9]. Crucially, most of these interactions are mainly physisorption (binding through physical forces), meaning that the expulsion of the captured CO2 (sorbent regeneration) will not require nearly as much energy as breaking the strong chemical bonds formed in amine scrubbing[10, 11]. The role of nanotechnology in carbon capture is not only with solid adsorbents [12]. In addition, there have been developments in liquid absorbents and membrane separations. Nanofluids, which involve diffusing nanoparticles into liquid solvents, with the aim of enhancing the properties of bulk solvents, such as their CO2 uptake rates and their thermotransfer capabilities[13, 14]. Likewise, membranes created from graphene or MOF–polymer composites at the nanoscale are designed for high CO2 selectivity and permeability beyond the upper limits of commercial polymer membranes[15]. These advances point to a future in which carbon capture systems could be smaller, more energy-efficient and more versatile than they are now[16]. Importance of this review: There are many reviews of carbon capture, but this work is focused primarily on recent nanotechnology developments for the process (2018–2025) and is presented in Arabic-English to make this updated scientific knowledge available to a wider audience[17, 18]. This covers latest developments for example carbon-based nanomaterials-MOFs, nanofluids, and nano enhanced membranes and multiple applications with respect to their performance comparison in comparison with conventional methods[19]. The review aims to bridge knowledge gaps on the market feasibility of these nano-solutions for practical applications[20].

It provides researchers and decision-makers a deep insight of nano-enabled carbon capture and potential applications for global climate change mitigation efforts[21, 22].Overview of Comparisons for CO_2 Capture Technologies Based on published data and recent research, the table and chart below show how conventional and nanotechnology-based methods differ in their ability to capture CO2. Adsorption capacity, regeneration energy consumption, selectivity, and operational stability are important parameters[23-26]. Table 1 shows a comparative summary based on key performance parameters [47], also Figure 1.

Table 1 shows a comparative summary based on key performance parameters [47].

Technology	CO2 Capture Capacity (mmol/g)	Energy Requirement for Regeneration	Selectivity	Stability under Real Conditions
Amine-based Chemical Absorption	1.5	Very High (120–150°C)	Moderate	Moderate (Degradation/Corrosion)
Zeolites / Activated Carbon	2.5	High	Low	Low at Ambient
Carbon Nanotubes (CNTs)	4.5	Low	High	Moderate
Graphene Sheets	3.8	Low	Moderate	High
Metal–Organic Frameworks (MOFs)	8.0	Very Low	Very High	Moderate
Nanofluids	2.5	Low	High	Moderate
Nano-Membranes (Graphene/MOF-polymer)	3.5	Low	Very High	High

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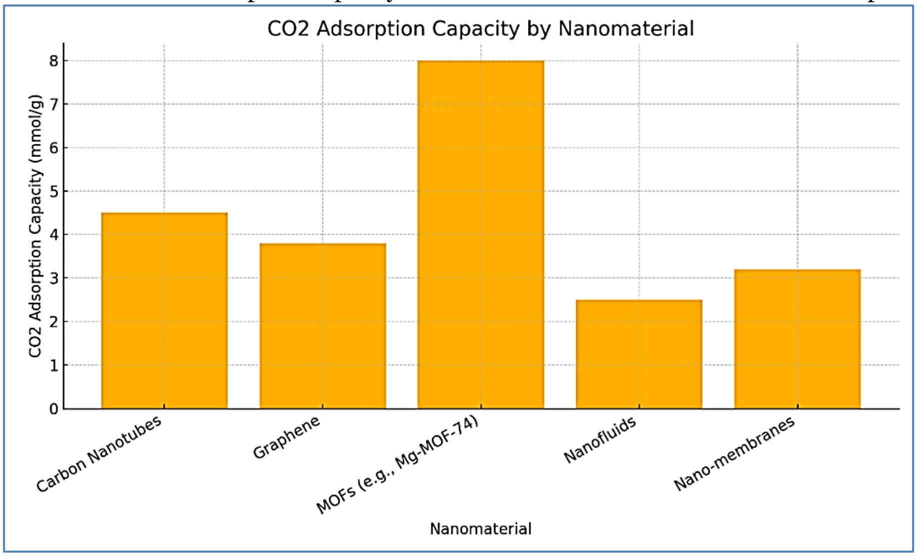
Figure 1 illustrates CO_2 adsorption capacity across different nanomaterials based on reported data.



Methodology

In order to review literature on nanomaterial-based carbon capture methods comprehensively and reliably, a systematic approach was taken to retrieve and appraise literature believed to be relevant. The primary steps are described below:Scope of review The reviewed scope was defined to be focused around CO_2 capture using nano-scale materials and technologies[27]. These include nano-adsorbents (nanotubes, Metal-Organo Frameworks (MOFs), zeolites with nano- structured enhancements), nano-enhanced absorbents (nanoparticle-infused solvents, colloquially known as nanofluids) and nanostructured membranes for CO_2 separation[28]. Studies describing only traditional approaches (i.e., a design of better amine solvents without any aspect of nanomaterials) or focusing on CO_2 use (CO_2 conversion into fuels/chemicals) were not considered unless they contained a separate section describing the capture of CO_2 using the promising aspect of nanotechnology [6, 29]. This focuses on the review of catches (the first phase of CCS), instead of the use of downstream.

Method: A systematic review was done using a scientific database to identify recent development [30]. The database used includes the Web of Science, Scope, Science and Google Scholars. For open wheat articles on related topics, Pubmed Central was also used. Search expressions included the words that were in the form of carbon capture nanotechnology, nanopacans CO_2 -absorbent and CO_2 catch MOF etc.

Relevant articles for reference lists (snowballing) were also scanned to identify multiple studies [31]. Literature searches to incorporate the latest development was mainly focused on publications from (to the beginning of 2025). We also included a

journalist reviewed journal articles (in favor of review and high-effect research articles), conference negotiations and relevant reports or book chapters, if they informed the process in a creative way. Studies were included that directly compare nanobased approaches to traditional methods or that report quantitative performance measurements (eg absorbency, energy consumption) for nano perspective systems. All sources Scientific reliability was intended to secure, stop some reports from Industry/Agency for Relevant Data on Traditional Technology Line Lines[32].

Methods: Literature snowballing was conducted to identify relevant papers, which were organized and qualitatively analyzed. We first classified identified results into groups according to nanotechnology type as follows: (1) carbonaceous nanomaterials for adsorption, (2) MOFs and other ultra-porous frameworks, (3) inorganic/metal oxide nanoparticles for CO_2 capture, (4) nanofluid absorbents, and (5) nano-membranes[33]. according to Table 2: showing classification of nanotechnology categories, example materials, and their primary mechanism. The comparative performance of representative studies by condition (e.g., CO_2 concentration, temperature, pressure, presence of competing gases, etc.) was then reviewed for each category. We then assessed the strengths (e.g., capacity, selectivity, energy efficiency) and weaknesses (e.g., stability, cost, complexity) of each approach. Some data were tabulated, where possible, e.g. a list of various materials and their CO_2 capacities, to enable comparison. Table 3: comparing CO_2 capture performance of different nanotechnology categories]. However, due to the narrative nature of this review, most comparisons are presented in-text with citations to the data sources.

Quality Control: Interpretations, as well as results from multiple sources, were cross-validated to ensure accuracy. When a certain claim (e.g., very high adsorption capacity) featured, we checked other works that either backed up this claim or conflicted it. We scrutinized the methods of the experiments (was the capacity measured in real-life or pristine lab conditions, for instance?) to contextualize the results. Discrepancies or debate in the literature are mentioned in the discussion section .References were organized using a reference management software (e.g. EndNote or Mendeley) to ensure all relevant sources were cited and no omissions occurred [34]. Based on the methodology set out above more than 100 relevant sources were reviewed and key information synthesized. The subsequent Results and Discussion sections comprise the aggregated findings, organized by the key strands of nano-enabled carbon capture pathways and then discuss their implications in terms of conventional pathways [35].

The methodical approach used to examine recent developments in CO_2 capture technologies based on nanomaterials is presented in this section. The scope excluded non-nano or post-capture utilization and was restricted to nano-enhanced capture techniques (adsorbents, absorbents, and membranes). Below is a summary of how different nanotech categories are classified and how their performances compare[25, 36, 37]. Figure 2: flowchart showing research steps used in the review process].

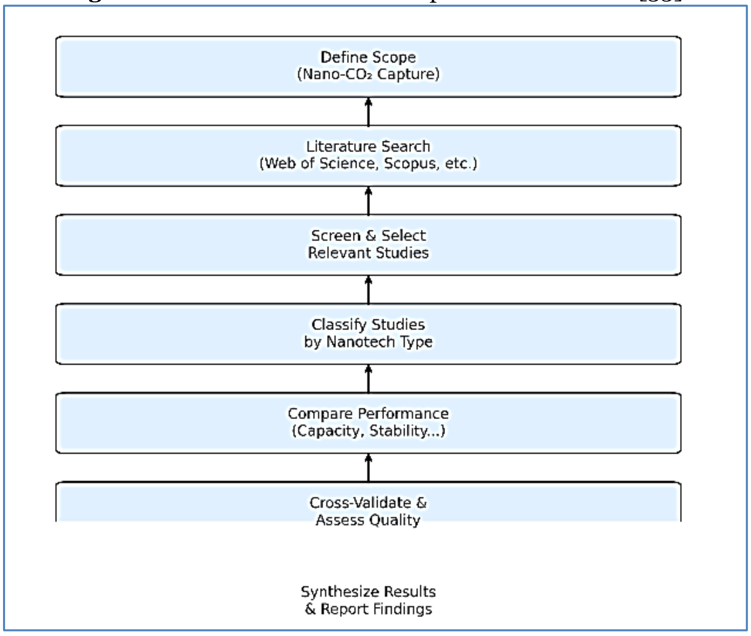
Table 2 Classification of Nanotechnology Categories[33]

Nanotech Category	Example Materials	Primary Mechanism
Carbonaceous Nanomaterials	Carbon Nanotubes, Graphene	Physisorption
Metal–Organic Frameworks (MOFs)	Mg-MOF-74, ZIF-8	Physisorption / Chemisorption
Metallic/Oxide Nanoparticles	MgO, CaO, Fe_3O_4	Chemisorption / Catalysis
Nanofluid Absorbents	Nano-Al_2O_3 in MEA	Enhanced Absorption
Nano-Membranes	Graphene Oxide, ZIF-MMM	Selective Permeation

Table 3 Comparing the CO_2 Capture Performance of Different Nanotechnology Categories [33]

Nanotech Category	CO_2 Capacity (mmol/g)	Energy Requirement	Stability	Cost
Carbon Nanomaterials	4.5	Low	Moderate	Moderate
MOFs	8.0	Very Low	Moderate	High
Metallic Nanoparticles	5.0	Moderate	High	Moderate
Nanofluids	2.5	Low	Low to Moderate	Low
Nano-Membranes	3.5	Low	High	Moderate

Figure 2 The Great Research Steps series flowchart.[33]



Results

We focused on applications of nanotechnology for carbon capture, and through our extensive literature review found substantial advancements in this area. The findings are categorized under three broad technical headings: (1) nano- structured solid adsorbents, (2) nano-enhanced liquid absorbents (nanofluids), and (3) nano-enabled membranes for gas separation. For each category, we summarize the performance of these new techniques compared to traditional methods based on representative studies from 2018-2025.[38].CO_2 Capture by Nano-Structured Solid Adsorbents.

1.1 Carbon-based nanomaterials: These include ingredients such as nanoscale active carbon, carbon nanotub (CNT) (single wall, multi-wall) and graphin and its derivatives (eg graphin oxide). Carbon -based nanomaterials contain exceptionally high specific surface regions and tuned porcity, which provides a great ability to absorb CO_2. These materials have been shown excellent CO_2 utility performance, which often performs better than traditional sorbet under similar conditions. For example, some diagrams from biomass-ritual nano-enabled carbon perform a hierarchical micropor and mesopor-oriented POR structure (ultralo compared to CO_2 under the partial pressure-AKA aka aka atmospheric CO_2 capture conditions) [39, 40]. Although pristine CNTs exhibit excellent intrinsic CO_2 adsorption capacity (around few mmol CO_2/g at 1 atm, similar to activated carbon) when CO_2 are physisorbed on the CNT surface through Farrelow mechanism, such adsorption is inefficient and has low capacitive effect; the CO_2

1.2 Ultraporous Nanomaterials – Metal–Organic Frameworks (MOFs) and analoguesMetal–organic frameworks (MOFs): are a prime example of ultraporous crystalline nanomaterials. They are composed of nodes of metal ions interconnected by organic linker molecules, creating open frameworks with nanoscale pores. POFs possess ultrahigh surface areas (typically > 5,000 m2/g) and adjustable chemistry in the same manner as MOFs. These features have led to significant interest in the use

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of MOFs for CO_2 capture. Recent findings show that many MOFs have high capacities for CO_2 adsorption. More specifically, Mg-MOF-74, a magnesium-based MOF, has demonstrated a very high CO_2 uptake of 8.0 mmol/g at 1 bar and room temperature, and is well above that of traditional zeolites or activated carbons under the same ambient conditions. This excellent performance is ascribed to open metal sites (OMSs) in its structure that strongly interact with CO_2 molecules (through Lewis acid-base interactions and quadrupole interactions), leading to a high CO_2 loading capacity of the material[42]. Furthermore, MOFs can be chemically modified after synthesis — such as by grafting on amine groups or other functional moieties onto the walls of the pores — to increase further CO_2 affinity and selectivity. Composite MOFs have already been reported, with nanoparticles or functional polymers introduced into the MOF pores achieving the high storage capacity of MOFs with additional

functionalities such as catalytic conversion of CO_2 or improved moisture stability[43].The MOF family is not alone: related classes of materials (e.g., covalent organic frameworks (COFs) and porous organic polymers) exist that offer similarly high surface areas and that have been investigated for CO_2 capture. For example, porous polymers have achieved moderate CO_2 recording with the advantage of increased stability compared to MOF. Such a rare cheap ingredients are Geolithic Imidazolate Frame (ZIF), a subcontinent of MOF showing mixed properties between MOF and Zeolits, and also promised (eg heat), as an example, emphasized a study that interactions in MOF -74 are mainly physically physically physical with a smaller input of heat. SOX/NOx species 464 that can damage some MOF (for example, 445 containing alkali metals 464 or soft ligaments), to cope with this challenge, workers work through the use of more stable MOF (ZR or Al-based groups. View polymer coatings). Another hurdle is the cost and complexity of MOF synthesis at scale, although advances are being made in greener and more scalable production processes[44]. To conclude, ultraporous nano-adsorbents such as MOFs offer extraordinary CO_2 capacities and tunable properties, rendering them some of the most powerful potential materials for future carbon capture systems, if stability and cost problems can be overcome.

1.3 Metallic Nanoparticles and Oxides: This class refers to nanoparticles of metals or metal oxides (or chemisorption solid carbonates), which is a chemical reaction used in CO_2 capture. As an example, the CO_2 capture can be performed by nanoparticles of MgO or CaO. The high surface area and short diffusion lengths of nanoscale particles greatly increase the rate of these carbonation reactions. Nanosizing MgO enhances its reactivity with CO_2 in comparison to bulk MgO, and decreases the temperature at which carbonating performed to a significant extent, as recently discussed in a review on MgO- based nanomaterials for CO_2 capture[45]. Likewise, CaO nanoparticle studies have been performed in cyclic carbonate looping processes in which enhanced reactivity may enable more CO_2 capture per cycle prior to deactivation from sintering.

In addition, metal nanoparticles can act as catalytic promoters in CO_2 capture. As an example, the loading of nanoscale copper or nickel to solid sorbents can enhance the adsorption process or the subsequent CO_2 conversion blurr into CCU – carbon capture and utilization. However, in pure capture aspect, a strategy has been to embed these reactive nanoparticles in some porous supports to prepare hybrid systems[46]. One such approach is to embed MgO nanoparticles into a porous carbon matrix: the carbon matrix acts as a high surface area scaffold with better access to gas, while the MgO actively chemisorbs CO_2. According to studies, these MGGO-I-carbon or MGO-I-silicatic composites have a better CO_2 recording and cyclical stability of MGOs, which may be asked for support that can be called to support the reactive phase that prevents particle sealing and aids to spread the reactive phase. Amin-functionized nanoparticles of amalgaming of of the use of merging amalgamating. It is a case of magnetic iron oxide nanoping coated with amin -rich polymer (eg polyethylinimin, Pei). These particles act as a solid Amin sorbant for CO_2 capture through carbamate formation, as is the case for liquid amine resolution that allows easy separation from mixture of a magnetic field application when applying a magnetic field.[47]. Another study was able to achieve high CO_2 capture efficiency from a gas stream using PEI-coated Fe_3O_4 nanoparticles, which were subsequently magnetically recovered and thermally regenerated for reuse, with little loss in capacity over multiple cycles.Conclusively, metal and metal oxide nanoparticles diversify carbon capture by providing chemisorptive processes, which act to immobilize CO_2 in more stable forms like carbonates, or by improving the existing performance of sorbents via catalysis. They proved particularly valuable for applications such as pre-combustion capture (where CO_2 is at greater pressure and temperature, more suitable for chemisorption) or capture-conversion integrated processes[48]. Key results in this area illustrate the benefit of pairing nano-scale reactants with supports or functional groups to maximize capacity and reversibility simultaneously nanofluids and Improved CO_2 Absorption. Apart from solid sorbents, a notable progress in utilizing liquid absorbents for CO_2 capture through nanotechnology has been carried out. Nanofluids — injecting nanoparticles into liquid solvents — is a promising technique to boost CO_2 absorption systems performance. The basic concept is that the nanoparticles will improve mass transfer and change fluid properties to increase CO_2 solubility into the liquid phase[49]. The outcome of many studies suggests that the incorporation of nanoparticles (metallic, metal oxides, carbon nanomaterials, etc.) to traditional amine solvents or other CO_2-reactive liquids was reported to enhance both the rate of instantaneous CO_2 absorption and often the cumulative amount absorbed within a certain time frame. There are several reasons:

Nanoparticles greatly increase the interfacial surface area and introduce turbulence at the gas–liquid interface that favors CO_2 diffusion into the liquid. They also enhance the thermal conductivity of the solvent, dissipating absorption heat (as CO_2 in amines is an exothermic process), thus circumventing local saturation and higher absorption driving force[48]. For instance, it was reported based on an experimental study that the addition of approximately 0.5 wt% of nano-Al_2O_3 in a MEA solution could increase the CO_2 absorption rate under flue gas conditions about 15% compared to MEA. A different work based on a bubble column absorber demonstrated that the addition of the silica nanoparticles to the water of the bubble column increased the surface renewal rate of the bubbling process (the interface refresh rate), resulting in the absorption of more CO_2 per given amount of time. These advances essentially mean reaching a target level of capture with a smaller absorber or capturing more with existing equipment[50]. An especially unique proposal regarding the subject of nanofluids is the formation of CO_2 bubbles called nano-bubbles or the CO_2 hydrate. Some nanocations worked to make small bubbles or even CO_2 hydrates under specific conditions such as nuclear agents for CO_2 gas, which are largely expanded by the GAS
-Facial Substance Area. Although it is still developed, it has the ability to achieve phase change in the frequency that CO_2 can be dissolved in liquid[51]. Nanofluides, for their share, also promise; However, on stability, they are mainly faced with challenges. Nanoparticles can go out or go out over time, especially under tough conditions such as industrial absorbents (high

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temperatures, continuous currents). For example, Agloma reduces the effective surface area, which can fight dishonesty equipment along with the benefits of nanofluid. To solve this problem, studies have discovered various stable methods: using surface active agents or disasters to maintain suspended particles, to retrieve each other, functionalization

of the surface of Nanokhanas (eg. A second problem is nanoparticle recovery — at some point, the solvents will have to be replaced or cleaned, and nobody wants to waste expensive nanoparticles along with the spent solvent. The cutters can also be removed by magnetically retrievable particles, as previously noted, or through filtration techniques. Indeed, magnetically susceptible nanofluids have been proposed where the particles can be recovered by magnets and re-introduced, minimizing loss[52]. Thus, nanofluids can be regarded as a complementary addition to the conventional absorption-based CO_2 capture systems. They can be implemented in retrofitting or upgrading existing solvent systems with only a jar of proper nanoparticle suspension added to the solvent without hidden modification of the hardware. So far, performance has improved with better kinetics and capacity but ensuring long-lasting stability and practical handling of these nanofluids is an active area of development. Even if these challenges are addressed, indeed,

nanofluid technology could be adapted to large-scale CCS where it would improve the efficiency of amine plants, carbonate loops, or novel solvent systems such as ionic liquids and amino-acid solutions[53].Nanostructured Membranes for Carbon Dioxide Separation, Another CO_2 capture approach is membrane separation, which exploits selective permeation of CO_2 through a membrane material in order to separate it from other gases (like N_2). Traditional membranes, primarily composed of polymers, struggle with the trade-off between permeability (flux) and selectivity (discrimination between gases). Nanotechnology has started to reshape this field through membranes breaking through traditional performance barriers. The advanced membrane fabrication technology was a breakthrough regarding the use of two-dimensional (2D) nanostructured materials such as graphene and graphene oxide (GO) and MXenes . Graphene-based membranes are atomically thin barriers with controllable pore structures, or interlayer channels that can be engineered to facilitate gas transport. A GO-based membrane yields a CO_2/N_2 selectivity over 30 under humidified surrounding, with CO_2 permeance of over 1000 GPU (gas permeation unit). These are impressive numbers; the high selectivity means that CO_2 can be efficiently separated from N_2, and the high permeance means that large volumes of gas can be processed per area of membrane. This performance is excellent because it is indeed possible to design the nano channels between GO layers to size-sieve gases (by partial reduction, interlayer cross-linkers, etc.): CO_2 (kinetic diameter ~3.3 Å) can diffuse through, while larger molecules are impeded[54]. Moreover, functional groups within GO membranes that preferentially interact with CO_2 (e.g., facilitated transport by amine groups) can further improve selectivity. Crucially, the researchers were able to produce the membranes on high-throughput support (high-throughput support). To achieve this goal, approaches such as layer-by-layer deposition or printing have been introduced to develop uniform GO membranes on ceramic or polymer supports measuring from a few square centimeters to square meters, which is a critical step in industrial scale production. An alternate approach is the design of mixed-matrix membranes (MMMs), which consist of incorporation of nanoparticles, or porous nano-fillers in a polymer matrix. By embedding nano-sized MOF crystals into a polymer, the best of both worlds may be achieved: polymers lend mechanical strength and processability , while the MOF contributes high CO_2 affinity and extra transport pathways. For example, MMMS with ZIF-8 (a MOF) in Pebax polymer exhibited a ~50% improvement in CO_2/N_2 selectivity compared to the polymer itself . Nano-fillers are more favorable to larger fillers as they provide even distribution and (thereby reducing defects that can lead to undesirable gas leakage) CMS (carbon molecular sieve) nanoparticles and porous organic cages fillers have also been proved successful in this domain[55].On the nanostructuring front, some researchers for example are developing materials that possess sub-nanometer porosity via novel routes such as block copolymer self-assembly or track- etching with nanometer accuracy. The outcome is a membrane with an extremely uniform pore size specifically designed for CO_2[56]. For example, one might make a polymer membrane and then add ~0.4 nm diameter pores (large enough for CO_2 to pass but not large enough for bigger N_2/O_2). These approaches typically utilize nanotechnology to fabricate the units (i.e. using nanostructured templates or etching at the nanoscale).[57]The outcome from these studies shows that the performance of nano-engineered membranes in different scenarios is above the Robeson upper bound (the traditional limit of polymer performance). Combining high CO_2 permeabilities with high selectivities requires fewer membranes to achieve the desired separation, and allows CO_2 to be captured at lower pressure differences or at a higher throughput, making membrane systems much more achievable[58, 59].Delivering membranes for post-combustion CO_2 capture has long been a challenge of the field: flue gas is at near-atmospheric pressure, while it remains a mix of a majority of N_2 (85%) and 15% CO_2 (this is not a favorable scenario for membranes, i.e., they perform better at higher CO_2 partial pressure). So, membranes will possibly outperform in niche or hybrid roles (e.g., polishing a CO_2 stream after a bulk capture by a different method, or in pre-combustion capture where the CO_2 may be of relatively high pressure)[60]. Nanotechnology is leading to membranes that are stronger and more efficient than ever before. For example, graphin -based membranes that are tolerant of water vapor and contaminants are very important. Further progress is likely to increase the design demonstration of MOF-on- membrane coating or 2D material laminates. As given above, the Tech-Hom message is that nanostructuring has captured a relatively high technique from a competitive technique with relatively high technology to increase or absorb/absorb under specific circumstances.[61].

Discussion

These results indicate significant progress in the ability to use nanotechnology to capture carbon, and the ability to overcome the challenges with existing traditional methods for CO_2 capture. This section considers the general capacity and effect of these Nano competition approaches, contradictions to traditional techniques and highlights the challenges and future roads [22].

He compared his methods with traditional techniques and found that the use of nanotechnology produces much more production in many matrixes. Because of this, even in very low pressure cases, there is a large CO_2 capacity for nano- Engineer adsorbents-one blessing for thorda gas currents or direct air catch scenarios where traditional sorbets are unable to remain acceptable [27,48,55]. A minimum of air (.0.04% CO_2) with carbon-based nanosorbanks and MOFs can be abstract when traditional amine solutions or geaxes need to be derived to focus equal amounts to focus equal amounts to focus equal amounts of carbon-based nanosorbanks and mash. [23,24]. In addition, extended mass transfer in nanofluides can lead to

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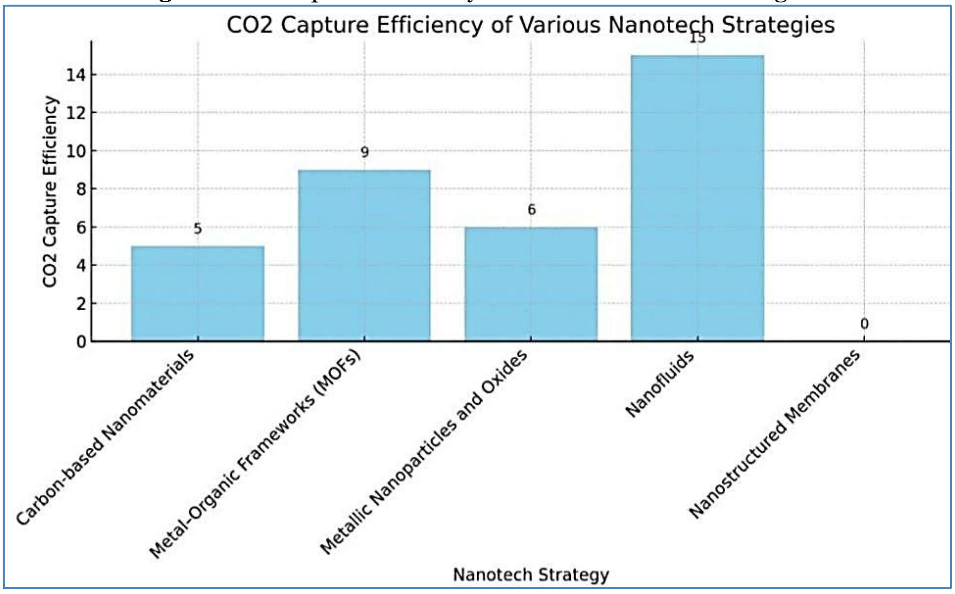
high mass transfer rates, something [48,53]. From an energy point of view, CO requires low energy input (temperature or vacuum swing). It directly addresses the high rebels problem related to the Amin-based systems [23,53]. According to an expense analysis, the replacement of amines with fixed physical adsorbents can reduce the energy required to capture CO with a very large factor, although details about the details of the material, process design, etc. [47,51]. The second side process is integration and footprints, an energy efficient and selective Nano-Mambrain system can capture CO in a single- phase process, where a traditional system undergoes several stages (absorption, stripping, compression). This can help simplify things in general, which means a low moving portion, and possibly some maintenance of overhead [29,54]. Additionally, nano-impact-enhanced processes may function at lower-cost conditions (e.g., adsorption near-ambient pressure/temperature cycling), potentially leveraging waste heat or passive chilling, making them a more seamlessly integrated power plant operation with minimal disruption [48,51,52]. As shown in the Table 4 for a comparative summary of nanotechnology-based CO_2 capture strategies, their efficiencies, and challenges .

Table 4 Nanotechnology CO_2 Capture Summary [51]

	Nanotech Strategy	CO_2 Capture Efficiency	High selectivity (>30), High permeance (>1000 GPU)	Challenges
1	Carbon-based Nanomaterials	High (2–8 mmol/g)	High surface area, tunable, cheap, durable	Low physisorption energy unless functionalized
2	Metal–Organic Frameworks (MOFs)	Very High (>8 mmol/g)	Ultra-high porosity, tunable, scalable	Moisture sensitivity, high cost
3	Metallic Nanoparticles and Oxides	Moderate–High	Chemisorption, catalytic roles, recyclable	Sintering, cost of metal NPs
4	Nanofluids	Enhanced absorption rate (10–20%)	Improved mass transfer, thermal control	Stability, aggregation, recovery
5	Nanostructured Membranes	High selectivity (>30), High permeance (>1000 GPU)	High permeability & selectivity, compact design	Fabrication scale-up, pressure limits

Figure 3 CO2capture efficiency of various Nanotech strategies



But comparing them must also take into account how mature and reliable they each are. For example, conventional amine scrubbing is a mature commercial technology with decades of operating experience; its pitfalls are well-known, and numerous engineering solutions have been developed to address the present problems (e.g., anti-corrosion treatments, solvent additives to prevent degradation, etc.)[23,47]. In contrast, many of the nanotech-based solutions are still only laboratories or pilot projects[55,58]. An adsorbent that works excellently in lab conditions may have problems and challenges working in a real power plant flue gas system – it can be poisoned (SOx, NOx, O_2 etc..), or lose activity over time due to minor transformation[48,56]. A review earlier this year observed that, although CO_2 capture on different nanomaterials has been demonstrated in a lab setting, translating that success to the scale of billions of tons of CO_2 still poses big challenges[60]. One difficulty noted was that capacity might still be limited in absolute terms — while a material might have a high capacity per kg, capturing billions of tons would require the manufacture and handling of immense amounts of that material, which pose logistical or environmental difficulties[59,60]. The other one is regeneration and cyclic stability – some tests in a lab only perform a few cycles; in reality, you need hundreds or thousands of cycles a year, and materials may fail or degrade unless they are extremely rugged[57,58].

In addition to technical performance, cost and economic viability for all carbon capture technology, economic viability and technology preparedness are necessary. Although many applications of new materials refer to dull economic words such as "low costs", it is just as acute than reality when it comes to complex nanoma patras that are still expensive to synthesize in bulk. MOF may require expensive ligands and solvents, and often long crystallization process [25,55]. A detailed economic analysis often shows that sorbent cost must decrease by a large amount to compete on a per-ton CO_2 captured basis with amines[47,51,52]. There are activities in scaling up production – e.g. continuous flow reactors for MOFs, manufacturing MOFs with less expensive

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precursors – and some progress is being made (some MOFs at kg scale, with the promise of tonnage scale within years)[25,55].

An additional economic consideration is the durability of the material. A very effective but very short-lived sorbent might not be practical due to the replacement costs outpacing any efficiency gains[52,56]. If a nanomaterial can last 5+ years in operation, one may be willing to pay a premium; if it lasts for only 3 months, however, it would probably be too expensive. Thus, proof of sustained stability for a longer duration is just as relevant as proving effective initial performance. This upscaling challenge is particularly relevant to materials such as MXANES or HIGH-end membrane [29,30,54]. A piece of opinion asked if it is better to spend money on scaling new materials (for example, MXES) that are now expensive to synthesize and even unknown environmental effects, or can improve existing, cheap solutions. This decision can balance its own interests based on the field, available resources and political incentives [51,52]. Stability and decline are special concern: e.g. Nanofluide stability (as discussed) requires constant energy and attention. Similarly, aging of the membrane or faizing can cause the dropout to perform; In a dirty gas environment, the membrane can be stopped, or if adequate pursuing procedures are not followed [48,53]. All of these factors mean that the raw performance number is to be seen in light of the real world's terms [54].

Environmental and safety ideas: The distribution of nanomaterials with large -scale brings with other ideas besides CO_2 capture. It is necessary to confirm that these new nanomaterials do not harm the environment or human health. Workers can be subjected to inhalation, for example if fine nanoporors are produced or manipulated and not erected. If the nanopes are issued in wastewater or in the environment, they may have unfortunate effects. Many carbon capture systems are attached and can be designed to limit such liberation, but a complete life cycle analysis of nanomaterials (synthesis, use and disposal) is required [52,59]. The opposite is that many of the questions (carbon, metal oxide, etc.) are not naturally toxic, only that their nanospeciality can interact in unknown and potentially harmful ways in the ecosystem. [52,60].

Regulatory intelligent; Any catch can imagine rules for plants, which are necessary for Nanotech that they have nanopartic management plans, as well as how they can safely familiarize themselves with sorbet for filtration on any ventilation and protocol. These are not unsafe problems but they are another factor that requires planning [47,25,61].

Roll in mitigation and policies for climate change: Given the big picture, better carbon capture technologies, including nanocapable people, will be required to reach climate goals. The current global capacity to capture CO is in millions of tonnes per year, while emissions are tens of billions [49]. To be part of the CCS solution, capacity must expand dramatically (EU, for example, calculates hundreds of crores of tons that will be required by 2050To be part of the CCS solution, capacity must expand dramatically (EU, for example, calculates hundreds of crores of tons that will be required by 2050 [50]. No

scales are required only with traditional CCs alone at favorable cost points to limit climate change; Plasma success (and yet unpredictable) can make these interval bridges. If it is said that a Nano-Adsorbent system can reduce catching costs from ~ $ 50-60/ton to $ 20/ton, it becomes economically viable in more scenario, potentially enables Gigon-scale Perpanio regions. [47,51].

However, these technologies get their ability, depending on politics and economic drivers. CCS will require a market required by strong carbon prices or rules that will attract investments in nanotek solutions. Otherwise, these new approaches may be re-set for demo or educational studies. [47,51].

Another debate point consists of Nanotech CCS with other strategies. Carbon capture is one of many units that deal with climate change (renewable energy, energy efficiency, nature -based solutions, etc.). The value of CCS (and therefore nano- cc) is that it can address emissions that are difficult to decrease in any other way (such as cement production or steel production) [50,51]. When the world strives for net-zero emissions, we can see more and more collaborative CO with a nanomaterial, and then convert it (perhaps with another nanochetic list) into a useful product (closure of the CCUS loop). [26,28,52], Or employed co -recovery of oil collection or synthetic fuel to all generations closes or completely renewable or completely renewable [50,52].

Future research instructions: Known challenges provide a roadmap for future R&D. The low hanging fruit here reduces the cost of nanometric new synthesis methods or different materials (for example, using affordable metals or bio-lines) using cheap metals or bio-rituals) is another area of attention; For example, researchers use general structures (eg flexibility and cruelty with a polymer with metal -carbon structure, and uses a durable outer layer to protect an active core) with core -coil nanopakanas. [25,52,55].

Data Maternities: Possibly play a large part: Scientific materials can use machine learning in the database to estimate which new materials (many of the theoretical options) will be the best feature of CO_2 characteristics and must focus on experiments faster. Some work has been done, for example, using genetic algorithms with ideal CO_2 bonding or using a nerve network to predict membrane performance [53,55].

Large pilot projects will also be necessary. A MOF will be precious to test operations from a power plate test, test laboratory findings and honor engineering design with a graphen membrane. It quickly focuses the partnership between academics and industry to set these materials through its pace under real circumstances. [29,54,55].

Hybrid solutions are another exciting opportunity: to take advantage of the strength in different approaches. For example, removing the bulk of COO from exhaust (fast canteix) can use a nanofluid absorber, while a MOF absorption can remove the most zero (high capacity in thin concentrations) of the remaining COO, and a membrane can only secure the remaining <1% COA. In this way, each stage addresses CO_2 in a part of the area, which can cope with the best, resulting in greater efficiency than any approach alone. [30,52,54].

Nano competent carbon capture appears to be an active and quickly developed field of research when we think about the future. Successful experiments to date show that it is a rich landscape for innovation, and with constant interdisciplinary work, some of these approaches can also become a mainstream practice in the coming decade or two [51,52].

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Conclusions

This study highlights the significant potential of nanomaterial-based technologies in advancing carbon capture systems across various applications. Nanomaterials such as carbon nanotubes, graphene, metal-organic frameworks (MOFs), porous organic polymers, and metal oxide nanoparticles have demonstrated superior CO_2 capture capabilities due to their high surface area, tunable surface chemistry, and enhanced interaction with gas molecules. These properties enable them to make them better than many traditional sorbet in the context of absorbent ability, selection and energy efficiency. Recent innovations, especially in membrane materials such as graphin oxide (GO), indicate remarkable improvement in permeability and selectivity, facilitates skilled COO separation from mixed gas currents. Additionally, nano-enhanced adsorption and absorption systems—such as those employing MOFs or nanofluids—have shown promise in reducing energy consumption during regeneration phases, especially when compared to traditional amine-based chemical absorption. Nanofluids, in particular, offer improved mass transfer rates, which could potentially allow for more compact absorption systems and reduce the overall footprint of capture units. Hybrid configurations that combine nanofluid absorption, MOF adsorption, and membrane separation are emerging as a promising avenue for maximizing capture efficiency while minimizing operational costs. These integrated systems demonstrate adaptability to various CO_2 sources, including flue gas, industrial emissions, and even ambient air, thereby expanding the operational scope beyond the limits of conventional technologies. The versatility of nanomaterials enables their use in both high-pressure pre-combustion and low-concentration direct air capture (DAC) scenarios, underscoring their relevance to both centralized and distributed emission sources. Nevertheless, several challenges remain. The transition from laboratory-scale successes to commercial-scale deployment necessitates the development of cost-effective, scalable, and environmentally sustainable production methods for nanomaterials. Long-term stability, durability under operating conditions, and potential environmental impacts must be rigorously evaluated. Techno- economic analyses and life cycle assessments will play a crucial role in validating the practical benefits and identifying trade- offs associated with nano-enabled carbon capture. Emerging pilot-scale demonstrations and economic simulations suggest that nanomaterial-based systems can reduce CO_2 capture costs substantially. While conventional amine systems incur capture costs of approximately $50–60 per ton, early results from MOF- and membrane-based systems indicate potential reductions to $20–30 per ton under optimized conditions. Such reductions could dramatically improve the economic viability

of carbon capture in hard-to-abate sectors and distributed emissions settings, where traditional approaches are often prohibitively expensive. Importantly, technological advancements must be accompanied by supportive policy frameworks to ensure large-scale adoption. Carbon pricing mechanisms, targeted subsidies, emissions regulations, and funding for low-carbon innovation are essential to incentivize private sector participation and drive commercialization. Inclusion of nano-enabled technologies in national decarbonization strategies, along with public-private partnerships, can further accelerate deployment and help establish reliable supply chains for nanomaterial production.

References

1. Li H. CO2 capture by various nanoparticles: Recent development and prospective. J Clean Prod. 2023;414:137679. https://doi.org/10.1016/j.jclepro.2023.137679 https://scholar.google.com/scholar_lookup?title=CO2+capture+by+various+nanoparticles%3A+Recent+development+and+prospective&author=Li+H&publication_year=2023&journal=J+Clean+Prod&volume=414&pages=137679
2. Khandaker T, Al-Mesfer MK, Al-Muhtaseb SA et al. Efficacies of carbon-based adsorbents for carbon dioxide capture. Processes. 2020;8(6):654. https://doi.org/10.3390/pr8060654 https://scholar.google.com/scholar_lookup?title=Efficacies+of+carbon-based+adsorbents+for+carbon+dioxide+capture&author=Khandaker+T&publication_year=2020&journal=Processes&volume=8&issue=6&pages=654
3. Cigala RM, Conti F, Privitera V et al. Biopolymeric nanocomposites for CO2 capture. Polymers (Basel). 2024;16(8):1063. https://doi.org/10.3390/polym16081063 https://scholar.google.com/scholar_lookup?title=Biopolymeric+nanocomposites+for+CO2+capture&author =Cigala+ RM&publication_year=2024&journal=Polymers&volume=16&issue=8&pages=1063
4. Ali A, Satti AN, Choudhary MA et al. Graphene-based membranes for CO2 separation. Mater Sci Energy Technol. 2019;2(1):83-88. https://doi.org/10.1016/j.mset.2018.12.002 https://scholar.google.com/scholar_lookup?title=Graphene-based+membranes+for+CO2+separation&author=Ali+A &publication_year=2019&journal=Mater+Sci+Energy+Technol&volume=2&issue=1&pages=83-88
5. Youns YT, Manshad AK, Ali JA. Sustainable aspects behind the application of nanotechnology in CO2 sequestration. Fuel. 2023;349:128680. https://doi.org/10.1016/j.fuel.2023.128680 https://scholar.google.com/scholar_lookup?title=Sustainable+aspects+behind+the+application+of+nanotechnology +in+CO2+sequestration&author=Youns+YT&publication_year=2023&journal=Fuel&volume=349&pages=128680
6. Alguacil FJ. Nanomaterials for CO2 capture from gas streams. Separations. 2023;11(1):1. https://doi.org/10.3390/separations11010001 https://scholar.google.com/scholar_lookup?title=Nanomaterials+for+CO2+capture+from +gas+streams&author=Alg uacil+FJ&publication_year=2023&journal=Separations&volume=11&issue=1&pages=1
7. Samanta A, Zhao A, Shimizu GKH et al. Post-combustion CO2 capture using solid sorbents: A review. Ind Eng Chem Res. 2012;51(4):1438-1463. https://doi.org/10.1021/ie200686q https://scholar.google.com/scholar_lookup?title=Post-combustion+CO2+capture+using+solid+sorbents%3A+A+review&author=Samanta+A&publication_year=2012&journal=Ind+Eng+Chem+Res&volume=51&issue=4&pages=1438-1463
8. Zhang H, Ma X, Zhong Z et al. Higher CO2 absorption using a new class of calcium hydroxide (Ca(OH)2) nanoparticles. Environ Chem Lett. 2018;16:1095-1100. https://doi.org/10.1007/s10311-018-0737-9 https://scholar.google.com/scholar_lookup?title=Higher+CO2+absorption+using+a+new+class+of+calcium+hydrox

ide+(Ca(OH)2)+nanoparticles&author=Zhang+H&publication_year=2018&journal=Environ+Chem+Lett&volume=16&pages=1095-1100
9. Lai N, Qin Y, Ran J et al. CO2 capture with absorbents of tertiary amine functionalized nano–SiO2. Front Chem. 2020;8:146. https://doi.org/10.3389/fchem.2020.00146 https://scholar.google.com/scholar_lookup?title=CO2+capture+with+absorbents+of+tertiary+amine+functionalized+nano-SiO2&author=Lai+N&publication_year=2020&journal=Front+Chem&volume=8&pages=146
10. Pashaei H, Irani M, Mousavi SM et al. Experimental investigation of the effect of nano heavy metal oxide particles in Piperazine solution on CO2 absorption using a stirrer bubble column. Energy Fuels. 2018;32(2):2037-2052. https://doi.org/10.1021/acs.energyfuels.7b04091 https://scholar.google.com/scholar_lookup?title=Experimental+investigation+of+the+effect+of+nano+heavy+metal+oxide+particles+in+Piperazine+solution+on+CO2+absorption+using+a+stirrer+bubble+column&author=Pashaei+H&publication_year=2018&journal=Energy+Fuels&volume=32&issue=2&pages=2037-2052
11. Rasaie M, Omidkhah MR, Asghari M et al. Highly selective physical/chemical CO2 separation by functionalized Fe3O4 nanoparticles in hollow fiber membrane contactors: Experimental and modeling approaches. Energy Fuels. 2022;36(8):4456-4469. https://doi.org/10.1021/acs.energyfuels.1c04101 https://scholar.google.com/scholar_lookup?title=Highly+selective+physical%2Fchemical+CO2+separation+by+functionalized+Fe3O4+nanoparticles+in+hollow+fiber+membrane+contactors%3A+Experimental+and+modeling+approaches&author=Rasaie+M&publication_year=2022&journal=Energy+Fuels&volume=36&issue=8&pages=4456-4469
12. Fan ST, Wang J, Zhang W et al. MOF-layer composite polyurethane membrane increasing both selectivity and permeability: Pushing commercial rubbery polymer membranes to be attractive for CO2 separation. Sep Purif Technol. 2022;297:121452. https://doi.org/10.1016/j.seppur.2022.121452 https://scholar.google.com/scholar_lookup?title=MOF-layer+composite+polyurethane+membrane+increasing+both+selectivity+and+permeability%3A+Pushing+commercial+rubbery+polymer+membranes+to+be+attractive+for+CO2+separation&author=Fan+ST&publication_year=2022&journal=Sep+Purif+Technol&volume=297&pages=121452
13. Hasan MR, Saha BB, Sarker M et al. Synthesis of ZIF-94 from recycled mother liquors: Study of the influence of its loading on post-combustion CO2 capture with Pebax based mixed matrix membranes. Adv Sustainable Syst. 2022;6(1):2100317. https://doi.org/10.1002/adsu.202100317 https://scholar.google.com/scholar_lookup?title=Synthesis+of+ZIF-94+from+recycled+mother+liquors%3A+Study+of+the+influence+of+its+loading+on+post-combustion+CO2+capture+with+Pebax+based+mixed+matrix+membranes&author=Hasan+MR&publication_year=2022&journal=Adv+Sustainable+Syst&volume=6&issue=1&pages=2100317
14. Kim H, Sohn H, Kang SW. CO2 separation membranes consisting of ionic liquid/CdO composites. J Nanosci Nanotechnol. 2018;18(8):5817-5821. https://doi.org/10.1166/jnn.2018.15461 https://scholar.google.com/scholar_lookup?title=CO2+separation+membranes+consisting+of+ionic+liquid%2FCdO+composites&author=Kim+H&publication_year=2018&journal=J+Nanosci+Nanotechnol&volume=18&issue=8&pages=5817-5821
15. Zaliman S, Ong CS, Yeong YF et al. 3D-imprinted superhydrophobic polyvinylidene fluoride membrane contactor incorporated with CaCO3 nanoparticles for carbon capture. Sep Purif Technol. 2022;287:120519. https://doi.org/10.1016/j.seppur.2022.120519 https://scholar.google.com/scholar_lookup?title=3D-imprinted+superhydrophobic+polyvinylidene+fluoride+membrane+contactor+incorporated+with+CaCO3+nanoparticles+for+carbon+capture&author=Zaliman+S&publication_year=2022&journal=Sep+Purif+Technol&volume=287&pages=120519
16. Liu Z, Jiang Y, Xu H et al. MOF-derived nano CaO for highly efficient CO2 fast adsorption. Fuel. 2023;340:127476. https://doi.org/10.1016/j.fuel.2023.127476 https://scholar.google.com/scholar_lookup?title=MOF-derived+nano+CaO+for+highly+efficient+CO2+fast+adsorption&author=Liu+Z&publication_year=2023&journal=Fuel&volume=340&pages=127476
17. Xia D, Zhu Q, Cheng H et al. Electrically heatable graphene aerogels as nanoparticle supports in adsorptive desulfurization and high-pressure CO2 capture. Adv Funct Mater. 2020;30(40):2002788. https://doi.org/10.1002/adfm.202002788 https://scholar.google.com/scholar_lookup?title=Electrically+heatable+graphene+aerogels+as+nanoparticle+supports+in+adsorptive+desulfurization+and+high-pressure+CO2+capture&author=Xia+D&publication_year=2020&journal=Adv+Funct+Mater&volume=30&issue=40&pages=2002788
18. Li X, Li J, Wang C et al. Redox-tunable Lewis bases for electrochemical carbon dioxide capture. Nat Energy. 2022;7(11):1065-1075. https://doi.org/10.1038/s41560-022-01108-5 https://scholar.google.com/scholar_lookup?title=Redox-tunable+Lewis+bases+for+electrochemical+carbon+dioxide+capture&author=Li+X&publication_year=2022&journal=Nat+Energy&volume=7&issue=11&pages=1065-1075
19. Li L, Zhang Y, Zhao H et al. Continuous CO2 capture and selective hydrogenation to CO over Na-promoted Pt nanoparticles on Al2O3. ACS Catal. 2022;12(4):2639-2650. https://doi.org/10.1021/acscatal.1c05663 https://scholar.google.com/scholar_lookup?title=Continuous+CO2+capture+and+selective+hydrogenation+to+CO+over+Na-promoted+Pt+nanoparticles+on+Al2O3&author=Li+L&publication_year=2022&journal=ACS+Catal&volume=12&issue=4&pages=2639-2650
20. Zou YH, Song Y, Wang Y et al. Porous metal–organic framework liquids for enhanced CO2 adsorption and catalytic conversion. Angew Chem. 2021;133(38):21083-21088. https://doi.org/10.1002/ange.202105120 https://scholar.google.com/scholar_lookup?title=Porous+metal–organic+framework+liquids+for+enhanced+CO2+adsorption+and+catalytic+conversion&author=Zou+YH&publication_year=2021&journal=Angew+Chem&volume=133&issue=38&pages=21083-21088
21. Hamalová K, Kárászová M, Dendisová M et al. Amine-doped PEBA membrane for CO2 capture. Mater Lett.

2023;333:133695. https://doi.org/10.1016/j.matlet.2022.133695
https://scholar.google.com/scholar_lookup?title=Amine-doped+PEBA+membrane+for+CO2+capture&author=Hamalová+K&publication_year=2023&journal=Mater+Lett&volume=333&pages=133695
22. Xie C, Zhang J, Wang H et al. Explainable machine learning for carbon dioxide adsorption on porous carbon. J Environ Chem Eng. 2023;11(1):109053. https://doi.org/10.1016/j.jece.2022.109053 https://scholar.google.com/scholar_lookup?title=Explainable+machine+learning+for+carbon+dioxide+adsorption+on+porous+carbon&author=Xie+C&publication_year=2023&journal=J+Environ+Chem+Eng&volume=11&issue=1&pages=109053
23. Rochelle GT. Amine scrubbing for CO2 capture. Science. 2009;325(5948):1652-1654. https://doi.org/10.1126/science.1176731 https://scholar.google.com/scholar_lookup?title=Amine+scrubbing+for+CO2+capture&author=Rochelle+GT&publication_year=2009&journal=Science&volume=325&issue=5948&pages=1652-1654
24. Siriwardane RV, Shen M, Fisher EP et al. Adsorption of CO2 on molecular sieves and activated carbon. Energy Fuels. 2001;15(2):279-284. https://doi.org/10.1021/ef000241s https://scholar.google.com/scholar_lookup?title=Adsorption+of+CO2+on+molecular+sieves+and+activated+carbon&author=Siriwardane+RV&publication_year=2001&journal=Energy+Fuels&volume=15&issue=2&pages=279-284
25. Wang J, Luo J, Feng S et al. From metal–organic frameworks to porous carbon materials: Recent progress and prospects from energy and environmental perspectives. Nanoscale. 2020;12(7):4238-4268. https://doi.org/10.1039/C9NR09677F https://scholar.google.com/scholar_lookup?title=From+metal–organic+frameworks+to+porous+carbon+materials%3A+Recent+progress+and+prospects+from+energy+and+environmental+perspectives&author=Wang+J&publication_year=2020&journal=Nanoscale&volume=12&issue=7&pages=4238-4268
26. Zhang X, Li H, Wang Y et al. Recent advances in non-noble metal electrocatalysts for nitrate reduction. Chem Eng J. 2021;403:126269. https://doi.org/10.1016/j.cej.2020.126269 https://scholar.google.com/scholar_lookup?title=Recent+advances+in+non-noble+metal+electrocatalysts+for+nitrate+reduction&author=Zhang+X&publication_year=2021&journal=Chem+Eng+J&volume=403&pages=126269
27. Keith DW, Holmes G, St Angelo D et al. A process for capturing CO2 from the atmosphere. Joule. 2018;2(8):1573-1594. https://doi.org/10.1016/j.joule.2018.05.006 https://scholar.google.com/scholar_lookup?title=A+process+for+capturing+CO2+from+the+atmosphere&author=Keith+DW&publication_year=2018&journal=Joule&volume=2&issue=8&pages=1573-1594
28. Liang Y. Transition Metal-Nitrogen Doped Carbon Materials for Electrocatalysis. PhD thesis. Monash University; 2017. https://scholar.google.com/scholar_lookup?title=Transition+Metal-Nitrogen+Doped+Carbon+Materials+for+Electrocatalysis&author=Liang+Y&publication_year=2017
29. Okoro EE, Oke EO, Okoro VO et al. Advances in the use of nanocomposite membranes for carbon capture operations. Int J Chem Eng. 2021;2021:6666242. https://doi.org/10.1155/2021/6666242 https://scholar.google.com/scholar_lookup?title=Advances+in+the+use+of+nanocomposite+membranes+for+carbon+capture+operations&author=Okoro+EE&publication_year=2021&journal=Int+J+Chem+Eng&volume=2021&pages=6666242
30. Song C, Liu Q, Ji N et al. Alternative pathways for efficient CO2 capture by hybrid processes—A review. Renew Sustain Energy Rev. 2018;82:215-231. https://doi.org/10.1016/j.rser.2017.09.074 https://scholar.google.com/scholar_lookup?title=Alternative+pathways+for+efficient+CO2+capture+by+hybrid+processes—A+review&author=Song+C&publication_year=2018&journal=Renew+Sustain+Energy+Rev&volume=82&pages=215-231
31. Bhattacharya M, Mandal MK. Synthesis of rice straw extracted nano-silica-composite membrane for CO2 separation. J Clean Prod. 2018;186:241-252. https://doi.org/10.1016/j.jclepro.2018.03.066 https://scholar.google.com/scholar_lookup?title=Synthesis+of+rice+straw+extracted+nano-silica-composite+membrane+for+CO2+separation&author=Bhattacharya+M&publication_year=2018&journal=J+Clean+Prod&volume=186&pages=241-252
32. Bhattacharya M, Mandal M. Synthesis of rice straw extracted nano-silica-composite membrane for CO2 separation. 2018. https://scholar.google.com/scholar_lookup?title=Synthesis+of+rice+straw+extracted+nano-silica-composite+membrane+for+CO2+separation&author=Bhattacharya+M&publication_year=2018
33. Rodgers RP, McKenna AM. Petroleum analysis. Anal Chem. 2011;83(12):4665-4687. https://doi.org/10.1021/ac2007956 https://scholar.google.com/scholar_lookup?title=Petroleum+analysis&author=Rodgers+RP&publication_year=2011&journal=Anal+Chem&volume=83&issue=12&pages=4665-4687
34. Riazi M. Characterization and properties of petroleum fractions. ASTM International; 2005. https://scholar.google.com/scholar_lookup?title=Characterization+and+properties+of+petroleum+fractions&author=Riazi+M&publication_year=2005
35. Wang X, Zhang X, Yang W et al. The progress of nanomaterials for carbon dioxide capture via the adsorption process. Environ Sci Nano. 2021;8(4):890-912. https://doi.org/10.1039/D0EN00891E https://scholar.google.com/scholar_lookup?title=The+progress+of+nanomaterials+for+carbon+dioxide+capture+via+the+adsorption+process&author=Wang+X&publication_year=2021&journal=Environ+Sci+Nano&volume=8&issue=4&pages=890-912
36. Liu Y, He S, Xu Z et al. Enhanced perfluorooctanoic acid degradation by electrochemical activation of sulfate solution on B/N codoped diamond. Environ Sci Technol. 2019;53(9):5195-5201. https://doi.org/10.1021/acs.est.9b00519 https://scholar.google.com/scholar_lookup?title=Enhanced+perfluorooctanoic+acid+degradation+by+electrochemical+activation+of+sulfate+solution+on+B%2FN+codoped+diamond&author=Liu+Y&publication_year=2019&journal=Environ+Sci+Technol&volume=53&issue=9&pages=5195-5201
37. Budd PM, Foster AB. Seeking synergy in membranes: Blends and mixtures with polymers of intrinsic microporosity.
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Curr Opin Chem Eng. 2022;36:100792. https://doi.org/10.1016/j.coche.2021.100792 https://scholar.google.com/scholar_lookup?title=Seeking+synergy+in+membranes%3A+Blends+and+mixtures+with+polymers+of+intrinsic+microporosity&author=Budd+PM&publication_year=2022&journal=Curr+Opin+Chem+Eng&volume=36&pages=100792
38. Seo S, Kim J, Park J et al. Catalytic activity of nickel nanoparticles stabilized by adsorbing polymers for enhanced carbon sequestration. Sci Rep. 2018;8(1):11786. https://doi.org/10.1038/s41598-018-30159-3 https://scholar.google.com/scholar_lookup?title=Catalytic+activity+of+nickel+nanoparticles+stabilized+by+adsorbing+polymers+for+enhanced+carbon+sequestration&author=Seo+S&publication_year=2018&journal=Sci+Rep&volume=8&issue=1&pages=11786
39. Seo SeokJu S, Kim J, Park J et al. Catalytic activity of nickel nanoparticles stabilized by adsorbing polymers for enhanced carbon sequestration. 2018. https://scholar.google.com/scholar_lookup?title=Catalytic+activity+of+nickel+nanoparticles+stabilized+by+adsorbing+polymers+for+enhanced+carbon+sequestration&author=Seo+SeokJu+S&publication_year=2018
40. Roullier C, Longeon A, Peduzzi J et al. A novel aryl-hydrazide from the marine lichen Lichina pygmaea: Isolation, synthesis of derivatives, and cytotoxicity assays. Bioorg Med Chem Lett. 2010;20(15):4582-4586. https://doi.org/10.1016/j.bmcl.2010.06.002 https://scholar.google.com/scholar_lookup?title=A+novel+aryl-hydrazide+from+the+marine+lichen+Lichina+pygmaea%3A+Isolation%2C+synthesis+of+derivatives%2C+and+cytotoxicity+assays&author=Roullier+C&publication_year=2010&journal=Bioorg+Med+Chem+Lett&volume=20&issue=15&pages=4582-4586
41. Nath J, Chaudhuri MK. Boric acid catalyzed bromination of a variety of organic substrates: An eco-friendly and practical protocol. Green Chem Lett Rev. 2008;1(4):223-230. https://doi.org/10.1080/17518250802440359

https://scholar.google.com/scholar_lookup?title=Boric+acid+catalyzed+bromination+of+a+variety+of+organic+substrates%3A+An+eco-friendly+and+practical+protocol&author=Nath+J&publication_year=2008&journal=Green+Chem+Lett+Rev&volume=1&issue=4&pages=223-230
42. Thaker HD, Som A, Ayaz F et al. Role of amphiphilicity in the design of synthetic mimics of antimicrobial peptides with gram-negative activity. ACS Med Chem Lett. 2013;4(5):481-485. https://doi.org/10.1021/ml400086b https://scholar.google.com/scholar_lookup?title=Role+of+amphiphilicity+in+the+design+of+synthetic+mimics+of+antimicrobial+peptides+with+gram-negative+activity&author=Thaker+HD&publication_year=2013&journal=ACS+Med+Chem+Lett&volume=4&issue=5&pages=481-485
43. Lu GH, Chen JJ, Zhang XK et al. Synthesis and bioactivity of novel strobilurin derivatives containing the pyrrolidine-2,4-dione moiety. Chin Chem Lett. 2014;25(1):61-64. https://doi.org/10.1016/j.cclet.2013.08.031 https://scholar.google.com/scholar_lookup?title=Synthesis+and+bioactivity+of+novel+strobilurin+derivatives+containing+the+pyrrolidine-2%2C4-dione+moiety&author=Lu+GH&publication_year=2014&journal=Chin+Chem+Lett&volume=25&issue=1&pages=61-64
44. Brethomé FM, Ferrari MC, Bernardo G et al. Direct air capture of CO2 via aqueous-phase absorption and crystalline-phase release using concentrated solar power. Nat Energy. 2018;3(7):553-559. https://doi.org/10.1038/s41560-018-0155-1 https://scholar.google.com/scholar_lookup?title=Direct+air+capture+of+CO2+via+aqueous-phase+absorption+and+crystalline-phase+release+using+concentrated+solar+power&author=Brethomé+FM&publication_year=2018&journal=Nat+Energy&volume=3&issue=7&pages=553-559
45. Ai Y, Wang S, Zhang Y et al. Visible-light-controlled ternary chiroptical switches with high-performance circularly polarized luminescence for advanced optical information storage and anti-counterfeiting materials. Chem Eng J. 2022;450:138390. https://doi.org/10.1016/j.cej.2022.138390 https://scholar.google.com/scholar_lookup?title=Visible-light-controlled+ternary+chiroptical+switches+with+high-performance+circularly+polarized+luminescence+for+advanced+optical+information+storage+and+anti-counterfeiting+materials&author=Ai+Y&publication_year=2022&journal=Chem+Eng+J&volume=450&pages=138390
46. Schlemmer W, Müller K, Stricker F et al. 2-Methoxyhydroquinone from vanillin for aqueous redox-flow batteries. Angew Chem Int Ed. 2020;59(51):22943-22946. https://doi.org/10.1002/anie.202010278 https://scholar.google.com/scholar_lookup?title=2-Methoxyhydroquinone+from+vanillin+for+aqueous+redox-flow+batteries&author=Schlemmer+W&publication_year=2020&journal=Angew+Chem+Int+Ed&volume=59&issue=51&pages=22943-22946
47. Bui M, Adjiman CS, Bardow A et al. Carbon capture and storage (CCS): The way forward. Energy Environ Sci. 2018;11(5):1062-1176. https://doi.org/10.1039/C7EE02342A https://scholar.google.com/scholar_lookup?title=Carbon+capture+and+storage+(CCS)%3A+The+way+forward&author=Bui+M&publication_year=2018&journal=Energy+Environ+Sci&volume=11&issue=5&pages=1062-1176
48. Yu W, Zhang Y, Yang D et al. Review of liquid nano-absorbents for enhanced CO2 capture. Nanoscale. 2019;11(37):17137-17156. https://doi.org/10.1039/C9NR04433D https://scholar.google.com/scholar_lookup?title=Review+of+liquid+nano-absorbents+for+enhanced+CO2+capture&author=Yu+W&publication_year=2019&journal=Nanoscale&volume=11&issue=37&pages=17137-17156
49. Tong D, Zhang Q, Zheng Y et al. Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. Nature. 2019;572(7769):373-377. https://doi.org/10.1038/s41586-019-1364-3 https://scholar.google.com/scholar_lookup?title=Committed+emissions+from+existing+energy+infrastructure+jeopardize+1.5+%C2%B0C+climate+target&author=Tong+D&publication_year=2019&journal=Nature&volume=572&issue=7769&pages=373-377
50. Davis SJ, Lewis NS, Shaner M et al. Net-zero emissions energy systems. Science. 2018;360(6396):eaas9793. https://doi.org/10.1126/science.aas9793
ISSN 3063-8186 (online), https://ijhsm.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

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DOI: 10.21070/ijhsm.v3i1.422

https://scholar.google.com/scholar_lookup?title=Net-zero+emissions+energy+systems&author=Davis+SJ&publication_year=2018&journal=Science&volume=360&issue=6396

51. Dubey A, Arora A. Advancements in carbon capture technologies: A review. J Clean Prod. 2022;373:133932. https://doi.org/10.1016/j.jclepro.2022.133932 https://scholar.google.com/scholar_lookup?title=Advancements+in+carbon+capture+technologies%3A+A+review&author=Dubey+A&publication_year=2022&journal=J+Clean+Prod&volume=373&pages=133932
52. Saleh TA. Nanomaterials and hybrid nanocomposites for CO2 capture and utilization: Environmental and energy sustainability. RSC Adv. 2022;12(37):23869-23888. https://doi.org/10.1039/D2RA04202H https://scholar.google.com/scholar_lookup?title=Nanomaterials+and+hybrid+nanocomposites+for+CO2+capture+and+utilization%3A+Environmental+and+energy+sustainability&author=Saleh+TA&publication_year=2022&journal=RSC+Adv&volume=12&issue=37&pages=23869-23888
53. Mohd Rozaiddin SA, Lau KK. A review on enhancing solvent regeneration in CO2 absorption process using nanoparticles. Sustainability. 2022;14(8):4750. https://doi.org/10.3390/su14084750 https://scholar.google.com/scholar_lookup?title=A+review+on+enhancing+solvent+regeneration+in+CO2+absorption+process+using+nanoparticles&author=Mohd+Rozaiddin+SA&publication_year=2022&journal=Sustainability&volume=14&issue=8&pages=4750
54. Hou R, Li Y, Liu J et al. Current status and advances in membrane technology for carbon capture. Sep Purif Technol. 2022;300:121863. https://doi.org/10.1016/j.seppur.2022.121863 https://scholar.google.com/scholar_lookup?title=Current+status+and+advances+in+membrane+technology+for+carbon+capture&author=Hou+R&publication_year=2022&journal=Sep+Purif+Technol&volume=300&pages=121863
55. Boyd PG, Chidambaram A, García-Díez E et al. Data-driven design of metal–organic frameworks for wet flue gas CO2 capture. Nature. 2019;576(7786):253-256. https://doi.org/10.1038/s41586-019-1798-7 https://scholar.google.com/scholar_lookup?title=Data-driven+design+of+metal–organic+frameworks+for+wet+flue+gas+CO2+capture&author=Boyd+PG&publication_year=2019&journal=Nature&volume=576&issue=7786&pages=253-256
56. Creamer AE, Gao B, Zhang M. Biomass-facilitated production of activated magnesium oxide nanoparticles with extraordinary CO2 capture capacity. Chem Eng J. 2018;334:81-88. https://doi.org/10.1016/j.cej.2017.09.161 https://scholar.google.com/scholar_lookup?title=Biomass-facilitated+production+of+activated+magnesium+oxide+nanoparticles+with+extraordinary+CO2+capture+capacity&author=Creamer+AE&publication_year=2018&journal=Chem+Eng+J&volume=334&pages=81-88
57. Huang C, Li Y, Sun Y et al. Template-free synthesis of hollow CaO/Ca2SiO4 nanoparticle as a cyclically stable high-capacity CO2 sorbent. ACS Sustainable Chem Eng. 2021;9(5):2171-2179. https://doi.org/10.1021/acssuschemeng.0c06507 https://scholar.google.com/scholar_lookup?title=Template-free+synthesis+of+hollow+CaO%2FCa2SiO4+nanoparticle+as+a+cyclically+stable+high-capacity+CO2+sorbent&author=Huang+C&publication_year=2021&journal=ACS+Sustainable+Chem+Eng&volume=9&issue=5&pages=2171-2179
58. Jung Y, Lee J, Kim J et al. Designing large-sized and spherical CO2 adsorbents for highly reversible CO2 capture and low pressure drop. Chem Eng J. 2022;427:131781. https://doi.org/10.1016/j.cej.2021.131781 https://scholar.google.com/scholar_lookup?title=Designing+large-sized+and+spherical+CO2+adsorbents+for+highly+reversible+CO2+capture+and+low+pressure+drop&author=Jung+Y&publication_year=2022&journal=Chem+Eng+J&volume=427&pages=131781
59. Shen Y. Preparation of renewable porous carbons for CO2 capture – A review. Fuel Process Technol. 2022;236:107437. https://doi.org/10.1016/j.fuproc.2022.107437 https://scholar.google.com/scholar_lookup?title=Preparation+of+renewable+porous+carbons+for+CO2+capture+–+A+review&author=Shen+Y&publication_year=2022&journal=Fuel+Process+Technol&volume=236&pages=107437
60. Rehman A, Nasir S, Jamil S et al. A rational design of cellulose-based heteroatom-doped porous carbons: Promising contenders for CO2 adsorption and separation. Chem Eng J. 2021;420:130421. https://doi.org/10.1016/j.cej.2021.130421 https://scholar.google.com/scholar_lookup?title=A+rational+design+of+cellulose-based+heteroatom-doped+porous+carbons%3A+Promising+contenders+for+CO2+adsorption+and+separation&author=Rehman+A&publication_year=2021&journal=Chem+Eng+J&volume=420&pages=130421
61. Elhambakhsh A, Keshavarz P. Investigation of carbon dioxide absorption using different functionalized Fe3O4 magnetic nanoparticles. Energy Fuels. 2020;34(6):7198-7208. https://doi.org/10.1021/acs.energyfuels.0c00687 https://scholar.google.com/scholar_lookup?title=Investigation+of+carbon+dioxide+absorption+using+different+functionalized+Fe3O4+magnetic+nanoparticles&author=Elhambakhsh+A&publication_year=2020&journal=Energy+Fuels&volume=34&issue=6&pages=7198-7208

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