

SUSTAINABLE ENGINEERED NANOFIBERS AND HYBRID NANOCOMPOSITES FOR CO₂ CAPTURE, CONVERSION, AND ENVIRONMENTAL REMEDIATION: CHALLENGES AND FUTURE PERSPECTIVES

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Abstract

Nanomaterials have emerged as promising advanced materials for addressing critical environmental challenges associated with ecosystem degradation and global warming. Increasing emissions of greenhouse gases, particularly carbon dioxide (CO₂), have intensified concerns regarding climate change and environmental sustainability. This review comprehensively examines recent advances in the application of nanomaterials for CO₂ capture, reduction, and conversion into value-added products and fuels. Particular emphasis is placed on nanomaterial-assisted CO₂ conversion technologies, including photocatalytic, electrocatalytic, thermostatic, and other emerging conversion approaches. The review further discusses the fundamental mechanisms, catalytic properties, and performance of different nanomaterials, along with the influence of their structural, surface, and physicochemical characteristics on CO₂ conversion efficiency. In addition, the major challenges associated with nanomaterial synthesis, stability, selectivity, scalability, energy consumption, cost, environmental safety, and potential toxicity are critically evaluated. Finally, future research perspectives and opportunities are highlighted to facilitate the development of efficient, sustainable, economically viable, and environmentally safe nanomaterial-based technologies for CO₂ mitigation and conversion.

INTRODUCTION

The effect of greenhouse gases (GHG) shows that a large amount of carbon is emitted, and products entering the atmosphere will have an adverse effect that will warm the earth, leading to disastrous effects on weather and potentially poor quality of air in the region [1, 2]. The design of energy-efficient carbon dioxide (CO₂) capture technology is important to decrease the impact of global

warming on climate, as we are not stopping the use of fossil fuels to meet our demand for energy [3-5]. In addition, CO₂ can be converted into useful by-products and chemicals. It is observed as part of sustainable energy development and green chemistry research. Carbon dioxide can be used as a renewable raw material [6, 7]. Carbon dioxide can also be utilized to synthesize many chemicals

as a reagent and can be used as a viable and environmentally friendly solvent system. Carbon dioxide is a feasible replacement for the consumption of petroleum raw materials in the production of important industrial chemicals [8, 9]. Thus, the development of new applications of carbon dioxide in the purification and synthesis of chemicals will slow down the global consumption of oil [10]. Simultaneously, the use of abundant by-products is highly beneficial because it not only produces products that are useful for households and industries but also represents a responsible step toward protecting our global ecosystem. That is why for reduction of global warming and its catastrophic effects and to acquire a future of sustainable energy, there is a need to develop new techniques which are based on new processes and materials to allow simultaneous capture of CO₂ and its conversion

CO₂ is produced from many sources, but it is mainly produced from the combustion of carbon-containing fuels, such as methane, petroleum, biomass, and coal. Currently, many options for capturing, storing, and converting CO₂ are being explored. Saline aquifers in the deep sea and depleted gas or oil fields or land offer potential storage facilities for CO₂. Efforts are currently focused on designing natural repositories to collect and store carbon dioxide. However, carbon dioxide must be removed from the exhaust gases before storage. CO₂ extraction from fumes (particles of dust, water, and nitrogen) is the main step of capturing carbon dioxide, which generally incorporates capture by solvent absorption. To meet energy and cost-effective targets of CO₂ capture, technology must be improved. Over time, research has also been inspired by improvements in the direct conversion of carbon. Conversion of CO₂ into products that are beneficial, rather than just to store.

Nanotechnology can help reduce carbon dioxide in the environment globally. Current research and development (R&D) has shown that materials supported by nanotechnology have a great ability to give feasible solutions to of energy-efficient and high-capacity carbon dioxide collection and cost-effective challenges [11]. The

next task is to turn carbon dioxide into products which could be valuable. This review offers a comprehensive overview of the processes involved in capturing carbon dioxide and its subsequent conversion. It summarizes existing techniques for capturing carbon dioxide and converting it into by-products, while also addressing the associated challenges. Additionally, this paper reviews recent research on carbon dioxide capture and storage, with a particular focus on the application of nanomaterials and the transformation of carbon dioxide into valuable products.

2 Carbon Dioxide (CO₂) Capture

Numerous contemporary carbon dioxide storage methods employ carbon capture devices to collect substantial quantities of carbon dioxide, which are then transported to designated storage locations. Traditional approaches involve storing these quantities under pressure, sealing them underground, and monitoring to ensure effective storage. This process is both costly and complex, necessitating further research and development to render current storage technologies commercially feasible and viable. Research centers and universities globally have invested tens of millions of dollars in efforts to design advanced techniques for carbon capture and explore alternative methods for carbon dioxide storage and conversion into useful products. This review illustrates the traditional techniques developed to date, alongside current research and development efforts in carbon capture, as detailed in the following sections.[12-14].

3 Nanotechnology-enabled carbon capture

Nanotechnology offers viable hardware solutions to this intricate technical issue. A novel approach to carbon capture employs nanostructured membranes. The separation of carbon dioxide using nanomaterials (NMs) is regarded as energy efficient, requiring only 8% of the energy produced. Furthermore, this application is cost-effective.[15, 16]. The nanostructured membrane technique for capturing carbon dioxide has the potential to substantially reduce installation costs. Additionally, fifty different types of

nanomembranes are currently under development.[15-18]. These encompass nanostructured polymer membranes, carbon molecular sieve membranes, and nanoscale ceramic membranes (Fig. 1). Ceramic nanomaterials exhibit greater stability and can

withstand extreme conditions, such as high temperatures, more effectively than polymer membranes. The subsequent section will detail the carbon capture process facilitated by various nanotechnologies.[19, 20].

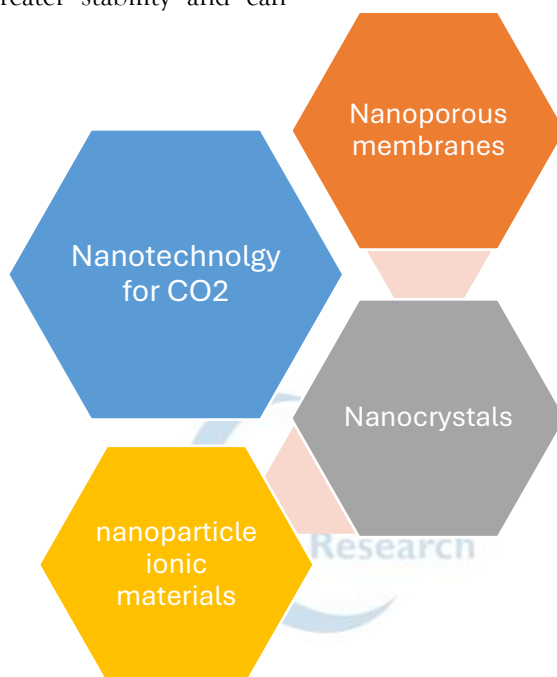


Fig.1. Classification of nanotechnology for CO₂

3.1 Nanoporous membranes

Research and development efforts have focused on producing nanoporous membranes for the separation of carbon dioxide from combustion and other high-temperature processes (temperature > 700 K). Modeling studies have demonstrated that high carbon dioxide separation factors can be achieved with membranes with well-defined thicknesses and porosities [21, 22]. The existence of these membranes is derived from theoretical studies on gas transport through ultra-thin nanoporous silica, with thicknesses ranging from approximately 5 to 25 nm [23, 24]

3.2 Nanocrystals for carbon capture

Alkaline oxides and hydroxides exhibit increased reactivity with CO₂ when reduced to nanoparticles, thereby enhancing their storage efficiency. In this context, colloidal magnesium oxide nanocrystals are synthesized due to their

utility in the long-term storage of carbon dioxide. These nanocrystals are regarded as a nanoscale system for CO₂ control and geological storage. Scientists and engineers utilize these nanocrystals as a model system to study the dissolution kinetics and mineralization processes in fluid rock reservoirs. This approach facilitates the exploration of effective methods for CO₂ storage. These nanocrystals provide a simplified model to simulate the intricate process of combining magnesium with stable carbonates through geologically complex minerals [25-27].

3.4 Nanoparticle Ionic Materials for carbon capture

A novel technique is being developed for carbon capture using ionic nanoparticle materials, nanotechnological interface materials, complex fluids, and polymers. These materials consist of a core of hard nanoparticles functionalized with an

organic crown, which may be a polymer crown. As a solvent-free granular fluid, Nanoparticle Ionic Materials (NIMS) is a highly adaptable functional material with notable miscibility and dispersibility. NIMS serves as a nanoscale analog and remains stable across a broad temperature range, rendering it non-volatile by ionic liquids. NIMS with high-affinity nanoporous cores can be engineered to enhance the solubility of carbon dioxide.[28, 29]

4. Perspectives for the use of nanomaterials for CO₂ capture and conversion technologies

The impact of greenhouse gases (GHG) indicates that the substantial emission of carbon-containing products into the atmosphere will adversely affect the Earth's temperature, leading to potentially disastrous weather effects and a decline in regional air quality [30]. The development of energy-efficient carbon capture techniques is a logical approach to mitigating the impact of global warming on the climate, given the continued reliance on fossil fuels to satisfy energy demands. Furthermore, carbon dioxide can be transformed into valuable by-products and chemicals, aligning with sustainable energy development and green chemistry research. As a renewable raw material, carbon dioxide can serve as a reagent in the synthesis of various chemicals and as an environmentally friendly solvent system. It offers a feasible alternative to petroleum-based raw materials for producing essential industrial chemicals. Consequently, advancing new applications of carbon dioxide in chemical purification and synthesis could reduce global oil consumption. Utilizing abundant by-products is advantageous, as it not only generates useful products for households and industries but also contributes to the protection of the global ecosystem. Therefore, to mitigate global warming and its catastrophic effects and to achieve a sustainable energy future, it is imperative to develop innovative techniques based on new processes and materials that enable the simultaneous capture and conversion of CO₂.

Carbon dioxide is generated from various sources, predominantly through the combustion of carbon-containing fuels, such as methane, petroleum,

biomass, and coal. Numerous strategies for capturing, storing, and converting CO₂ are currently under investigation. Saline aquifers located in the deep sea, as well as depleted gas or oil fields on land, present potential storage sites for CO₂. Efforts are currently focused on designing natural repositories for carbon dioxide storage. However, it is essential to remove CO₂ from exhaust gases prior to storage. The extraction of CO₂ from emissions, which contain dust particles, water, nitrogen, and carbon dioxide, is a critical step in the capture process, typically involving solvent absorption. Technological advancements are necessary to achieve energy and cost efficiency in CO₂ capture. Research is increasingly directed towards the direct conversion of carbon, aiming to transform CO₂ into useful products rather than merely storing it. Nanotechnology offers promising potential for reducing global carbon dioxide levels. Current research and development activities have demonstrated that nanomaterials can provide viable solutions to challenges related to high-capacity and cost-effective carbon dioxide capture. The challenge remains to convert this carbon dioxide into beneficial products. Nanomaterials can offer appropriate hardware solutions for this complex technological challenge. A recent advancement in carbon capture involves the use of nanostructured membrane materials. Scientists and engineers have asserted that the separation of CO₂ using nanostructured membranes is energy-efficient, consuming only 8% of the energy produced. Furthermore, the application of this low-cost carbon nanostructured membrane technique for carbon dioxide capture is expected to significantly reduce installation costs. This study examines nanostructured polymer membranes, carbon molecular sieve membranes, and ceramic nanoscale membranes. Ceramic nanoscale membranes exhibit greater durability and resistance to extreme conditions, such as high temperatures, compared to polymer membranes. Future research could focus on the design of nanostructured catalysts with enhanced functionalities, as a promising area of investigation.

The conversion process utilizing a catalyst must be effective and conducted under mild reaction conditions, with particular emphasis on economic viability. Numerous catalytic methods require extreme conditions for reactions, and the energy produced by the resulting fuel is often less than the energy expended in its production. To address this issue, the development of an appropriate nano catalyst presents a promising solution. Although scientists and engineers have made considerable advancements in this technology, further research is necessary to fully understand the role of nano catalysts. In addition to mitigating the impact of other environmentally harmful chemicals, future research should prioritize the production of multifunctional nanomaterials to achieve efficient carbon capture and conversion. This approach will not only decrease the concentration of greenhouse gases in the environment but also substantially reduce the emissions of chemical substances detrimental to human health. In the coming years, the application of nano-carbon capture and conversion techniques to produce valuable commodities such as carbonates, chemicals, fuels, plastics, and building materials will become a central aspect of carbon capture and storage strategies. During the combustion process of coal in factories or power plants, CO₂ is released, and when this release is combined with the CO₂ storage process, it results in the most efficient and effective method. Under current circumstances, carbon dioxide capture constitutes the most advanced effective capture technologies, which are generally employed solely to comply with government regulations regarding carbon dioxide capture. The process of capture and subsequent conversion will introduce ecologically beneficial factors to plants that typically emit toxic fumes. Furthermore, the application of nanotechnology-activated chelation methods is not confined to large-scale mechanized factories. The technique of carbon capture and transformation can be applied to various processes, such as urban air purification, and can potentially be adapted for portable home use as the technology advances. The future development of any process or technology will

contribute to cleaner air and represent progress towards achieving a sustainable civilization.

4.1 Nanomaterials for CO₂ hydrogenation

Nanomaterials have emerged as highly promising catalytic materials for CO₂ hydrogenation because their nanoscale dimensions provide high surface areas, abundant active sites, tunable electronic properties, and strong interactions between catalytic metals and supporting materials[31]. CO₂ is a thermodynamically stable molecule, and its efficient conversion requires catalysts capable of promoting its adsorption and activation while facilitating hydrogen dissociation and subsequent hydrogenation reactions[32]. Nanostructured catalysts can significantly enhance these processes by exposing highly reactive crystal facets, defects, edges, oxygen vacancies, and metal-support interfaces. Copper, nickel-, nickel, cobalt-, iron-, ruthenium-, palladium-, and platinum-based metal nanoparticles have been extensively investigated for converting CO₂ into valuable products such as methanol, methane, carbon monoxide, and higher hydrocarbons [33]. Copper-based nanomaterials are particularly important for methanol synthesis because copper (Cu) sites facilitate hydrogen activation and CO₂-derived intermediate conversion, while oxide components such as ZnO, ZrO₂, CeO₂, and In₂O₃ can improve CO₂ adsorption and stabilize reaction intermediates [34]. Nickel nanocatalysts have been widely investigated for CO₂ methanation due to their strong hydrogen dissociation capability, relatively low cost, and high catalytic activity; however, nanoparticle sintering and carbon deposition can reduce their long-term stability. Metal oxides with oxygen vacancies, particularly ceria, zirconia, and indium oxide, have also attracted considerable attention because surface defects can enhance CO₂ activation and influence reaction pathways. Furthermore, bimetallic and alloy nanoparticles provide opportunities to modify the electronic structure and geometric arrangement of active sites, potentially improving catalytic activity, product selectivity, and resistance to deactivation compared with monometallic systems. The catalyst support is equally important because

nanostructured oxides, porous silica, zeolites, carbon materials, and metal-organic-framework-derived materials can improve metal dispersion, control nanoparticle size, and create favorable interfacial sites [35]. Recent catalyst design strategies increasingly focus on controlling particle size, morphology, porosity, surface defects, and metal-support interactions at the atomic and nanoscale levels. Core-shell structures, single-atom catalysts, supported nanoclusters, and defect-engineered materials are particularly attractive because they can maximize metal utilization and provide well-defined catalytic environments[36]. Nevertheless, several challenges remain before nanomaterial-based CO₂ hydrogenation can achieve broader industrial implementation. Nanoparticles may undergo agglomeration or sintering under elevated reaction temperatures and pressures, leading to a loss of active surface area, while catalyst poisoning, carbon deposition, and structural transformations may further decrease performance[37]. In addition, the synthesis of sophisticated nanomaterials can involve expensive precursors and complex preparation procedures, creating difficulties for large-scale production. Future research should therefore combine nanoscale catalyst engineering with mechanistic understanding, operando characterization, computational modelling, and scalable synthesis methods to establish relationships between catalyst structure, reaction intermediates, activity, selectivity, and stability[38]. Overall, rationally designed nanomaterials offer substantial opportunities for improving CO₂ hydrogenation and transforming captured carbon dioxide into useful fuels and chemicals, particularly when the required hydrogen is produced from renewable energy sources.

4.2 Nanomaterials for CO₂ electrochemical/electrocatalytic reduction

The electrochemical conversion of carbon dioxide into fuels and raw materials can store intermittent renewable electricity, thereby reducing greenhouse gas emissions and at the same time providing a new green way to synthesize chemicals rich in

carbon. energy. Therefore, electrochemical reduction (ECR) and the electrochemical synthesis of CO₂-related chemicals have received considerable attention [39].

In recent years, thermochemical, photochemical, and electrochemical methods have been used to actively investigate the catalytic reduction of CO₂ into fuel. ECR is of interest because of its various benefits over other methods [40]. It promotes the CO₂ reduction reaction efficiently and selectively while inhibiting the competitive hydrogen evolution reaction (HER) [41]. Nanostructured metal catalysts have gained significant attention in the electrochemical reduction of CO₂ because of their unique properties compared to polycrystalline catalysts. They have a high catalytic surface area and contain most edges or low coordination sites, and they exhibit different catalytic behaviors than fully coordinated sites on the flat surface of their bulk samples[42]. The improvement in performance has been illustrated in nanostructured catalysts. Generally, nanostructured precious metals such as gold, silver, and palladium exhibit highly selective CO₂ conversion under a relatively low overpotential. For example, compared to the reversible hydrogen electrode (RHE) in an aqueous solution of 0.5 M KHCO₃, the monodisperse 8 nm gold nanoparticles show a Faraday efficiency (FE) as high as 90% at -0.67 V [43].

4.3 Nanomaterials for CO₂ adsorption

Nanomaterials have attracted considerable attention for CO₂ adsorption because of their high specific surface area, tunable pore structures, abundant active sites, and adjustable surface chemistry [44]. Compared with conventional adsorbents, nanoscale materials can provide enhanced interactions with CO₂ molecules, resulting in improved adsorption capacity and selectivity. Important nanomaterials investigated for CO₂ capture include metal oxides, porous silica, carbon nanotubes, graphene-based materials, zeolites, metal-organic frameworks (MOFs), and functionalized nanoparticles [45]. Metal oxides, such as MgO, CaO, ZnO, and Al₂O₃, have potential for CO₂ adsorption

through interactions between acidic CO₂ molecules and basic surface sites. Carbon-based nanomaterials offer high surface areas, chemical stability, and controllable porosity, while surface functionalization with nitrogen-containing or amine groups can further strengthen CO₂ adsorption. MOFs are particularly promising because their exceptionally high porosity and chemically adjustable frameworks enable selective CO₂ capture under different pressure and temperature conditions [46]. Similarly, nanosized zeolites provide well-defined micropores that facilitate molecular separation and adsorption. Despite these advantages, practical applications remain limited by synthesis cost, moisture sensitivity, material stability, regeneration energy, and scalability. Therefore, current research focuses on developing inexpensive, durable, recyclable, and highly selective nanomaterials capable of efficient CO₂ capture from industrial flue gases and atmospheric sources.

4.5 Nanomaterials membranes for CO₂

Many separation processes use nanocomposite membranes, and considerable progress has been made in improving their performance[47]. The interaction between the two entities uniquely combines the advantages of each component and reduces their inherent limitations. Nanomaterials can be combined with the polymer matrix in various ways, including (i) the most common nanomaterials and polymers being directly mixed to form a mixed matrix membrane (MMM) [38] and (ii) surface assembly after the nanomaterials are bound to the surface of prefabricated membranes by grafting or coating. For thin-film composite membranes utilized for nanofiltration, gas separation, direct osmosis, reverse osmosis, and nanocomposite membranes can be designed more flexibly, that is, by including nanofillers into the substrate and/or selecting the layer and surface structure[48]. Nanocomposite membranes are hailed as one of the game changers in membrane technology, irrespective of their structure and configuration. The correct selection of nanomaterials (dispersed phase) and polymers (continuous phase) is one of the most crucial

aspects in designing nanocomposite membranes. Defining a set of material selection questions, such as the intended use and the specific membrane characteristics required for that application, can provide beneficial guidance for visualizing the results of a functionally dominated membrane[49]. It is particularly important to understand the material properties, not only from a basic point of view, but also because this knowledge has laid a solid foundation for designing nanocomposite membranes and their final performance. Custom membrane characteristics are also the most important[50]. The emergence of characterization technology provides sufficient information for newly discovered nanomaterials, thus helping to establish function-structure relationships.

5. Challenges in the use and development of nanomaterials for CO₂ capture and conversion technologies

Unfortunately, nanomaterials have received the full attention of researchers, industries, and governments; however, less attention has been paid to their recycling and waste management strategies. The number of studies on the fate of nanomaterials after the end-of-life cycle of nanoproducts is limited. Nanomaterials pose risks to the environment and human health; therefore, proper management and recycling of waste can reduce their toxicity. After the end of their useful life, nanomaterials can enter the recycling system, be incinerated, or landfilled. These particles can circulate in air, water, and soil. If not properly managed, processed, or recycled, nanomaterials can become emerging pollutants. Modeling studies have shown that metallic nanoparticles can be landfilled when incinerated. The flow of nano-titanium dioxide, nano-zinc oxide, nano-silver, and carbon nanotubes in the circulatory system was simulated. It was found that most of the material goes to landfills and incineration plants as waste, and a small portion is recycled for new products. For example, in Switzerland, 43 tonnes / year of titanium dioxide goes into the recycling system, of which 23 tonnes / year ends up in waste incineration plants, 13 tonnes / year goes to

landfills, 2-3 tonnes / year plastics are released abroad or for the production of cement and concrete aggregates, and 2% of the total goes to wastewater. The good news is that when nanomaterials are present in recyclable waste, some recycling processes have already recovered most of them. For example, thermal procedures such as inert gas condensation and vacuum separation can be used to recover up to 99% of zinc nanoparticles from zinc-manganese battery waste. Through filtration and extraction, up to 70% of the purified carbon nanotubes were recovered from the waste materials of the supercapacitors. However, owing to limitations in social behavior, cost, product design, recycling technology, and separation thermodynamics, recycling processes are generally inefficient or non-existent. have proposed standards for the disposal and recycling of nano waste, including policies regulating nanotechnology, precautionary principles for developing NMs, and agreements to deal with potential threats to the environment, human health and well-being, the environment and biodiversity, marketing approaches, and safe disposal. In the near future, nanotechnology is expected to play an important role in emerging technologies. With the emergence and widening of their scope, the disposal of waste nanomaterials has become a difficult task. It requires a lot of research, awareness, and strategies for disposing of consumer waste, industrial recycling, profitability, policy development, and political will.

6. Environmental impacts of use of nanomaterials

Because of their unique properties, nanomaterial toxicity and their impact on the environment are still poorly understood [51]. The increasing use of nanomaterials in different consumer products and commercial purposes can increase the probability of nanomaterial introduction to human beings[52, 53]. An objection has also been raised regarding whether the production of nanomaterials may create additional problems. With respect to nanomaterials importance, both the positive and negative effects of

nanotechnology on the environment are described following.

1. Positive effects

Nanotechnology has many significant financial and environmental advantages. Nanomaterials can be used in airplanes as a replacement for traditional composites to minimize weight of aircraft, that can reduce consumption of fuel and can save thousands of barrels of it (table.1.). Additionally, nanomaterials are used in the manufacturing of wind turbine blades to reduce their weight and increase their efficiency. They are gradually being utilized in automobile exhaust systems and petroleum refining systems to stimulate chemical reactions, which help to minimize pollution. Scientists have gone to great lengths to develop carbon nanotube “scrubbers” to remove CO₂ from power plant emissions. In addition, scientists and engineers are developing wires with low resistance from carbon nanotubes, which will help reduce transmission power loss. NMs play a significant role in lowering manufacturing costs and enhancing solar panel efficiency, which produces energy safely and cleanly. NMs are being investigated for the conversion of waste heat from power plants and power stations. Computers into a usable source NMs have been applied successfully to purify water and air using techniques of oxidation, filtration, and adsorption with higher efficiency than traditional methods. Nanomaterials can be used to respond to polluting contaminants, leading to their conversion into non-toxic particles. NMs are resistant to contaminants that cause pollution and possess self-cleaning characteristics. NMs can detect contamination at low concentration. Nanomaterials can be utilized for precision production, which requires no large industrial facilities and produces less waste than conventional methods. Nanomaterial surface coatings can save cleaning agents, water, and energy owing to their self-cleaning properties. In addition, nanomaterials are being utilized to manufacture batteries that are more efficient and environmentally friendly. In addition, NMs can clean oil spills by breaking down oil into

biodegradable compounds. The positive impacts of nanomaterials are as follows:

Table.1. Positive impact of nanomaterials for environment and for CO₂

Lighter and stronger structure	Reduce fuel consumption Increase energy conversion
Boost chemical Reaction	Reduce pollution and expenses
Carbon dioxide isolation	Reduces greenhouse gases
Low resistance conductor	Increase power transmission efficiency
More efficient solar cell	Increase performance and reduce costs for solar energy generation
Self-Cleaning	Save water energy and cleaning agent
Precision manufacturing	Generation of less waste Reduce requirements of large industrial plants
Purification, filtration and oxidation	Reduce and control pollution Convert toxic into nontoxic
Disaster management	Cleaning up the oil spills

2. Negative effects

Because the environmental impacts of nanomaterials cannot be clearly determined and many parameters are involved (such as the identification of nanomaterials, low detection limits, and unknown environmental concentrations), it is difficult to draw conclusions regarding the ecological effects and environmental stability of nanomaterials. Even small changes in the nanoparticle structure can fundamentally alter their characteristics and make them toxic compounds. According to the U.S. Environmental Protection Agency, “nanomaterials toxicity is hard to determine because of their unique characteristics, high reactivity, and insolubility in liquids.” Because nanomaterials are highly reactive, their characteristics in environmental samples change between sample collection and analysis. In addition, it is difficult to determine the source of NMs in a sample. The ecological effects of silver sulfide (Ag₂S) nanoparticles have been studied. Therefore, it has been reported that plants, such as dicotyledonous cucumber and monocotyledonous wheat, can absorb nano-silver if nano-silver is present in the soil. The upregulation of genes (associated with the ethylene signaling pathway) due to the uptake of nanoparticles is accompanied by a decrease in

plant growth. In addition, NMs promote the upregulation of plant defense systems, which also helps reduce plant growth. Because most Ag₂S nanoparticles aggregate on the leaves of the tested plants, this phenomenon increases the chance of nutrient transfer from these structures through the food chain. Certain nanomaterials transfer (such as titanium dioxide) can also cause genotoxic effects (low dose of 0.25 mM), thereby destroying the DNA (high concentration) on plants (such as onions and tobacco) found that A level. We do not know the toxicity mechanism associated with nanoparticles. However, some groups claim that nanoparticle toxicity is mainly related to the dissolved substances or metals leached from nanomaterials. This fact is confirmed by testing nanoparticle toxicity under different conditions, such as nano ZnO with pH 4.5, nano ZnO with pH > 7, and nano ZnO used in Lemna minor [54]. It is also believed that the phytotoxicity of NMs is affected by the type of NMs, such as nano-Zn and nano-ZnO, which have negative effects on germination and ryegrass/cornseed growth, respectively. In contrast, the effects of multi-walled carbon nanotubes, aluminum, and alumina on seed germination and plant growth are negligible. Further Fig. 2 illustrates the negative impact of nanomaterials on environment.

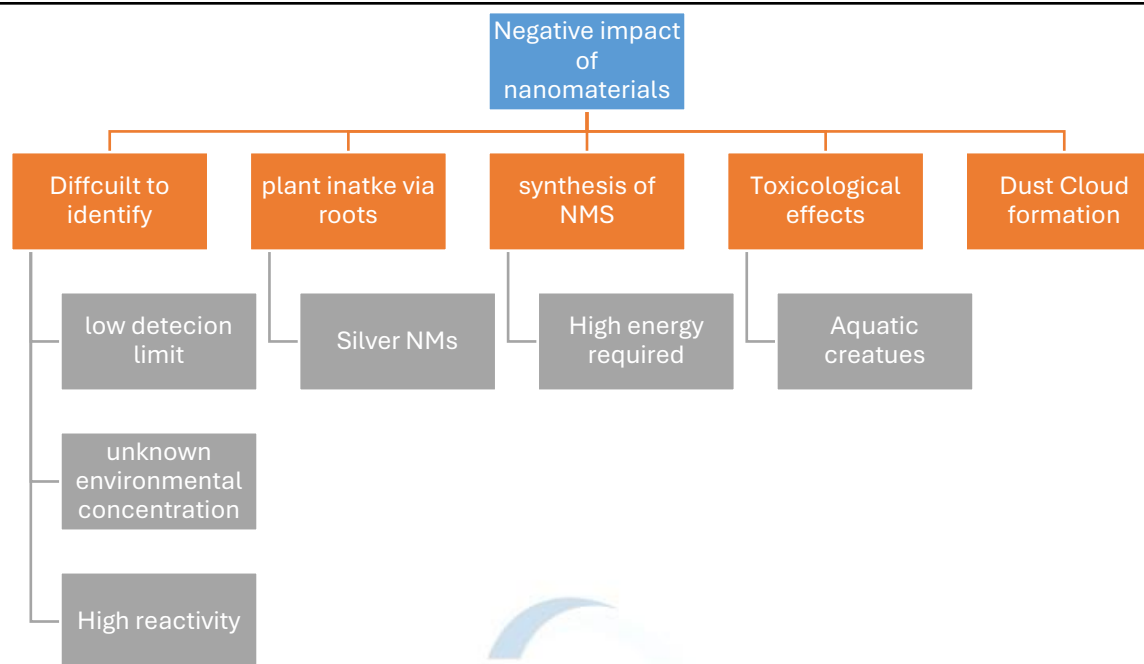


Fig.2. Negative impact of nanomaterials on environment

6. Conclusions

Nanomaterials have gained attention as potential solutions for addressing significant environmental issues related to greenhouse gas emissions, climate change, and global warming. Carbon dioxide (CO₂), among the various greenhouse gases, plays a significant role in the greenhouse effect, making it a primary focus for strategies aimed at reducing emissions and capturing and utilizing it. This review provides a critical analysis of recent progress in the use of nanomaterials for capturing, reducing, and converting CO₂ into valuable products. The discussion highlights the distinctive physicochemical properties of nanomaterials, such as their large surface area, adjustable surface chemistry, increased adsorption capacity, and catalytic properties, which make them appealing for CO₂ management.

Researchers and scientists should prioritize the creation, synthesis, and production of nanomaterials for CO₂ capture, aiming to enhance their environmental and technological advantages while reducing any potential adverse impacts. The development process for these materials must consider the entire life cycle, including the choice of safe and sustainable raw

materials, synthesis techniques, energy usage, CO₂ capture efficiency, regeneration needs, recyclability, stability, and disposal methods. Nanomaterials should be designed to offer a large surface area, effective and selective CO₂ adsorption, quick adsorption-desorption kinetics, and minimal energy requirements for regeneration. Simultaneously, issues such as nanoparticle release, toxicity, environmental persistence, secondary pollution, and energy-intensive production should be addressed through suitable surface functionalization, immobilization, recovery, and safe-by-design strategies. This approach allows for the enhancement of the beneficial properties of nanomaterials while mitigating their environmental and health risks, thereby promoting the development of efficient, sustainable, and environmentally responsible nanotechnology-based CO₂ capture systems.

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