Review Article

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Role of nanotechnology in climate change mitigation: Opportunities, challenges, and future directions

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Abstract

Climate change, recognized as one of the most critical global public health emergencies, has led to extreme weather events and caused thousands of deaths annually, particularly in underserved areas due to limited financial resources. Nanotechnology, with its unique quantum properties, enhanced surface area, and heightened reactivity, has emerged as a promising tool for climate crisis management. The aim of this study was to explore the role of nanotechnology in mitigating climate change, offering insights into the opportunities and challenges associated with its deployment. Nanotechnology has transformed the renewable energy field by advancing sustainability, improving efficiency, and reducing costs. Nanomaterial also enhances the effectiveness of carbon capture and conversion processes, providing a viable path in the fight against climate change. Additional opportunities include lowering greenhouse gas emissions, improving energy conservation, and enabling cleaner technologies. Furthermore, nanotechnology holds the potential to revolutionize the mitigation of air, water, and land pollution, contributing to a more climate-resilient environment and supporting global climate goals. Despite these opportunities, its integration into climate change mitigation poses significant obstacles. Concerns include the generation of reactive oxygen species that may induce cellular dysfunction and carcinogenesis, as well as challenges related to sophisticated manufacturing processes, high material costs, and inadequate policy frameworks. While nanotechnology demonstrates significant potential in mitigating the effects of climate change, future studies should focus on comprehensive safety evaluations, cost-effective production methods, and strategies to minimize long-term environmental and health effects to ensure its sustainable and responsible application.

Keywords: Nanotechnology, climate change, nanomaterials, energy efficiency, carbon capture

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Introduction

Climate change, one of the global health megatrends, stands as one of the most critical challenges of the 21st century, with far-reaching impacts on natural ecosystems, human societies, and economies. Over the past two centuries, anthropogenic activities, particularly the burning of fossil fuels, have contributed to a 1.1°C rise in global temperatures above pre-industrial levels, leading to an increase in the frequency and severity of extreme weather events such as droughts, hurricanes, and floods [1]. This crisis affects all facets of life, especially in low- and middle-income countries, where limited financial resources and infrastructure make it difficult to cope with the impacts of environmental degradation, food insecurity, and forced migration [2]. According to the World Health Organization (WHO, 2024), climate change is expected to contribute to an estimated 250,000 additional deaths annually between 2030 and 2050, due to malnutrition, malaria, diarrheal disease, and heat stress. Direct health costs are projected to reach US$2–4 billion per year by 2030. These projections emphasize the need for urgent, multi-sectoral strategies to limit global warming and build climate resilience.

In the search for sustainable solutions, nanotechnology has emerged as a powerful tool with unique properties that can be harnessed for climate change mitigation. Defined by the manipulation of materials at the nanoscale, nanotechnology offers properties such as increased surface area, reactivity, and unique quantum effects, which make it well-suited for applications in areas critical to climate mitigation [3]. These properties have positioned nanotechnology as a promising innovation across energy efficiency, renewable energy production, carbon capture, and environmental remediation. For instance, nano-enhanced photovoltaic (PV) cells have demonstrated significant improvements in energy conversion efficiency, with potential efficiency gains of up to 30% over conventional cells, a development that could play a crucial role in accelerating the adoption of solar energy [4]. Similarly, in wind energy, nanocoating has the ability to enhance the durability and performance of turbine blades, making wind energy more viable in a wide range of environmental conditions [4].

Beyond renewable energy applications, nanotechnology also shows significant promise in carbon capture and storage (CCS) technologies. In environmental remediation, nanomaterials are being applied to filter pollutants from air, water, and soil, addressing the contamination issues exacerbated by climate-induced changes in ecosystems. The aim of this study was to critically explore the role of nanotechnology in climate change mitigation, comparing major applications across energy, carbon management, and remediation pathways, while identifying associated challenges and research priorities.

Methods

The information for this analysis was obtained from peer-reviewed publications released between 2010 and 2024 across major scientific databases. Keywords utilized in the search strategy included combinations of the following terms: renewable energy, carbon capture, climate change mitigation, nanotechnology, environmental remediation, nanomaterials, and energy efficiency. Each article was evaluated for peer-review status, scientific rigor, and relevance of the articles, with priority given to articles published in high-impact journals and formal reports from international organizations such as the Intergovernmental Panel on Climate Change (IPCC), United Nations Environment Programme (UNEP), and WHO. This study is structured as a descriptive review supported by critical synthesis across thematic sections.

Nanotechnology in renewable energy

In the context of solar energy, critical parameters encompass the underlying photovoltaic technology, the light-absorption properties of the materials, charge transport dynamics, and overall efficiency. Incorporating nanomaterials into solar cell technology represents an increasingly prominent approach, providing innovative pathways to achieve higher conversion efficiencies and lower manufacturing costs. Such advances include Quantum dots (QDs), nanostructured materials, such as nanowires, nanotubes, nanorods, and Perovskite materials. The use of nanocrystals and QDs in PV cells enhances light absorption and electron mobility, leading to higher efficiency [5]. Nanotechnology facilitates the use of cheaper materials and manufacturing processes, which can lower the overall cost of solar PV systems [6]. It also contributes to the recyclability of PV materials, addressing concerns about material sustainability in solar energy production [7]. By improving energy efficiency, nanotechnology indirectly reduces greenhouse gas emissions associated with energy production [6].

Nanostructured thin-film solar cells improve efficiency through three mechanisms: extended optical paths via internal reflection, reduced electron-hole recombination due to shorter travel distances, and tunable band gaps for optimized light conversion. These thin-films can enhance light absorption and charge transport, leading to significant efficiency gains, with studies showing improvements of up to 56% in some cases. By precisely controlling nanostructures like nanopillars and nanowires, researchers can reduce light reflection, increase the path length of light within the active layer, and create more efficient pathways for electrons to move, thereby boosting overall solar cell performance [8-10]. QDs boost solar cell efficiency by using their tunable band gap to absorb a wider range of sunlight and by achieving Multiple Exciton Generation to produce more electrons from a single photon. Laboratory efficiencies for QD-sensitized cells have reached over 18% by 2022, with potential for higher theoretical limits, and their solution-based manufacturing could lead to lower costs than silicon [8,11,12]. Perovskite nanomaterials exhibit high performance in fuel cells and oxygen reduction reactions, demonstrating metrics such as high electrical conductivity, high surface area, low overpotentials, fast kinetics, high four-electron transfer efficiency, and good durability [13]. Recent advancements also include the development of environmentally-friendly lead-free perovskite nanocrystals, which show promise in photodetectors due to their water stability and luminescent properties [13,14].

Improved aerodynamics of wind turbines can be achieved by using nanomaterials such as graphene nanocomposites and carbon nanotubes, which lighten and strengthen blades. Carbon nanotube (CNT)-reinforced composites show promise for wind turbine blades, offering significant potential for weight reduction and increased tensile strength, though high material costs currently hinder widespread adoption compared to traditional composite materials. Studies have demonstrated properties like 20% weight reduction and improved mechanical performance with CNT reinforcement [15-17].

Nanocatalysts address key biofuel production barriers: CaO nanoparticles achieve 95% transesterification efficiency versus 80% for conventional catalysts [18,19], while Nickel oxide nanocatalysts reduce tar formation by 60% in biomass gasification. However, biofuel lifecycle emissions remain 40–70% of fossil fuels, limiting their climate mitigation potential compared to direct electrification [8,20,21]. Nanocatalysts improve biofuel production metrics: NiO nanoparticles reduce gasification tar by 60% while lowering operating temperatures from 800°C to 650°C [22], and Au-TiO_2 catalysts achieve 92% selectivity for HMF-to-biofuel conversion [23]. However, nano-enhanced biofuels face fundamental limitations: lifecycle emissions remain 50–70% of fossil fuels [24], production costs exceed $4/gallon, and land-use competition with food production persists [25]. These constraints suggest nanocatalysts offer incremental improvements rather than transformative climate solutions [8,26,27].

Nanotechnology in carbon capture and storage (CCS)

Nanomaterials play an important role in carbon capture technology, providing novel methods to reduce carbon emissions. From flue gas emissions and industrial processes, their features improve the effectiveness of carbon absorption and conversion processes, making them crucial in the fight against climate change. Several nanomaterials are known to have the ability to capture up to 70% more CO_2 than traditional materials, potentially reducing nearly 36 billion metric tons of CO_2 currently emitted worldwide each year [28]. Carbon nanomaterials such as nanostructured metals, carbon nanotubes, metal organic framework, graphene, and graphene oxides, among others, possess unique properties for electrochemical sensing, including large surface area and high surface-to-volume ratios, in addition to increased interfacial adsorption, leading to good electrocatalytic efficiency [29]. Carbon nanotubes, graphene oxides, and carbon aerogels are prominent for their high surface area and adsorption capacity [30]. Based on current research, the exact percentage of CO2 capture efficiency for carbon nanotubes, graphene oxides, and carbon aerogels varies widely. Capture efficiencies can range from moderate to over 90% depending on specific synthesis, functionalization, and operating conditions [31,32]. Carbon nanomaterials provide advantages such as biocompatibility and efficient electron transfer rates [33]. Nanomaterials use physical and chemical interactions to extract CO_2 from gas streams, far surpassing standard materials [34], which will aid in reducing greenhouse gas emissions through carbon capture and storage technology

Nanotechnology plays a critical role in improving carbon sequestration by developing nanoporous materials that provide significant benefits for safe carbon storage. Metal-organic frameworks (MOFs), zeolites, and nanoporous polymers offer highly variable pore shapes and vast surface areas, improving the capacity and durability of CO2 storage. Sulfur-Doped Porous Carbons (SDCs) demonstrate enhanced CO_2 uptake due to sulfur functionalities that increase surface reactivity and porosity, achieving up to 3.37 mmol/g at 0°C [35]. Moreover, nanosized zeolites, known for their high selectivity and thermal stability, serve as effective adsorbents, facilitating efficient CO_2 capture through adsorption and membrane separation processes [36]. Biomass-Derived Nanoporous Carbons (BNCs) with a high surface area of 3572 m^2/g, exhibit remarkable CO_2 adsorption capabilities, reaching 5.28 mmol/g at 1 bar [37]. Therefore, Nanoporous materials offer innovative solutions for carbon sequestration by securely storing CO2 through high surface area and tunable pore structures. These materials improve carbon storage stability, lower CO2 levels, and help mitigate climate change impacts.

Nanotechnology for energy efficiency

Sustainable development requires effective climate change mitigation, particularly through improved energy conservation. Building insulation represents a critical strategy for reducing heating and cooling demands. Within this context, nano-insulation materials (NIMs) have emerged as promising candidates for high-performance thermal insulation, owing largely to their engineered open or closed nanoporous structures that significantly limit heat transfer [38]. Building insulation based on nanomaterials is considered one of the most effective means of reducing energy consumption in the hot desert climate. The application of an energy-efficient insulation system can significantly decrease the energy consumed via a building's air-conditioning system during the summer. Hence, building insulation has become an interesting research topic, especially with regard to the use of insulation based on nanomaterials due to their low U-values [39]. Vacuum Insulation Panels (VIPs) can increase building energy efficiency by 8 to 10 times with very thin layers [40]. Aerogel materials such as Silica Aerogel, Carbon Aerogel, Polymer aerogels, metal Aerogels, and metal-oxide aerogel. Aerogel is a unique, ultralight material of superior thermal and acoustic insulation properties. Interestingly, Nanofiber composites can provide fire resistance, electromagnetic shielding, and recyclability, addressing multiple building insulation needs [41]. The incorporation of nanofibers enhances the mechanical strength of insulation materials, allowing them to withstand significant stress without deformation [42].

The development of nano-optical materials in light-emitting diodes (LEDs) represents a promising avenue for significantly reducing energy consumption in both residential and commercial lighting. By enhancing internal spontaneous emission rates and improving external light extraction efficiency, these materials contribute to superior luminous performance while minimizing energy demand. For instance, Ag nano hollow cylinders can increase internal spontaneous emission by a factor of 3.64 [43]. Carbon Nanostructures result in lower turn-on voltages and higher external quantum efficiencies, contributing to improved luminance across various colors [44].

Nanotechnology has improved the LED efficiency in providing nanophotonics and color conversion. The Resonant Photonic Architectures which enable the design of luminescent materials that serve as alternatives to traditional phosphors, enhancing color conversion in white LEDs. This integration allows for better light-matter interactions at the nanoscale [45]. Mesoscopic Structures, which are vertically integrated III-nitride nano-LEDs, have demonstrated extremely low power consumption, ranging from 2nW to 30nW, showcasing their potential for energy-saving applications [46]. For instance, a novel luminaire design using nano materials improved the efficacy of warm-white LEDs by 15%, leading to reduced energy requirements for the same light output. This advancement contributes to more energy-efficient lighting solutions [47].

Environmental remediation through nanotechnology

Nanoremediation is a key application in water treatment, where nanoscale engineered materials are used to address contaminants like dissolved organic compounds and heavy metals. While nanomaterials offer potential across all water treatment areas, conventional large-scale filtration remains dominant for removing suspended particles. Nanomaterials excel due to their high surface area and unique properties that enable efficient adsorption and catalytic degradation of pollutants in water [48]. Photocatalysis, driven by nanomaterials like titanium dioxide (TiO_2) and zinc oxide (ZnO), is a promising method for degrading organic pollutants and pathogens in water. Under UV light, these nanoparticles generate reactive oxygen species that break down contaminants into less harmful byproducts [48]. This technique has also been used to remove heavy metal impurities through a reduction process involving direct electron transfer from the catalyst to the dissolved metal ion. This is particularly easier for Cu^{2+}, Hg^{2+}, and the noble metals [48,49]. However, many common heavy metals, such as Pb^{2+}, Ni^{2+}, Cd^{2+}, Co^{2+}, and Zn^{2+}, are difficult to remove by photodeposition due to their highly negative reduction potentials and slow kinetic pathways, highlighting the need for more advanced research [50,51].

Furthermore, traditional filtration methods such as reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF) are greatly enhanced by nanomembranes, which solve typical problems including fouling and restricted permeability. Incorporating nanomaterials such as graphene oxide, carbon nanotubes (CNTs), and zeolites into polymeric or ceramic membranes significantly improves water flux and salt rejection [53]. Nanomaterial-based water treatment demonstrates laboratory advantages: graphene oxide membranes achieve 90% higher flux than conventional RO [54], other research has indicated that the water flux of GO membranes can be 4 to 10 times higher than most commercial nanofiltration membranes [55] , TiO_2 photocatalysis degrades 100% of organic pollutants [56] , and iron oxide nanoparticles adsorb heavy metals at a 492 mg/g capacity [57]. However, commercial deployment remains minimal due to cost barriers (nano-membranes: \$500/m^2 vs conventional: \$50/m^2), energy requirements (UV photocatalysis adds 2–3 kWh/m^3) [57,58]. The most widely used technology for direct air capture (DAC) of CO_2 involves amine-functionalized porous materials, which depend on amine-based chemisorption followed by a regeneration process. MOF adsorbents for DAC show improved selectivity but face the same fundamental cost barrier as amine systems (\$600–1000/ton CO_2 vs \$50–100/ton for point-source capture), limiting climate mitigation potential [60].

Moving forward, platinum, palladium, and cerium oxide nanoparticles are essential in catalytic converters for controlling automotive emissions. These advanced materials promote the oxidation of carbon monoxide (CO) into CO_2 and the reduction of nitrogen oxides (NO_x) into harmless nitrogen gas (N_2). Compared to conventional catalysts, nanocatalysts provide a larger surface area and higher catalytic activity, minimizing material usage while improving efficiency. Furthermore, innovations in nanostructured materials, such as single-walled carbon nanotubes (SWCNTs), demonstrate substantial potential for adsorbing methane and other greenhouse gases, thereby contributing to additional reductions in atmospheric emissions [61]. While some organic soil contaminants can be treated through bioremediation by indigenous microorganisms, others are resistant or recalcitrant, requiring engineered remediation methods to meet regulatory standards. Inorganic contaminants, on the other hand, typically heavy metal ions from industrial sources like Zn, Cr, Cu, Pb, As, Hg, Se, and U, do not naturally degrade and tend to persist in the environment over extended periods. As a redox-active material, Zerovalent iron (ZVI) can degrade various organic compounds and immobilize toxic heavy metals, preventing their leaching into groundwater. Nano-zerovalent iron (nZVI), a more advanced form of ZVI, is particularly effective for targeted treatment of high-concentration areas containing non-aqueous phase liquids (NAPLs), such as chlorinated hydrocarbons and heavy metals. Graphene oxide and CNTs exhibit high adsorption capacities for organic pollutants, facilitating their breakdown while maintaining low environmental toxicity, making them ideal for in-situ remediation. Additionally, nanoclays stabilize soils contaminated with hydrocarbons and reduce the mobility of heavy metals by adsorbing and encapsulating pollutants, improving soil structure, and minimizing dispersion [62].

Risks and challenges of nanotechnology in climate change mitigation

Despite the unique properties that distinguish nanomaterials from bulk materials and enable their applications in industries such as electronics, cosmetics, and medicine, they pose health risks due to interactions with biological systems. In particular, metal-based nanomaterials (NMs), such TiO_2 and silver nanoparticles (AgNPs), are well known for promoting the production of reactive oxygen species (ROS), leading to oxidative damage [63]. This damages lipids, proteins, and DNA, among other biological components, leading to inflammation and cellular dysfunction. Additionally, NMs can easily cross cellular membranes and collect inside tissues. This capability has raised significant concerns about their extended presence in the body, which could lead to mitochondrial damage, impaired cell function, and disruption of metabolic processes [64]. The interaction with genetic material is another potential health danger. Studies have shown that exposure to some types of NMs can cause DNA strand breakage and chromosomal abnormalities, increasing the risk of mutations and carcinogenesis [65].

Ecologically, NMs can attach to and interact with other environmental contaminants, and this could make ecological risk assessments more difficult. Silver and metal oxide nanoparticles, for instance, can transport other harmful compounds, changing their distribution and ecological effects [66]. NP buildup in water bodies may affect aquatic life. Research has demonstrated that in species such as fish, algae, and daphnia, oxidative stress and membrane disruption result in reduced growth rates, reproductive issues, and mortality [67]. NMs in soils can alter the development patterns and metabolic processes of plants and soil microorganisms. They may bioaccumulate in plants that absorb them, potentially leading to trophic transmission up the food chain [68]. Complex, multi-step procedures that require precise control over material properties like reactivity, surface area, and particle size are commonly used to create nanomaterials. Chemical vapor deposition, sol-gel processes, and molecular self-assembly processes require large energy inputs and specialized equipment [69]. Because of the complexity of these production processes—which not only limit the economically feasible quantity of materials but also increase costs—scaling nanotechnology applications for broader climate interventions remains challenging [70]. The price of raw materials is a major additional obstacle to scalability. Rare or expensive starting materials are required for many nanotechnology applications, especially for those that need carbon-based structures like complex metal oxides, fullerenes, and nanotubes, or quantum dots [71]. Furthermore, high-precision, energy-intensive techniques are typically used in the synthesis of nanoparticles, which significantly raises production costs. The viability of using nanotechnology at the scale required to affect global climate systems is further limited by these costs [72].

Another requirement for expanding nanotechnology is the seamless integration of nanomaterials into existing industrial and energy infrastructures, which requires significant retrofitting that would cause operational and financial challenges. For example, incorporating catalysts based on nanoparticles into carbon capture systems or coating solar panels with coatings reinforced by nanomaterials requires modifications that can be costly and challenging to implement on an industrial scale [73]. Additionally, the release of engineered nanomaterials (ENMs) into the environment necessitates stringent regulatory control and compliance processes due to the possibility of unforeseen ecological and health impacts [74]. Such regulatory frameworks can significantly increase operating costs for firms, since they need investments to monitor and manage emissions of nanoparticles during manufacture, use, and disposal. Moreover, technological constraints are known to challenge scalability. The properties of nanomaterials can change unexpectedly as they are produced at larger scales, from micro-scale laboratory studies to macro-scale industrial manufacturing. These variations in traits might affect the dependability and efficiency of nanotechnology applications, which might lead to issues with the effectiveness of climate interventions [75]. To overcome these limitations, standardized, scalable methods must be developed for manufacturing nanomaterials that maintain the appropriate properties without becoming unnecessarily expensive [76].

Reassessing nanotechnology adoption: deployment gaps and climate-scale impact

A stark reality that contradicts the "revolutionary potential" narrative common in nanotechnology literature is revealed in **Table 1**. Only perovskite solar cells demonstrate both technical maturity (TRL 7–8) and transformative climate impact potential measured in gigatons of CO_2 reduction annually. As illustrated in **Figure 1**, most nanotechnology applications fall into two categories: (1) commercially viable but climatically marginal (catalytic converters, LED efficiency), or (2) scientifically impressive but economically nonviable (carbon capture materials, advanced membranes).

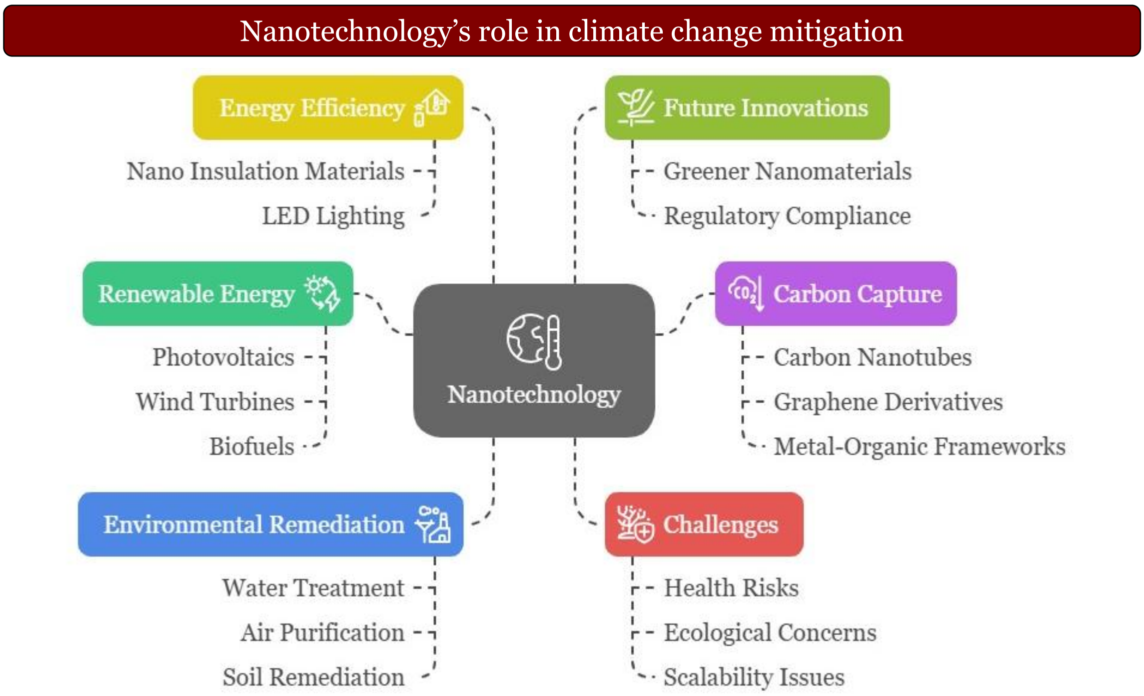

Figure 1. Cross-cutting barriers to nanotechnology climate solutions and the affected applications with respect to barriers.

The cost premium column is particularly revealing. Applications with <5× cost premiums (solar PV, catalytic converters) have achieved or are approaching commercialization, while those with 10–250× premiums (membranes, CCS materials) remain confined to laboratories despite decades of research. This suggests a critical threshold: nanotechnologies must reach cost parity or demonstrate extraordinary performance gains (>10×) to justify premiums above 5×.

Nanotechnology adoption is further limited by a series of systemic barriers, including economic, technical, regulatory, thermodynamic, and lifecycle barriers that hinder deployment across multiple applications (**Figure 2**). The tier structure makes explicit that promising laboratory results do not automatically translate into climate solutions. Tier 3 applications, despite receiving substantial research attention, face fundamental barriers such as thermodynamic limits for DAC and lifecycle emissions for biofuels that incremental improvements cannot overcome. The investment priority column reflects this reality: technologies should be prioritized based on deployment potential and climate impact, rather than scientific novelty (**Figure 3**).

Prospects and innovations

The impact of climate change is becoming increasingly alarming due to global warming and environmental degradation. It is crucial to switch from traditional practices that exacerbate pollution and global warming to more sustainable technologies [77]. One promising approach to combating climate change is nanotechnology, which provides creative substitutes.

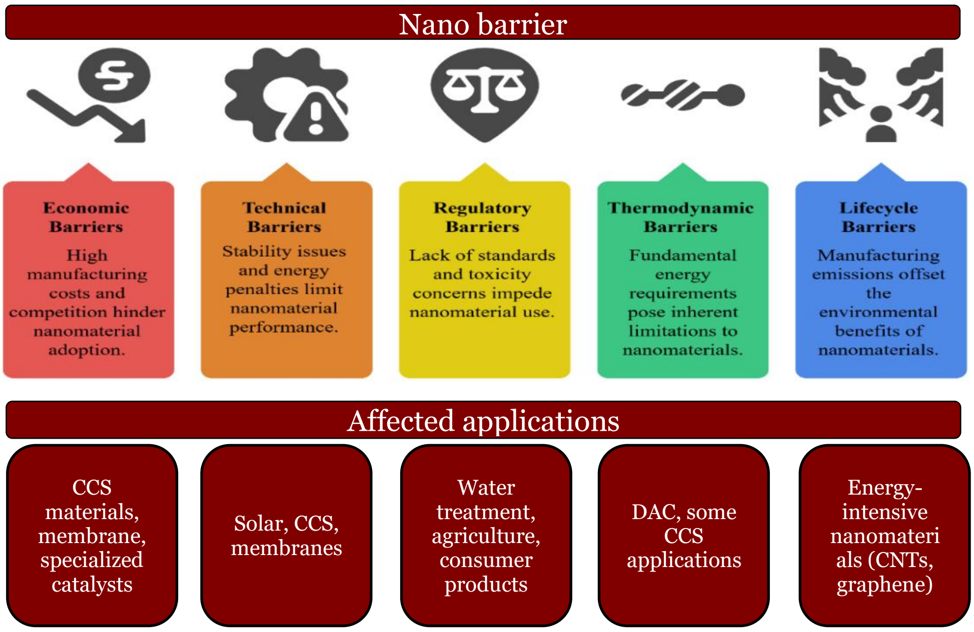

Figure 2. Role of nanotechnology in climate change mitigation.

Environmental protection has shown great promise for nanomaterials, including metal-organic frameworks (MOFs), carbonaceous materials, nanozeolites, nanosilica, nanosensors, nanocoatings, nanolubricants, nanometals, nanocatalysts, nanopackaging, and nanocomposites. Applications in bioenergy, wastewater treatment, environmental remediation, greenhouse gas sequestration, and sustainable materials are made possible by their special qualities [78].

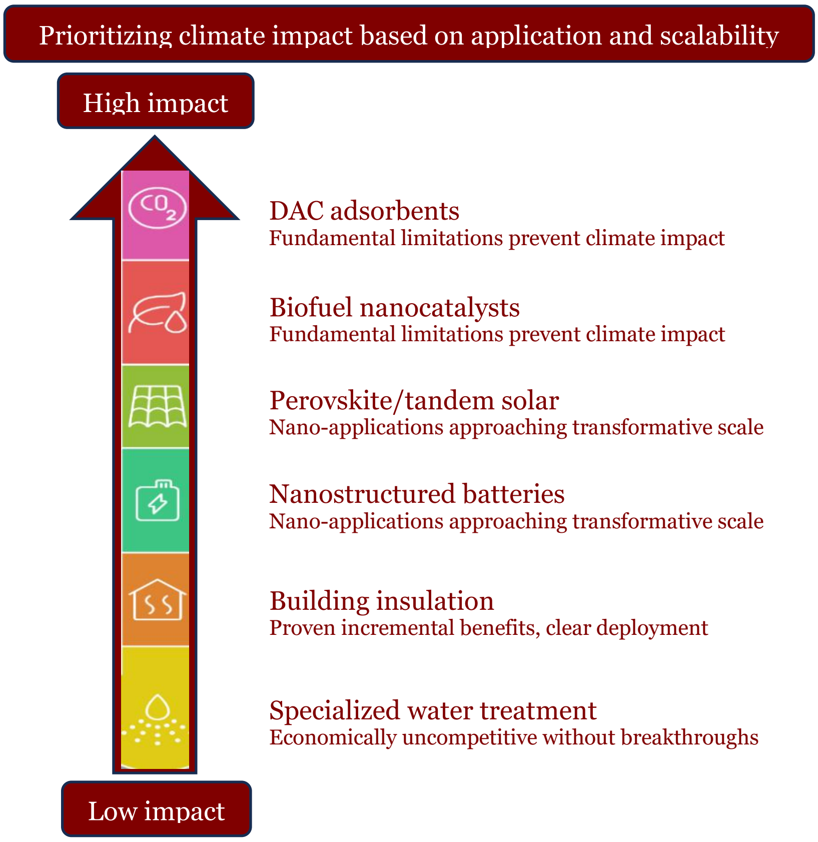

Figure 3. Recommended research and investment priorities.

Nanotechnology and nanobiotechnology are emerging technologies that offer innovative solutions to environmental challenges, such as wastewater treatment, greenhouse gas emissions, fuel crises, and pollutant remediation (**Table 2**). These technologies leverage the unique properties of nanoscale materials, such as enhanced surface areas and reactivity, to provide efficient and sustainable environmental applications [79].

Environmental nanotechnology (E-nano) focuses on developing nanoscale tools and processes for remediation, such as removing heavy metals and pollutants from wastewater to address global water scarcity. Traditional water treatment methods are reaching their limits, necessitating the adoption of advanced nanotechnology-based techniques such as adsorption, membrane separation, photocatalysis, and nanoscale sensing. These methods effectively treat contaminants, ensuring clean, potable water while reducing environmental impact. The role of nanotechnology in ecological protection highlights its potential as a next-generation tool in mitigating climate change, promoting sustainability, and addressing global environmental challenges [80].

Nanomaterials are a promising solution for environmental remediation, but their potential to accumulate in the environment and food chain raises safety concerns. Sustainable technologies must be developed to harness the benefits of NMs while minimizing risks. Transitioning from chemically synthesized NMs to green-based and polymer-modified alternatives is essential, as they offer improved efficiency and reduced environmental impact [81]. Supporting materials like plant waste, bone char, and fly ash can enhance NM performance by providing cost-effective, readily available absorbents. Future directions should focus on coating NMs with surfactants to optimize pollutant targeting and ensure their decomposition post-remediation. Strategic evaluation of environmental and health impacts, cost, and operational efficiency is crucial. By advancing sustainable, efficient, and eco-safe nanomaterials, their potential in combating climate change can be fully realized while safeguarding human and environmental health [82].

Nanotechnology has become an important tool in the agricultural, environmental, and public health sectors, offering diverse solutions to mitigating the effects of climate change. These advancements support sustainable practices and contribute to long-term climate change mitigation [83]. The rapid growth of nanotechnology necessitates robust regulatory frameworks to ensure safe and sustainable applications of NMs, while mitigating potential health and environmental risks.

Global regulatory bodies have established frameworks to govern the use of nanotechnology in agriculture, with the Environmental Protection Agency (EPA) and United States Department of Agriculture (USDA) overseeing pesticides and agricultural biotechnology in the USA, and the European Chemicals Agency (ECHA) and European Food Safety Authority (EFSA) in the European Union. Key regulatory measures include mandatory risk assessments and labelling requirements to ensure consumer awareness. International standards, such as those by the International Organization for Standardization (ISO), provide consistent definitions and guidelines for nanomaterials. Continued research and development are encouraged to advance safe and effective nanotechnology-based agri-products, fostering innovation while minimizing potential risks.

Integrating nanotechnology in agriculture, governed by stringent safety standards and collaborative efforts among stakeholders, presents significant opportunities for climate change mitigation [84]. Organizations like the WHO, United Nations Environmental Program (UNEP), and United Nations Institute for Training and Research (UNITAR) have taken significant steps to develop guidelines and build capacity in environmental governance [85,86]. These guidelines aim to protect workers handling NMs and align with Sustainable Development Goals (SDGs). At the same time, the UNEP and the United Nations Institute for Training and Research (UNITAR) have created training programs and resources to enhance awareness and regulatory compliance for nanotechnology.

Table 1. Critical comparative assessment of nanotechnologies for climate change mitigation

Application	Key nanomaterials	Performance vs conventional	Current cost premium	TRL	Deployment status	Primary barriers	Climate impact potential	Investment priority
Tier 1: Near-term viable								
Solar PV (perovskite/QD)	Perovskite nanocrystals, quantum dots	30% efficiency vs 20–22% silicon	Approaching parity	7–8	Pilot production, early commercial	Stability (<25 yr), lead toxicity	High: multi-$GtCO_2$/yr reduction potential	High
Catalytic converters	Pt-Pd nanoparticles, core-shell structures	15–20% precious metal reduction; 2% efficiency loss after 20k cycles	-$50–100/vehicle (savings)	9	Commercial	Limited by EV transition	Low: incremental only	Low
Building insulation	Aerogels, VIPs, nanofibers	8–10× thermal resistance	$20-40/m² vs $2-5/m² (4–20×)	7–8	Growing niche market	Brittleness, moisture sensitivity, cost	Medium: 30–40% building energy reduction	Medium
Tier 2: Medium-term (major barriers)								
Carbon capture (point source)	MOFs, graphene oxide, CNTs, nanoporous carbons	5.28 mmol/g vs 2.1 mmol/g zeolite; 70% more CO_2 captured	$300–500/kg vs $2/kg (150–250×)	4–5	Laboratory/bench scale	Cost, stability (50–100 cycles), regeneration energy (40–50% penalty)	Medium (if cost solved): could enable CCS at scale	LOW (until 10× cost reduction)
Water treatment (membranes)	Graphene oxide, CNTs, TiO_2	90% higher flux; 85–95% pollutant removal	$500/m² vs $50/m² membranes (10×); $0.50–1.20/m³ vs $0.20-0.40/m³	5–6	<1% market share	Cost, energy (+2–3 kWh/m³), regulatory uncertainty	Minimal: water treatment <1% global energy	Low
Wind turbine coatings	Graphene nanocomposites, CNTs, TiO_2 nanocoatings	15% weight reduction, 23% tensile strength increase	3–4× material cost	6–7	Emerging commercial	Cost-benefit marginal at scale	Low-medium: incremental efficiency gains	Medium
LED efficiency	Nano-optical materials, carbon nanostructures	15% efficacy improvement; 3.64× spontaneous emission	Near competitive	8–9	Commercial	Already mature market	Low: lighting ~6% global electricity	Low
Tier 3: Long-term/speculative								
Biofuel production	Ni-oxide, CaO, Au-TiO_2 nanocatalysts	95% vs 80% transesterification; 60% tar reduction	>$4/gal vs <$3/gal gasoline	3–4	Laboratory	Lifecycle emissions 50–70% of fossil fuels; land competition; thermodynamic limits	Very low: fundamentally carbon-positive	Very low

Application	Key nanomaterials	Performance vs conventional	Current cost premium	TRL	Deployment status	Primary barriers	Climate impact potential	Investment priority
Direct air capture	MOF adsorbents	Improved selectivity vs amines	\$600–1000/ton CO_2 vs \$50–100/ton point-source	3–4	Demonstration only	Thermodynamic minimum 8-10 GJ/ton; requires energy <\$0.01/kWh (currently \$0.03–0.05/kWh)	Minimal: economically implausible at climate-relevant scale (Gt/yr)	Very low
Soil remediation	nZVI, nanoclays, graphene oxide	60–80% heavy metal immobilization	Unknown (site-specific)	3–5	Pilot demonstrations	Subsurface mobility, long-term stability, ecotoxicity unknown	None: public health benefit, not climate	N/A
Air filtration (particulate)	TiO_2, Ag, activated carbon nanoparticles	Enhanced PM2.5 capture	2–5× filter cost	7–8	Commercial (indoor/auto)	Marginal benefit over HEPA	None: air quality, not climate	N/A

Table 2. Nanomaterials application in climate change mitigation

Mitigation mechanism	Nanomaterial type	Specific materials	Application	Performance metrics	Reference
CO_2 capture and adsorption	2D Materials + ionic liquids	Graphene, Nitrogenized Graphene (C_3N) with IL coating	Interface-enhanced CO_2 capture	Enhanced accumulation at IL-gas interface	[2,15,16,20]
	Carbon nanostructures	SWCNTs, MWCNTs-APTS	Gas adsorption systems	67% CO_2 deconcentration	[17,18]
	Doped carbon materials	Transition metal-doped graphene, CNTs, fullerenes	Pollutant gas adsorption	Superior CO_2 vs other gases	[3,18]
Photocatalytic CO_2 conversion	Semiconductor nanoparticles	Quantum dots, Metal oxides	Solar-driven CO_2 reduction	Products: CH_4, CH_3OH, HCHO, HCOOH	[4,8,9,10]
	2D materials	Graphitic carbon nitride (g-C_3N_4)	Photocatalytic conversion	Tunable band gaps	[4,8]
	Modified semiconductors	Surface-functionalized, co-catalyst deposited	Enhanced photocatalysis	Reduced charge recombination	[4]
Energy storage and conversion	Battery electrodes	Nanostructured electrode materials	Lithium batteries, supercapacitors	Large surface area, high conductivity	[5]
	Hydrogen storage	Nanostructured materials	Hydrogen storage systems	High storage capacity	[5]
	thermal storage	Nanomaterials for thermal energy	Heat storage applications	Enhanced thermal properties	[5]
	metal-CO_2 batteries	Unconventional phase nanomaterials	Energy storage + CO_2 utilization	83.8% energy efficiency boost	[6]
Fuel cell technology	Core-shell nanoparticles	Cobalt-doped Pt-Pd nanoparticles	PEMFC catalysts	2% efficiency loss after 20,000 cycles	[7,8]
	Alloy nanomaterials	Pt-transition metal alloys	ORR catalysts	Reduced Pt dependency	[7,8]
Agricultural applications	Delivery systems	Nano fertilizers, nano pesticides	Precision agriculture	Reduced application rates	[1,64]
	Protective coatings	Nano coatings	Crop protection	Enhanced efficiency	[1]
	Fuel additives	Nano-blended fuels	Agricultural machinery	Improved combustion	[1]
Environmental monitoring	Sensing materials	Nano sensors	GHG emission detection	Real-time monitoring	[1]
	Catalytic materials	Nano catalysts	Emission reduction	Enhanced reaction rates	[1]

Emerging regulatory frameworks, such as those proposed by the United States and European nations, can be horizontal (cross-sector) or vertical (sector-specific) and can be mandatory or voluntary. However, harmonizing global standards remains challenging due to differences in regulatory approaches and varying socio-economic priorities. Future efforts must address issues like nomenclature, toxicological evaluation, traceability, and consumer awareness. Developing comprehensive frameworks that balance flexibility and control is critical for fostering innovation while ensuring health and environmental safety [87,88].

Conclusion

As climate change continues to impact societies worldwide, nanotechnology has emerged as a promising tool for mitigation, particularly in low- and middle-income countries. Nanomaterials enhance energy efficiency, renewable energy production, carbon capture, and environmental remediation, while reducing air, water, and soil pollution. Their high surface area, tunable properties, and catalytic activity offer advantages over traditional approaches, enabling applications such as advanced fuel cells, photocatalytic CO_2 conversion, interface-enhanced CO_2 capture, and energy storage systems. Agricultural applications further contribute to reducing emissions from major greenhouse gas sources.

Despite these opportunities, challenges remain, including manufacturing costs, scalability, material stability, and potential health and environmental risks. Translating laboratory advances into practical solutions will require scalable synthesis methods, lifecycle assessments, and multifunctional nanomaterials optimized for specific mitigation strategies. Regulatory frameworks, risk assessments, and interdisciplinary collaboration with governments and policymakers are essential to ensure safe and effective deployment. With continued research and responsible governance, nanotechnology can play a pivotal role in global climate change mitigation.

Ethics approval

Not required.

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Competing interests

All authors declare that there is no conflict of interest regarding this manuscript.

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Underlying data

Data underlying this study can be requested from the corresponding authors upon reasonable request.

Declaration of artificial intelligence use

This study used Napkin AI in image generation. We confirm that all AI-assisted processes were critically reviewed by the authors to ensure the integrity and reliability of the results. The final decisions and interpretations presented in this article were solely made by the authors.

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