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Prospects of Nanotechnology to Mitigate Global Challenges of Climate Change and Public Health

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Abstract:

Nanotechnology holds immense promise in mitigating the intertwined global challenges of climate change and public health by offering high-efficiency nanomaterials that enable innovative, efficient, and often sustainable solutions. Climate change, acknowledged as one of the most critical global public health crises, has led to extreme weather events and caused thousands of deaths annually, particularly in economically deprived areas. There is a significant increase in global warming due to human intervention and the uncontrolled use of technology in all areas of life. Climate change also increases the occurrence and transmission of pathogens that pose a threat to human life. Extreme heat can cause a variety of illnesses, including cardiovascular events. Temperature and seasonal variations raise the danger of waterborne illnesses and can introduce new diseases to large regions. Eco-friendly and effective methods, materials, and procedures are needed to reduce and manage climate change and its health effects. This review addresses recent developments in nanotechnology with potential benefits to combat climate change and public health. Despite several advantages, there are still significant obstacles to its use into public health and climate change mitigation. Although nanotechnology shows great promise in reducing the negative health effects of climate change, more research should be done on thorough safety assessments, economical production techniques, and ways to reduce long-term environmental and health impacts to guarantee its responsible and sustainable use.

Keywords: Nanotechnology, Nanomaterials, Climate change, Public health, Global challenge.

INTRODUCTION

The main cause of the global climate shift is anthropogenic activities, which has intensified during the past 200 years. This has led to changes in the severity and frequency of meteorological conditions, as well as an increase in the global average temperature (global warming) and atmospheric CO_2 concentration (Change, 2014; Fischer and Knutti, 2015). The world is now dealing with the negative effects of climate change, and it may experience a major crisis in the future that will impact all life forms. Since global warming is the main contributor to climate change, it must be tackled right away and given careful consideration (Feigin *et al.*, 2023; Masson-Delmotte *et al.*, 2018).

Nanotechnology has become a potent tool with special qualities that can be used to mitigate climate change in the quest for sustainable solutions. Nanotechnology, which is defined by the manipulation of materials at the nanoscale, has qualities including reactivity, enhanced surface area, and special quantum effects that make it ideal for use in fields that are crucial to mitigating the consequences of climate change (Malik *et al.*, 2023b). Nanotechnology has emerged as a promising innovation in the fields of carbon capture, energy efficiency, renewable energy production, and environmental remediation because to these characteristics. For example, energy conversion efficiency has been shown to increase significantly with nano-enhanced photovoltaic (PV) cells, potentially increasing by up to 30% over conventional cells. This research could be vital in hastening the adoption of solar energy (Jones *et al.*, 2024). Nanotechnology has great potential for use in carbon capture and storage (CCS) technologies in addition to renewable energy applications. Nanomaterials are being used in environmental remediation to filter contaminants from soil, water, and air, resolving contamination problems made worse by ecosystem changes brought on by climate change (Musa *et al.*, 2025).

Nanotechnology is increasingly being exploited for medical purposes and is of significant interest in eliminating or limiting the activity of various pathogens. The role of nanotechnology has been rapidly increasing in the current decades (Matharu *et al.*, 2018). Conventional medical devices that are connected to a patient are being transformed into intelligent systems for ongoing assessment and prompt critical care decision-making by the advent of nanoscience and nanotechnology. Measuring the biomarkers of illness (nucleic acids, antibodies, proteins, and cells) present in tissue or bodily fluids in deviant amounts when illness arises is essential to improving the prognosis of patients (Wishart *et al.*, 2021). The identification of pathogens is required for early diagnosis of an infection. Even though infections are often difficult to diagnose, especially in very ill patients, the excessive use of medications has increased the level of resistance to antibiotics (Ashraf and Iqbal, 2021; Ashraf *et al.*, 2020; Iqbal and Ashraf, 2021; Martin-Loeches *et al.*, 2013). In order to establish a foundation and facilitate comprehension and appreciation of this rapidly developing and crucial field of science, it is imperative that basic nanotechnology principles be introduced in an approachable manner, accompanied by examples of contemporary clinical infectious diseases and public health applications (Chen *et al.*, 2023).

Nanotechnology has emerged as a key instrument in the agricultural, environmental, and public health sectors, offering a variety of options to mitigate the consequences of climate change. These developments encourage sustainable practices and help mitigate climate change over the long term (Khot *et al.*, 2012). The rapid development of nanotechnology calls for strong regulatory frameworks to guarantee the safe and sustainable use of NMs while reducing possible dangers to human health and the environment. The aim of this review was to critically explore the role of nanotechnology in climate change and public health mitigation, comparing major applications across various pathways, while identifying associated challenges and research priorities.

Climate Change and Public Health

Human induced climate change and the wide array of problems directly caused by it is the greatest threat to human health globally (Atwoli *et al.*, 2021). Globally, governments are working to mitigate the consequences of climate change and control its aftermath; nevertheless, the majority of tactics and plans that are put into action have lengthy timescales. However, since the effects of climate change are already apparent, it is necessary to evaluate and enhance the way climate change policies are being implemented (Change, 2013). There is currently a lack of literature on the implications of climate change on public health and the measures taken to control these hazards (Romanello *et al.*, 2023). The effects of human-induced climate change have been extensively studied, but only a small portion of the research being conducted has examined the direct and indirect connections between public health and climate change. There is no clear-cut explanation for this, but one theory is that funding for studies of the more immediate implications of climate change has been higher. Research on the subject has grown over time (Organization, 2021).

Climate change disproportionately affects the underprivileged populations and developing countries, exacerbating prevailing inequalities and posing substantial challenges to their health and well-being (Eckstein *et al.*, 2021). It exacerbates respiratory conditions and raises air pollution levels, which jeopardises access to clean air (Doherty *et al.*, 2017). Sources of safe drinking water are in danger because of contamination, floods, and droughts. The disruption of agricultural output due to shifting precipitation patterns and temperatures puts food security at risk by causing undernutrition and malnutrition. Additionally, food-borne and water-borne diseases can spread more easily in warmer climates (Hatfield *et al.*, 2011). It creates new difficulties for managing and stopping the spread of infectious diseases. Variations in temperature and precipitation patterns impact the geographic distribution and occurrence of vector-borne illnesses, subjecting host populations to extended and more severe seasons of transmission. Among the many negative effects of climate change on humanity, the impact on mental health is one that is frequently disregarded. Extreme weather events like storms and floods also put people at risk for inadequate shelter because they destroy infrastructure and force people to relocate (Black *et al.*, 2013). Climate change-related environmental deterioration, resource shortages, and economic upheavals can impair healthcare access, interfere with public health systems, and worsen already-existing health inequities (Vaidya *et al.*, 2024).

Nanotechnology has a direct positive impact on public health when used to combat climate change. For instance, decreased greenhouse gas emissions result in less air pollution and fewer respiratory illnesses, while crop nutrients boosted by nanotechnology increase agricultural resilience to climate change, enhancing nutrition and food security (Bahrami *et al.*, 2026).

Nanotechnology for Climate Change Mitigation

The term "climate change" describes notable, long-term statistical changes in climatic variables that affect delicate elements including wind, humidity, precipitation patterns, and temperature extremes (McMichael, 2013). The core of climate change is the alteration of weather patterns over long timescales, usually decades to millions of years, which can include variations in temperature, precipitation, and other climate-related factors. The higher concentration of greenhouse gases in the atmosphere, which trap heat and cause global warming, is primarily to blame for this change (Bhattacharya, 2019; Connors *et al.*, 2025). Climate change, driven primarily by greenhouse gas (GHG) emissions (especially CO_2 from fossil fuels), demands transformative technologies for mitigation (Kotru *et al.*, 2025). Nanomaterials such as metal-organic frameworks (MOFs), carbonaceous structures, nanocomposites, and nanocatalysts offer sustainable means of reducing emissions, improving energy efficiency, and repairing environmental damage (Chausali *et al.*, 2023). Nanotechnology provides high-impact opportunities for climate change solutions as illustrated in figure (1).

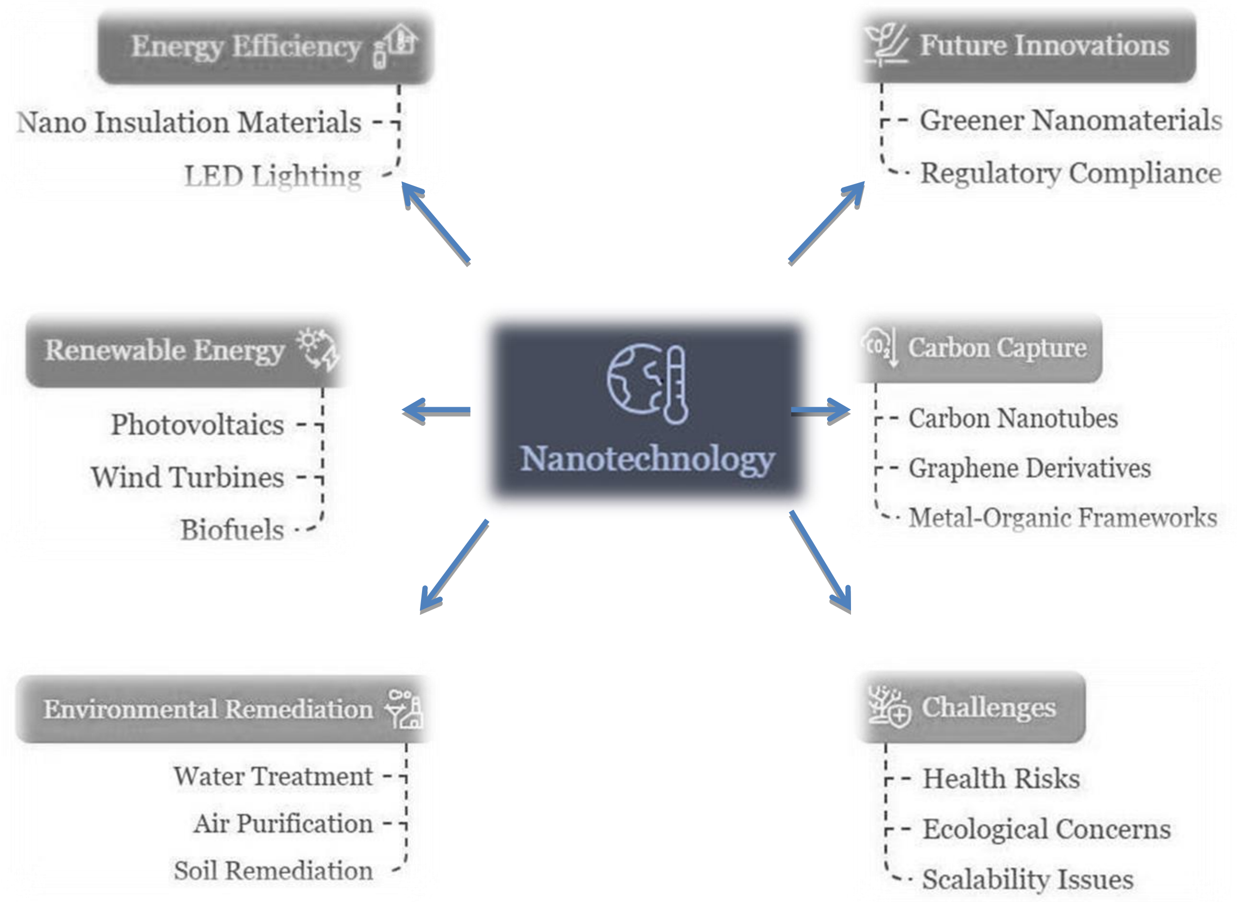

Fig. 1. Cross-cutting obstacles to climate solutions using nanotechnology and the impacted applications in relation to these barriers (Musa *et al.*, 2025).

Greenhouse carbon capture and storage (CCS)

Nanomaterials are crucial to carbon capture technology because they offer new ways to cut carbon emissions. Their characteristics increase the efficiency of carbon absorption and conversion processes from flue gas emissions and industrial processes, making them essential in the fight against climate change (Ibrahim *et al.*, 2016). Carbon nanostructures offer benefits including effective electron transfer rates and biocompatibility (Yang *et al.*, 2013). Nanomaterials significantly outperform conventional materials in their ability to remove CO_2 from gas streams through physical and chemical interactions (Alguacil, 2023), which will help lower greenhouse gas emissions through carbon capture and storage technology.

Nanotechnology plays a crucial role in enhancing carbon sequestration through the development of nanoporous materials, which offer substantial advantages for secure carbon storage. Nanoporous materials e.g. Biomass-Derived Nanoporous Carbons (BNCs) provide effective carbon sequestration solutions by safely storing CO_2 due their large surface area and adjustable pore architectures. These substances strengthen the stability of carbon storage, reduce CO_2 concentrations, and mitigate the effects of climate change (Musa *et al.*, 2025).

Energy efficiency

Effective climate change mitigation is essential for sustainable growth, especially through increased energy efficiency. Insulating buildings is a crucial tactic for lowering the need for heating and cooling. Nano-insulation materials (NIMs) have become attractive options for high-performance thermal insulation in this context, primarily because of their tailored open or closed nanoporous architectures that drastically reduce heat transfer (Kalnæs and Jelle, 2014). Vacuum Insulation Panels (VIPs) can boost building energy efficiency by 8–10 times using very thin layers (Elbony and Sedhom, 2022). Aerogel materials include metal aerogels, metal-oxide aerogels, silica aerogels, carbon aerogels, and polymer aerogels. One special substance with exceptional thermal and acoustic insulation qualities is aerogel, which is incredibly light. It's interesting to note that nanofiber composites can answer certain building insulation requirements by offering recyclability, fire resistance, and electromagnetic shielding (Lv *et al.*, 2024). Insulation materials may tolerate high levels of stress without deforming when nanofibers are added because they increase their mechanical strength (Xu *et al.*, 2024). Nanotechnology has improved the light-emitting diodes (LEDs) efficiency in providing nanophotonics and color conversion (Galisteo-López and Lozano, 2021), and contributed to more energy-efficient lighting solutions (Bi *et al.*, 2015).

Environmental remediation

Nanoremediation is a crucial process that uses materials created at the nanoscale to remove contaminants such as heavy metals and dissolved organic molecules in water treatment. Although there is promise for nanoparticles in every aspect of water treatment, traditional large-scale filtration is still the most common method for eliminating suspended particles. Nanomaterials are excellent because of their large surface area and special characteristics that allow for the effective adsorption and catalytic breakdown of contaminants in water (Linley and Thomson, 2021). Nanomaterial-driven photo-catalysis is a potential technique for breaking down organic contaminants and pathogens in water. These nanoparticles produce reactive oxygen species, which convert pollutants into less dangerous by-products under ultraviolet light exposure (Linley and Thomson, 2021; Zarzzeka *et al.*, 2024). Although nanomaterials show promise in environmental clean-up, there are safety issues due to their ability to accumulate in the environment and food chain. The development of sustainable technologies is necessary to maximise the advantages of NMs while reducing their hazards. Since green-based and polymer-modified NMs offer greater efficiency and a smaller environmental effect than chemically synthesised ones, it is imperative to switch to these alternatives (Visa, 2016). It is essential to strategically assess the effects on the environment and human health as well as operational efficiency and cost. The potential of sustainable, effective, and environmentally safe nanomaterials to mitigate climate change while preserving human and environmental health can be fully realised (Asghar *et al.*, 2024).

Sustainable Agriculture

In recent years, there has been an increase in the application of nanotechnology in sustainable agriculture. It has a number of uses in agriculture, including the creation of nanoscale tools and materials to increase agricultural output, improve food safety and quality, increase water and nutrient efficiency, and lessen pollution in the environment. This area has benefited greatly from nanotechnology, especially in the creation of nanoscale delivery systems for agrochemicals like growth regulators, fertilizers, and insecticides. These nanoscale delivery technologies are superior to traditional delivery methods in a number of ways, such as improved efficacy, reduced environmental impact, and improved penetration and distribution (Ashraf *et al.*, 2025; Shukla *et al.*, 2024). The use of nanoparticle formulations, including nano-pesticides, nano-herbicides, nano-fertilizers, and nano-emulsions, has been extensively studied to improve crop health and shelf-life of agricultural products (Ashraf *et al.*, 2025; Quintarelli *et al.*, 2024).

Nanotechnology for Public Health Challenges

Public health faces threats amplified by climate change, including heat-related illnesses, vector-borne and fungal diseases, respiratory issues from pollution, and infectious disease spread (Singh *et al.*, 2024b). These threats affect different populations differently depending on exposure and vulnerability. The global disruption of social dynamics, including socioeconomic status, public health infrastructure, and health status, is indicative of this consequence (Abdul-Nabi *et al.*, 2025; Iqbal, 2021). Planetary ecosystems and global health are facing significant problems due to the rapid advancements in technology, industry, and research. A crucial paradigm for resolving these problems and a key component of sustainability in the future is the One Health concept, which emphasises the inherent relationships between human health, animal health, and their shared ecosystems (Hernando-Amado *et al.*, 2019).

Nanotechnology has the potential to completely transform healthcare by providing previously unheard-of possibilities in drug delivery, cancer treatment, infectious disease prevention, and diagnostics (Durgam and Oroszi, 2025). The distinct characteristics of nanomaterials create opportunities for a wide range of applications and have enormous potential for revolutionary breakthroughs in a number of scientific and technological fields (Baig *et al.*, 2021). In recent years, nanotechnology has become a disruptive force in the healthcare industry, providing unparalleled opportunities to improve the functionality and uses of medical equipment as well as ongoing innovation in medicine development (Parvin *et al.*, 2025). Nanoscale manipulation of matter has opened the door to ground-breaking discoveries that could lead to significant improvements in patient care, treatment approaches, and diagnostics. Particular fields showcasing the promise of nanotechnology in healthcare include medical diagnostics, where nanomaterials are employed to enhance the precision and sensitivity of biosensing and imaging methods, allowing for the earlier and more accurate identification of illnesses (Barbosa *et al.*, 2021; Singh and Amiji, 2022). Despite the enormous promise, there are now many obstacles to overcome in the technical and intricate world of regulatory laws for the use of nanotechnology in medicines and medical devices (Ali *et al.*, 2023; Kumah *et al.*, 2023).

Healthcare applications of nanotechnology

The science of nanotechnology has shown great promise for developing a wide range of biological and health care applications. Nanotechnology, involving the manipulation of materials at the nanoscale (1-100 nm), has transformed healthcare through nanomedicine, enabling precise diagnostics, therapies, and regenerative solutions. Applications include targeted drug systems that reduce adverse effects and increase efficacy, as well as better imaging and biosensors (Ma *et al.*, 2024). Several main-stream applications of nanotechnology in recent years are mentioned in Figure (2).

Medical diagnostics and imaging

Early intervention in public health emergencies is facilitated by the quick and sensitive detection of viruses, contaminants, or biomarkers via nano-enhanced sensors and imaging (such as quantum dots and gold nanoparticles). Through nanomaterials that enhance imaging modalities and biosensors, nanotechnology improves diagnostic speed, sensitivity, and accuracy. For example, gold nanoparticles (Au NPs) cluster in tumours for CT evaluation, while superparamagnetic iron oxide nanoparticles (SPIONs) act as contrast agents in MRI for tumour tracking and cell imaging (Ma *et al.*, 2024). Near-infrared fluorescence is made possible by quantum dots (QDs) for incredibly quick biological visualisation, and biosensors such as glycan-blotted field-effect transistors are capable of attomolar virus detection. Nanoparticles help in the quick identification of genetic disorders, malignancies, and infectious diseases in point-of-care testing with nanopore sequencing and microfluidic equipment (Malik *et al.*, 2023a).

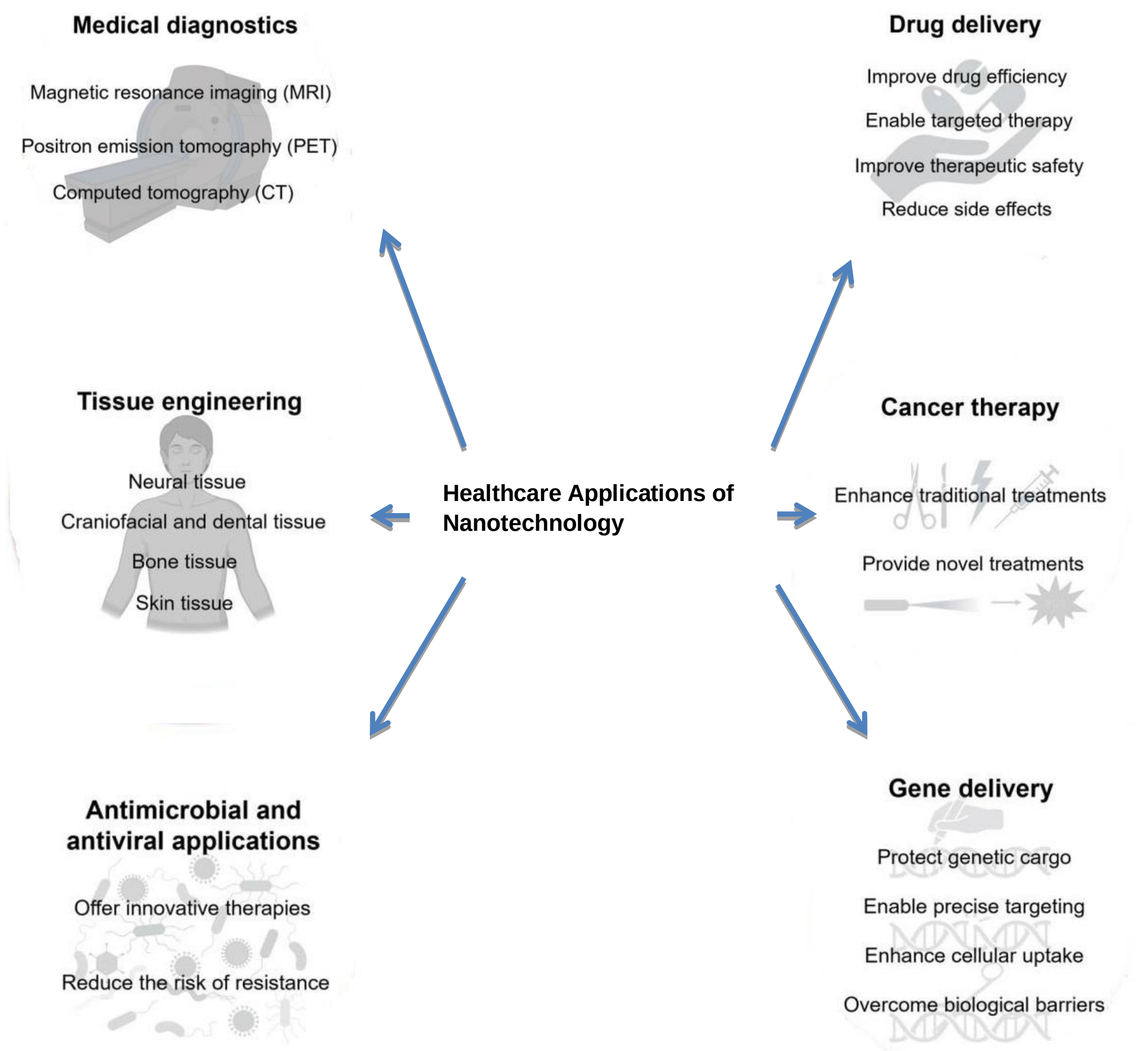

Fig. 2. Applications of nanotechnology in healthcare. These applications cover a wide range of medical specialities, including cancer treatment, antibacterial and antiviral uses, tissue engineering, medication and gene delivery, and diagnostics (Ma *et al.*, 2024).

Drug delivery and therapeutics

Nanotechnology offers smart-responsive drug release, precise and effective drug-targeted administration, and exceptional in vivo stability, and has revolutionised the field of drug delivery, leading to increased bioavailability, decreased adverse effects, and enhanced therapeutic efficacy (Malik *et al.*, 2023a). Numerous physicochemical issues related to pharmaceuticals, such as low solubility, stability, off-target deposition, and restricted penetration across biological barriers, have been addressed by the development of a broad range of organic and inorganic nanomaterials (Liu *et al.*, 2023).

Targeted drug delivery is a fundamental component of nanomedicine, which uses nanoparticles to decrease toxicity while increasing pharmacokinetics, solubility, stability, and bioavailability. Passive targeting through the increased permeability and retention (EPR) effect is made possible by systems like liposomes, polymeric nanoparticles (like PLGA), and dendrimers, or active targeting using ligands like folic acid or antibodies (Ma *et al.*, 2024). Smart nanofibers and nanobots offer on-demand release, which has uses in wound healing and antiviral delivery (Haleem *et al.*, 2023). Green nanotechnology employs eco-friendly assemblies like gold or silver nanoparticles for sustainable drug systems (Malik *et al.*, 2023a). Nanotechnology also boosts vaccine development, as seen in mRNA vaccines using lipid nanoparticles for stable delivery (Singh *et al.*, 2021).

Cancer therapy

Cancer is still one of the leading causes of death worldwide, and the standard methods for treating individual tumours are radiation therapy, chemotherapy, and surgical resection (Długosz *et al.*, 2023). Nevertheless, cancer patients frequently face a poor quality of life and a limited survival expectation despite these treatment alternatives. Both passive targeting, which is made possible by the small size of NPs, and active targeting, which is accomplished by specific modifications to the NPs and provides greater therapeutic precision, have been introduced as complementary and alternative cancer treatment strategies as a result of the rapid development of nanotechnology (Subhan *et al.*, 2021). Nanotechnology makes it possible for multifunctional theranostics in oncology, which combines therapy and imaging. When it comes to medication delivery, photothermal therapy (PTT), and photodynamic therapy (PDT), nanoparticles use carbon nanotubes, dendrimers, and magnetic particles to target tumours with high precision. Smart nanoparticles offer reduced toxicity, controlled release, and diverse administration routes for various cancers, from brain to colon (Malik *et al.*, 2023a).

Regenerative medicine and tissue engineering

Nanomaterials encourage cell proliferation to repair damaged nerves, bones, and wounds. This helps with the treatment of injuries and chronic diseases (Ma *et al.*, 2024; Malik *et al.*, 2023a). Tissue engineering is the integration of biology, engineering, and materials science to develop substitutes that restore or enhance tissue function. This involves using scaffolds, cells, and bioactive molecules to create functional tissues for medical applications, with the goal of repairing damaged tissues and reducing the need for organ transplants (Lanza *et al.*, 2020). Key research areas include neural, dental, bone, and skin tissue engineering due to the high frequency of injuries and diseases affecting these tissues, as well as their complex structures and functions (Zheng *et al.*, 2021). These fields have a great deal of clinical need and have the potential to enhance patients' quality of life. Through improvements in biomaterials characteristics, cell interactions, and tissue regeneration processes, nanotechnology breakthroughs have greatly enhanced therapeutic outcomes in several domains.

Antimicrobial and antiviral applications

The overuse or abuse of traditional antibiotics in a variety of fields, including medicine, agriculture, and livestock husbandry, has led to increased resistance to antibiotics, decreased effectiveness of antibiotic treatments, and the emergence of superbugs (Collignon and Beggs, 2019; Singh *et al.*, 2024a). This resistance arises when bacteria adapt to withstand antibiotics, frequently by altering target sites, generating enzymes that render antibiotics inactive, and employing efflux pumps to expel the medications, decreasing membrane permeability to stop antibiotic entry, or creating protective biofilms that obstruct antimicrobial penetration (Berendonk *et al.*, 2015). These adaptations lead to longer hospital admissions, increased death rates, and the requirement for more costly and potentially harmful alternative therapy in addition to making infection control more difficult. Innovative anti-microbial techniques are desperately needed because conventional antibiotics are unable to overcome these resistance mechanisms.

Nanotechnology developments offer promising paths toward resolving these issues. In contrast to traditional antibiotics, nanomaterials allow for intentional engineering designs such as size control, surface modification, crystalloid alteration, and stimuli-responsive functionalisation, which provide special interactions with bacterial cells (Makabenta *et al.*, 2021). The antibacterial qualities of silver nanoparticles in coatings and textiles help fight against pandemics and hospital-acquired diseases (Tobin and Brenner, 2021). This includes PPE for public health emergencies and water treatment (Adrah *et al.*, 2023). Since there is ample evidence that nanomaterials, and particularly nanoparticles, exhibit broad-spectrum antibacterial activity, nanotechnology may be a viable alternative to antimicrobial medications. Nanoparticles may prove to be an essential and practical therapeutic option for treating drug-resistant infections (Iqbal, 2023; Iqbal and Ashraf, 2023).

Gene therapy and personalized medicine

Nanocarriers deliver genes precisely, enabling treatments for genetic disorders and tailored therapies based on individual profiles (Malik *et al.*, 2023a). These innovative nanoplatforms have advanced significantly in the delivery of gene therapies, building on their use in drug delivery applications. A variety of diseases can be prevented or treated through gene therapy, an experimental technique that introduces nucleic acids (DNA or RNA) into patient cells to either enable the expression of new genes or regulate the expression of target genes by correcting, disrupting, or replacing them (Tang and Xu, 2020; Uddin *et al.*, 2020). Nanoparticles are proving to be highly effective vectors for resolving important gene delivery issues. By providing answers to the drawbacks of conventional viral vectors, the creation of these cutting-edge nanomaterials has greatly increased the potential of gene delivery methods. It is projected that further advancements in the design and functionalisation of nanomaterials will lead to safer and more efficient gene delivery systems, which will ultimately improve therapeutic results and increase the range of their uses (Ma *et al.*, 2024).

Prevention and environmental health

Nanomaterials in filters and coatings, like hospital antiviral surfaces or virus-capturing air purifiers, stop the spread of pathogens (Vazquez-Munoz and Lopez-Ribot, 2020). Nano-filters are used in water purification to eliminate impurities, reducing health hazards from contaminated sources that are made worse by climate change (Coussens and Goldman, 2005). This relates to climate efforts, since cleaner environments lessen disease vectors like mosquito-borne illnesses in warmer locations.

Overall, nanotechnology has the potential to transform public health by increasing the effectiveness and accessibility of interventions, particularly in regions with low resources, indirectly protecting public health from climate-driven environmental degradation (Pautler and Brenner, 2010).

Challenges and Future Directions

Nanotechnology integration into the mitigation of public health and climate change presents considerable challenges in spite of these opportunities. There are drawbacks such as oxidative stress toxicity, bioaccumulation, and genotoxicity; the hazards differ depending on the size, shape, and composition of the particles (e.g., Ag NPs producing inflammation). Persistence in ecosystems and changes and releases that effect biodiversity are examples of environmental impacts. Future research should concentrate on thorough safety assessments, economical production techniques, and tactics to reduce long-term environmental and health effects in order to ensure the sustainable and responsible use of nanotechnology, even though it shows great promise in reducing the negative health effects of climate change. The future holds personalized therapies, AI-guided formulations, and nanorobots for precise interventions.

Every health system must be prepared for the direct and indirect effects of climate variability on diseases, global solidarity must be reinforced, and strategies for resilience-building against climate-sensitive risks must be implemented. We can create a better and more resilient future by acknowledging the link between public health and climate change and including climate adaptation into public health preparedness and policy.

CONCLUSION

Nanotechnology offers revolutionary improvements in healthcare, ranging from regenerative remedies to targeted therapies, substantiated by extensive literature. Nanotechnology is a potent ally in the fight against public health risks and climate change, promoting a sustainable future with effective, focused solutions. In order to improve community resilience and adaptability and lessen the negative effects of climate change on environmental health, both behavioural and technical adjustments are needed. Its potential to improve world health and climate will be maximised if safety and innovation are balanced through strict rules. In this field, academic institutions are crucial in developing a new multidisciplinary, inclusive, and varied workforce.

CONFLICT OF INTEREST

Author of this article declares that there is no potential conflict of interest.

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