Harnessing Nanotechnology for Climate Change Mitigation: Environmental Applications and Sustainable Innovations

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Abstract- As of this minute, there are innumerable environmental issues which the globe is dealing with for over the past decades. But the climate change is indeed perhaps the biggest threat facing the environment. The rise of 1.5–2 °C surface temperature has been reported in past 40–50 years. harsh due in next 50–100 years the earth temperature will be make harsh living conditions and results would be disastrous. The major cause of climate is global warming change. Global warming is caused by the emission of carbon mixing gases (greenhouse gases) from The most common cause of global warming is carbon dioxide, fossil fuel combustion in industries, transport, electricity generation, agriculture and commercial sources. Besides that pollution, urbanisation, population etc. also contribute to climate change in Greater extent by broader parallels ways messing things up in the ecosystem. Owing to the unique properties of the nano materials, nanotechnolgy provides a diverse uses in environmental, agricultural, food and energy fields. Not only the environmental nanotechnology address against environmental in nature of problems, but nanotechnological products from the processes are seen as the powerful and novel tools/modes to achieve sustainable objectives. Nanotechnological materials, for example, nano composites, functionalized nano materials, metal organic frameworks, nano catalysts, bulking agents, carriers, carbon based materials, nano zeolite, nano silica, and other additives such as nano level lubricants, nano level coatings and etch have huge potential in Greenhouse gas sequestration and reduction, biofuel generation, wastewaters treatment and environmental clean-up in an eco-friendly way. The paper aims to present an overview of the nanotechnology solutions for addressing climate change. The purpose of this paper is to examine the long-term's trends and patterns of architectural and its proximity to the other types of design new nanocompounds on the environment and the advancement of sustainable means to address the climate change related problems.

Indexed Terms- Climate change, Global warming, Environmental remediation, Environmental nanotechnology, Nanocomposites, Biofuel, Nanocatalyst, Carbonaceous materials.

I. INTRODUCTION

Climate change, which is the result of 200 years of anthropogenic activities, is reflected in overall higher global temperatures and in the increase of atmospheric CO_2 together with a higher frequency and intensity of weather anomalies [1,2]. These alterations present grave consequences for every living being, and are why record warm temperatures and the warming of the globe which they herald are an urgent worldwide issue. Historical Recorded Temperature from 1880 shows that the Earth has been warmed 0.14°F (0.08°C) every 10 years with rate is twice from 1981 [3]. In 2017, the global average temperature was already 1 degrees Celsius (1.8 degrees Fahrenheit) beyond pre-industrial levels, and growing by 0.2 degrees per decade. The year 2020 was the second warmest after 2016, and in 2021 the temperature was the seventh year in a row that global temperatures have exceeded 1°C above pre-industrial levels [4].

Natural and industrial GHGs (including CO_2, methane, ozone, HFCs, SF_6 and PFCs) are the principal cause of global warming by retaining heat in the atmosphere. These gases do not only disintegrate the O3 layer, but they also have some climate consequences including glacier melt, flooding, drought, and reduction in crop yield [5–7].

Nanotechnology, the technology of particle size of at least one dimension in the range 1–100 nm, has found applications as game changer in agriculture, environment, energy, medicine, and food industries [8–11]. Its advantages originate from special properties of nanoparticles (NPs), especially the relatively large surface area and surface-to-volume ratio, which improves contact, energy transmission, and gas adsorption [12]. In agriculture, nanotechnology has brought new materials such as nanofertilizers, nanopesticides, nanosensors for agro-climatic and environmental monitoring [13]. Pathogen, toxins, and heavy metal nanobiosensors for food packaging There has been an increasing use of nanobiosensors for food packaging applications to detect pathogens, toxins, and heavy metals [10]. The development of biodegradable biobased nanopackaging would contribute greatly to the reduction of plastic pollution [10,14].

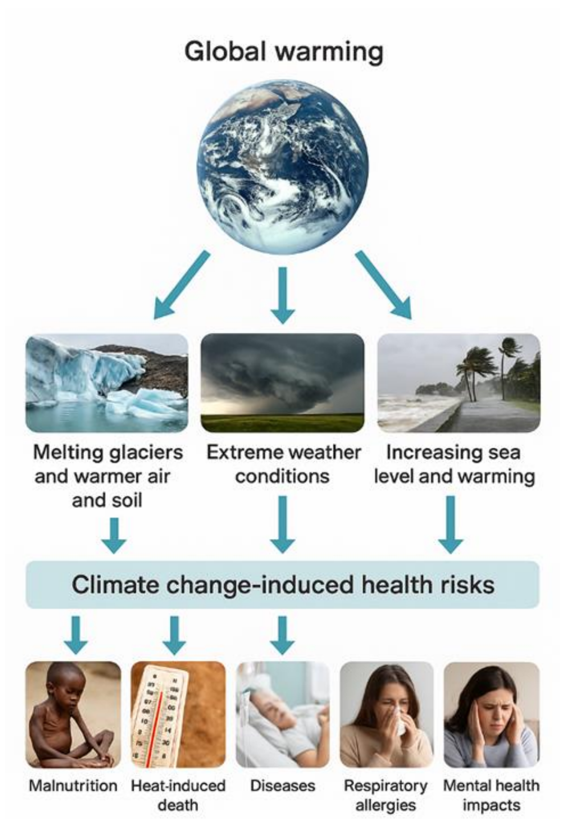


Fig. 1 shows climate-related health impacts.

Materials of nanometer or at least nanometer-level grains via nanosynthesis, such as nanocatalyst, nanocoating, and nanolubricant, are sustainable alternatives to the conventional materials. For instance, nanocatalysts improve fuel combustion efficiency, and reduce GHG emissions whereas nanolubricants and coatings, reduce engine friction and hence CO_2 release [12]. Furthermore, the nanotechnology accelerates the growth of renewable energy systems (like solar, biofuels, fuel cells), which helps us decrease the dependence on fossil fuels and minimize climate change. In environmental treatment, nanomaterials significantly degrade dyestuffs and other pollutants in water [15] and many are capable of adsorbing GHGs.

Table 1. Key function and applications of different types of Nanomaterial

Nanomaterial Type	Key Properties / Functions	Applications
Nanocatalyst	Speedup reactions, improve efficiency, control emissions	Fossil fuel, chemical industry, material production, pollution reduction, medicine
Nanotubes	Single and multi-walled; used in composites; enhanced efficiency	Raw materials and products for composites
Nanofibers	Material-efficient, air purification, monitoring of heavy metals, luminous materials	Environmental monitoring, heavy metal detection, air pollutant filtration
Nanocomposites	Increased strength, novel properties, polymer composites, water treatment	Water treatment, chemical and aerospace industries
Nanopowders	Organic/inorganic, pressure sensors, antigen/protein	Biosensors, solar cells, pressure sensing,

	detection, solar applications	pollutant detection

In green buildings, nanomaterials including but not limited to nanoglass, nanosilica, nanocoatings, and carbon nanotube are incorporated for dry insulation, solar heat utilization, and potentially refrigerant-free cooling [16,17]. However, environmental and health concerns associated with the toxicity and long-term stability of some NPs (e.g., Hg and Sn) require very strict safety regulations [18].

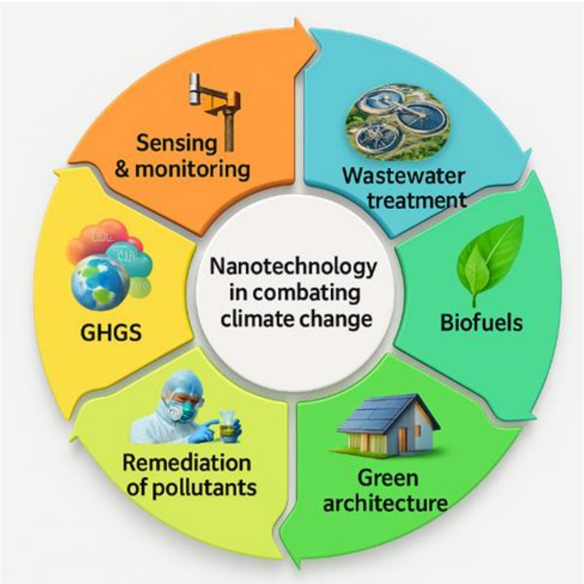


Fig. 3. Nanotechnology in combating climate change.

Despite the profusion of reviews that cover the applications of nanotechnology, in-depth analyses for the potential applications in climate change are few. In this paper, we fill this gap by reviewing emerging trends and environmental implications of nanotechnology and sustainability in the context of the climate crisis.

II. EFFECTS OF CLIMATE CHANGE

Earth's climate system has been seriously disrupted by climate change, resulting in major changes — warming of land, air and ocean, shifting in ocean currents, acidification, sea level rise, glacial melt, and extreme weather. Its consequences are multifaceted, affecting from environmental, agricultural and socio-health perspectives.

2.1 Environmental Impacts

Climate change represents a major threat to the environment, impacting many environmental systems. Documented impacts are already detrimental:shoreline and local flooding, loss of biodiversity, degradation of marine ecosystems, formation of new glacial lakes, heat stress and seasonal changes leading to extreme weather events. Moreover, rivers and oceans are warming faster [19].

Table 2: Efficacy of absorbed pollutants using different nanomaterials

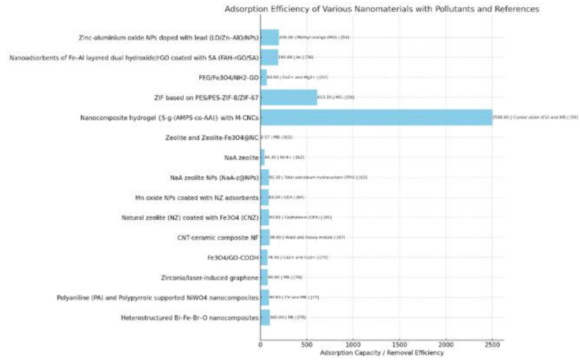
Adsorbent (Nanomaterial)	Adsorbed Pollutants	Efficiency	References
Multiwalled carbon nanotube (MWCNT) carboxylic	Amido black 10B	131 mg/g	[32]
acid cysteamine MWCNTs (carboxyl functionalization)	Alkylbenzene sulfonates	168 mg/g	[33]
Amino polyethylene glycol (a@PEG), polyhydroxylbutyrate (PHB), functionalize MWCNTs	Chemical oxygen demand (COD)	@PEG-CNTs (99.68%) > PHB-CNTs (97.89%) > P-CNTs (96.34%) > a@PEG-PHB-CNTs (95.42%)	[34]
Magnetic ammonia-functionalized MWCNTs	Methylene blue (MB)	178.57 mg/g	[35]
MWCNTs	Arsenite(III)	60–80%	[36]
MWCNTs	4-tert-octylphenol (endocrine disruptor)	94%	[37]
MWCNTs from activated carbon derived from wood sawdust, and doped with nickel-ferrites (Ni–Fe)	Metronidazole and levofloxacin	840.38 and 650.45 m2/g	[38]
MWCNTs	Tetracycline (TC)	qm = 494.91 mg/g	[39]
Surface oxidized nanocobalt magnetic nanomaterial embedded with nitrogen-doped CNTs (Co@CoO/NC)	TC and rhodamine B (RhB)	RhB (679.56 mg/g), TC (385.60 mg/g)	[40]
Zinc oxide–graphene	Rhodamine blue (RB)	42 mg/g	[41]
Graphene oxide hydrated manganese oxide nanocomposites	Lead(II)	553.6 mg/g	[42]
Graphene oxide Lanthanum oxide(III); Neodymium (III); Gadolinium (III); Yttrium (III)	Lanthanum(III), Neodymium(III), Gadolinium(III), Yttrium(III)	85.67 mg/g (La(III)); 188.60 (Nd(III)); 225.50 (Gd(III)); 135.70 (Y(III))	[43]
Thermally reduced graphene (TRG) and graphene nanoplatelets (GNP)	Oil	Batch adsorption: 1550 mg/g (TRG); 805 mg/g (GNP). Fixed bed: 1100 mg/g (TRG); 850 mg/g (GNP)	[44]
Graphene nanoplatelets (GNP) and graphene magnetite (GM)	Emulsified oil	100 mg/g (GNP); 85 mg/g (GM)	[45]
Functionalized graphene nanosheets (FGNs)	Copper(II)	103.22 mg/g	[46]
Polyurethane (PU)/graphene oxide (GO) electrospun membrane	MB and RB	109.88 mg/g (MB); 77.15 mg/g (RB)	[47]
Nitrogen-doped graphene quantum dots (NGQDs) over graphene sheets	MB (electrophotocatalysis)	93.00%	[48]
Nitrogen-doped graphene quantum dots (NGQDs) over graphene sheets	MB (photocatalysis)	95.00–100.00%	[49]
Reduced graphene oxide/titanate nanotube composites	Malachite green (MG)	113.5 mg/g and 91.72%	[50]
Graphene oxide (GO) functionalized by thiosemicarbazide (TSC), (GO-TSC)	MB	196.8 (GO) and 596.642 mg/g (GO-TSC)	[51]
Hydrogel of GO decorated with silver nanoparticles (Ag NPs)	MB	130.37 mg/g	[52]
Hydrocomposite (HCP) of GO supported by chitosan (GO/CSHCP)	Congo red (CR), Acid Red 1 (AR1), Reactive Red 2 (RR2)	43.06 mg/g (CR); 41.32 mg/g (AR1); 40.03 mg/g (RR2)	[53]

2.2 Agricultural Impacts
Climate change has significantly impacted farm productivity. Variable weather and extreme events undermine both the quantity and quality of crop yield [20–22]. Changes to the timing and duration of growing seasons and increased heat and water stress place pressure on farming systems [23–25]. Soil salinity and drought are increasingly becoming alarming due to which there is a need to develop sustainable technologies to combat stress, improve resilience, and reduce vulnerability, leading to better yield formation.

2.3 Other Impacts
The health of human populations is also threatened by climate change. Problems including heat-related deaths (especially in the European population), allergic reactions, infectious diseases, cardio-respiratory disease, malnutrition and mental stress are increasing [26]. Climate change has intensified worldwide risks such as hunger, displacement and biodiversity loss. Hundreds of species are on the brink of extinction because of forest fires, disease and unsuitable habitats. An average of 23.1 million were displaced annually by extreme weather between 2010 to 2019 [27]. In addition, climate change changes soil microbiomes -- important for soil fertility and biogeochemical cycles, and gut microbes, resulting in health issues such as intestinal inflammation [28,29].
In summary, ecosystems, health, agriculture, and global socio-economic structures among others are at a risk from climate change and life as usual is no longer as habitual.

III. NANOMATERIALS - TYPES AND USAGE (CONCISE)

Due to their particle dimensions ranging between 1 and 100 nm, nanomaterials have specific physicochemical and biological properties for various applications. Nanotechnology specifically deals with the design, synthesis and manipulation of these nano-architectures and their applications in almost all the domains.



Categorization of advanced nanomaterials There are four general categories of advanced nanomaterials, classified as super nanomaterials, smart nanomaterials, active nanomaterials, and swarm nanomaterials:

For example, super nanomaterials are perfectly monocrystalline and do not contain dislocations and show extreme strength. It includes, for example, materials for aerospace, such as aircraft wings or diamond bolts.

Smart nanomaterials are those that can change their physical properties in response to external triggers, such as light, heat, or pressure. One example is smart paint, which alters light refraction through atomic rearrangements.

Active nanomaterials are those that contain sensors, actuators and processors to sense altered environmental conditions and respond to them, which are useful for adaptive systems [64].

Swarm nano materials is a batch of nanomachines that work together in order to solve some problem and can be considered as a subcategory of active nano materials.

These materials are being used in energy, electronics, health care, construction and environmental remediation. It is the inherent multifunctions and adaptability that made them the cornerstones of developing sustainable technologies (table 1).

IV. ENVIRONMENTAL REMEDIATION WITH NANOTECHNOLOGY TO ADDRESS CLIMATE CHANGE EFFECTS

Moreover, nanotechnology provides new and sustainable answers to the leading environmental threats, such as pollution, greenhouse gas (GHG) emissions, and the energy shortage—the major causes danger of climate change (Fig. 3). It offers state-of-the-art-technologies for environmental cleanup, renewable energy, green science and safe monitoring for pollution.

4.1 Environmental Remediation using Nanotechnology

Pollution greatly contributes to climate change by contaminating the air, water, and land with health hazards, acid rain, and ozone depletion. In this context, environmental nanotechnology (E-nano) offers potential alternatives to the traditional approaches for pollutant remediation [30].

4.1.1 Treatment of Heavy Metals and Pollutants by Bioremediation

Conventional treatment processes were also been found to be limited in removal of contemporary contaminants. Nanomaterials bring water treatment to a new level by adsorption, membrane separation, photocatalysis, and sensing [31]. These include nanofibers, nanocomposites and metal-organic frameworks (MOF), that can remove harmful pollutants much more effectively (see Tables 1–2).

4.1.2 Greenhouse Gas Sequestration (GHGS)

GHGs such as CO_2, CH_4, and SF_6 trap heat and contribute to global warming. GHGS strategies that are based on nanotechnology are:
(i) reducing the use of fossil fuels,
ii) Seizure and utilization of GHGs, and
iii)Enhancement of the process efficiency [12,78].
Nanomaterials of large surface area and containing functional groups such as CNTs nanozeolites and nanofilms are employed for the adsorption of GHGs [79] (Table 3).

4.2 Nanotechnology for the Generation of Renewable Energy

GHGs are the gases that high fossil fuels emit. Some of the environmentally-friendly alternatives are the biofuels (bioethanol, biodiesel, and biogas) and renewable energies (solar, wind, geothermal, ocean). Nanocatalysts have been utilized to increase biofuel production by immobilizing enzymes (cellulases, laccases) on magnetic or metal oxide supports and thereby: increasing the efficiency of the conversion [121,122].

In solar cells, nanomaterials like thin films, polymer cells and quantum dots are employed to increase the photovoltaic efficiency. Nanostructured semiconductors are also advantageous for thermoelectric conversion. High performance nanocomposites and coatings improve power equipment in wind and ocean energy generation [30]. For the hydrogen fuel cells, costly catalysts (e.g., platinum) are replaced by core shell and alloy materials thanks to a low-cost electric generation [123,124] (Table 4).

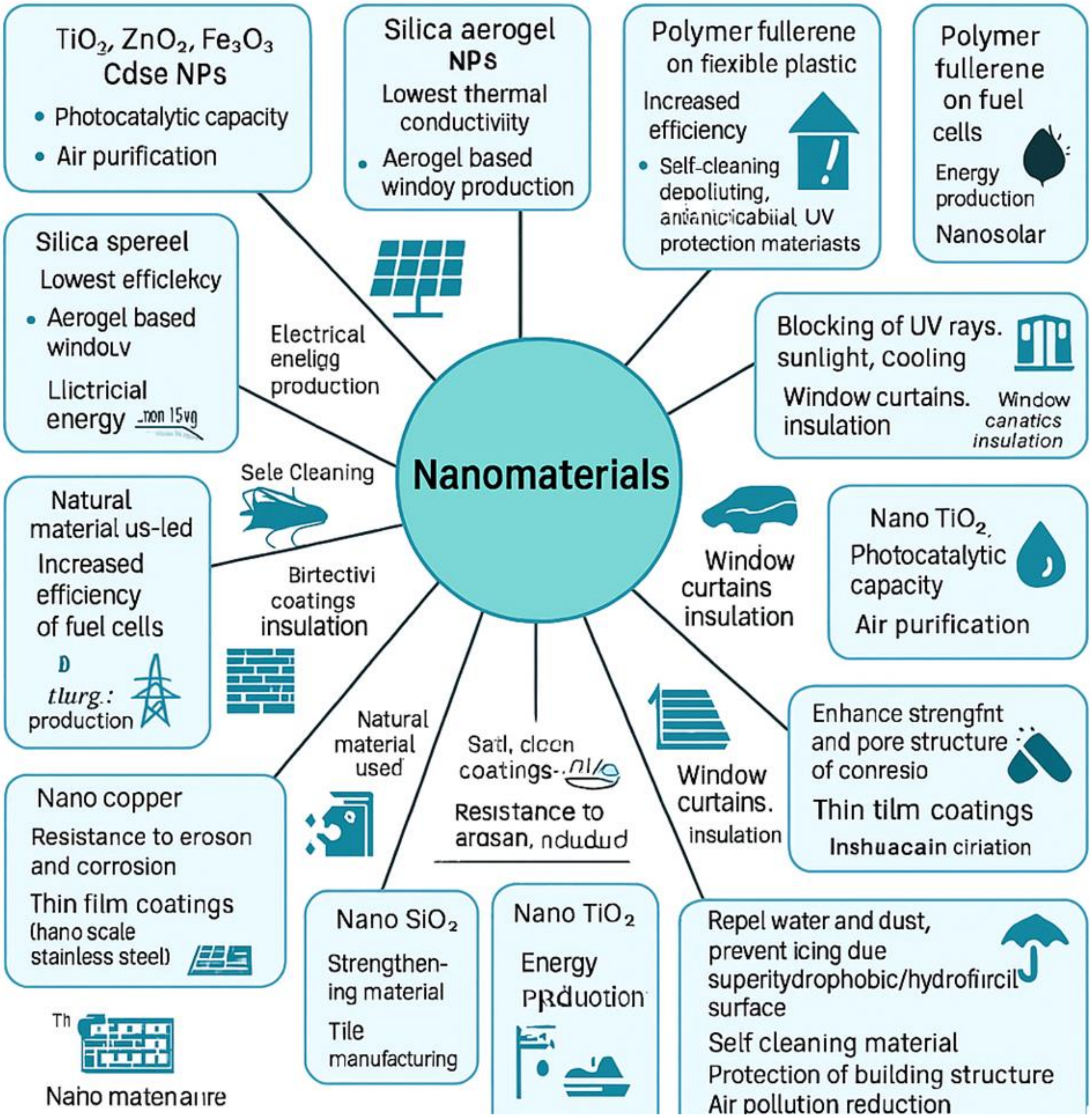
4.3 Architecture Green and Sustainable

Sustainable architecture is integral to our battle against global warming and the misuse of energy. Nanostructured materials (e.g., eco-coatings, nanoadsorbents, solar films) are employed to improve energy efficiency in smart homes and buildings [16,159]. Clean/green technologies; Nanotechnologies for clean/green construction are in line with world climate targets [160–162]. Table 5 Synthesis of nanomaterials Building components applications of nanomaterials are shown in Table 5.

4.4. Environmental Monitoring and Sensing

Nanosensors with their increased surface reactivity and optical properties, can be very sensitive and accurate for analyzing pollutants and monitoring environmental variations [10,163]. Biosensors, which employ a biological receptor such as antigen, antibody, or enzyme, target specific chemical/biological analytes [164]. A comprehensive inventory of nanosensors applied for environmental monitoring is summarized in Table 6.

In summary, the broader prospects of nanotechnology in addressing the environmental implications of climate change were presented in terms of pollution abatement, GHG sequestration, sustainable energy harvesting, smart infrastructure and real-time sensing.



V. ECOTOXICOLOGY OF NANOMATERIALS

Nanomaterials (NPs) exhibit unique physicochemical properties including large surface area, reactivity and optical activity, resulting in wide applications in catalysis, medicine, energy, agriculture, and environmental remediation, mainly because of their nano-size. Nonetheless, the very properties that make NPs biologically active and targeting may also have the potential of enhancing the risk of toxicity for human and ecosystems [188].

In the nanoscale, materials may demonstrate a far different toxicological properties compared to the bulk ones. For example, while bulk asbestos is non-carcinogenic, nanosized asbestos is carcinogenic [188]. Carbon-derived nanostructures such as CNTs and graphite are known to be toxic to some extent; however CNTs also do not have an established record as a potential hazardous agent in an organism.

Nanoparticles can slip into the environment undetected, tainting the air, soil and water. Heavy metal NPs (e.g., As or Pb) have high stability and are non-biodegradable and bioaccumulative, leading to risks after accumulation in plant, animal, and human tissues [18]. The lung is still the main portal of entry for the human body, affecting the respiratory system causing oxidative stress and chronic inflammation, formation of granulomas, and fibrosis [189,190].

Silver NPs Silver NPs are also characteristic examples of widely distributed consumer products highly affecting aquatic ecosystem which disturb the algae, fish, and microbial communities [191]. However, NPs are not well-characterised with respect to the long-term environmental and health influences of their presence within the biosphere.

To handle risks, standardisation regarding exposure monitoring, toxicity testing, and integrated LCAs are necessary. Nonetheless, LCAs are currently constrained by data gaps with respect to nanoparticle bioavailability, toxicity, and environmental transport [193,194]. Less toxic alternatives, such as carbon-based NPs (like graphene or fullerenes) could provide safer alternatives [192].

In this light, the responsible development of risk assessments and regulation of these materials should take into account the benefits they provide.

VI. REGULATION ISSUES OF NANOMATERIALS

In view of the rapid development of nanotechnology, it is important to create specific legislation and safety standards. The Government of India through its Department of Science and Technology (DST) released the “Guidelines and Best Practices for Safe Handling of Nanomaterials in Research Laboratories and Industries” in India. Nano science initiatives were started by the Government through DST Nano Mission (2001) and Nano Science and Technology Initiative (2007). The Eco Toxicity and Biodegradability Rules, 2008 and the Hazardous Waste Rules, 2008 also regulate the disposal and trans boundary movement of nanowaste.

But India does not have any such dedicated legislation such as TSCA (USA). Under the Environment Protection Act, 1986, it is the discretion of the government to formulate the subordinate chemical safety legislations and yet, there is lack of a comprehensive

Table 3: An account of various nanomaterial and nanosensors used for monitoring and sensing environmental pollutants

Type of Nanomaterials - nanosensor	Application - Analyte/parameters tested	References
Carbon nanotubes - Electrochemical	Water quality monitoring -Ammonium, CoII, organo-phosphate pesticides	[165]
Molybdenum disulfide (MoS_2) - Electrochemical	Biomedical and environmental monitoring- Glucose, uric acid, DNA, proteins, heavy metals, pesticides, nitrite etc.	[166]
TiO2/Ag0.35V2O5 - Gas sensor	Environmental monitoring - Ethanol	[151]
Copper oxide/reduced graphene oxide nanocomposite - Gas sensor	Environmental monitoring -Ammonia	[167]
Ag nanoparticles - Optical nanosensor: SERS	Water quality monitoring -Pesticides, bacteria, viruses, protozoa	[168]
Gold nanowires - Electrical	Water quality monitoring -Halides	[169]
Metal oxide semiconductor nanowires- Electrical	Water quality monitoring -VOCs, NO2	[170]
Magnetic beads - Magnetic nanosensor	Water quality monitoring- Salmonella enteric, Newcastle disease virus, E. coli 0157:H7	[171]
Magnetite (Fe_3O_4); maghemite (γ-Fe2O3) - Magnetic nanosensor	Water quality monitoring -Mycobacterium bovis, Influenza A	[172]
Silica-coated polystyrene nanoparticles (PSNPs) - Luminescent TOP nanosensors	Environmental parameters -Temperature, oxygen, pH	[173]
Nanoactuators, nanosensors, and nano energy harvesters - Flexoelectric nanosensors	Pressure measurement -Pressure	[174]
AuNPs - ICTS nanosensors	Diagnosis devices -Bacterial and viral antigen, proteins	[175]
AuNPs - DNA-Nanosensor	Antibiotics detection -Streptomycin	[176]
Capped mesoporous silica nanoparticles - Fluorogenic aptasensors	Antibiotics detection -Ochratoxin A	[177]
AuNPs/PANI/GSPE- Electrical	Pesticide detection -Organophosphorus pesticides	[178]
DNA-functionalized gold nanoparticle- Electrical	Pollutant detection -Silver ions	[179]
Luminescence nanoprobe- Electrical	Pollutant detection -Heavy metals	[180]
AuNPs- Electrical	Pathogen detection -E. coli K88	[181]
Zr-based MOFs - Nanosensor	Pesticide detection -Organophosphorus pesticides	[182]
Nanoporous Au- Electrical	Pollutant detection -Pb2+	[183]
Graphene - Chemical nanosensor	Pollutant detection -Nitrotriazolone	[184]
Indium-doped ZnO nanoparticles - Chemiresistive nanosensor	Pollutant detection -Trinitrotoluene	[185]
Dual-emission DNA-templated silver nanoclusters - Fluorophore ratiometric nanosensor	Pollutant detection -Pb2+	[186]
Lignin-derived structural memory carbon nanodots (CSM-dots) - Fluorescent Nanosensor	Pollutant detection -Ag+	[187]

nanomaterial-specific regulation for safe commercialization.

At the global level the nanotoxicity assessment has been driven by a number of initiatives. Key contributions are being made by the Nanotechnology Research Coordination Group (UK) and the National Nanotechnology Characterization Laboratory (USA) [195]. The International Alliance for Nano Environment and Human Health and Safety Harmonization is working to devise standard testing procedures [196]; the National Research Council (NRC) advocates high-throughput nanotoxicity screening in the US.

In particular, the OECD Working Party on Manufactured Nanomaterials (WPMN), formed in 2006, guides international activities on the safety and regulation of nanomaterials [197].

CONCLUSIONS AND FUTURE OUTLOOK

Climate change, with its global repercussions that result from increased environmental decay and rising temperatures, continues to be a concern. Immediate action is required to minimize these impacts by use of alternative, cleaner technologies and processes. Nanotechnology is an emerging technology, which can provide environmentally friendly alternatives for many products areas.

Nanomaterials such as nanosensors, nanocatalysts, nanocoatings, nanolubricants, MOFs, nanozeolites, nanocarbon, and functionalized nanostructures are characterized by the inherent physicochemical properties and are therefore regarded as suitable for integrated applications in bioenergy, pollutant removal, greenhouse gas control, environmental restoration and green building.

Nanotechnology as a game changer in climate change mitigation by improving energy efficiencies, minimising resource requirements and providing new solutions to environmental issues, nanotechnology provides a transformative instrument to help mitigate climate change. The Gifts also support the development of smart materials, renewable energy options and pollution control technologies consistent with climate goals.

In order to exploit its full strength, supportive international policies and local strategies are needed. In the future, nanotechnology has significant potential in developing novel, affordable, and sustainable solutions to address climate change, further cementing its key role in safeguarding our environmental future.

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