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Advancing Science, Technology, and Engineering through Sustainable Nanotechnology

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Abstract

The pursuit of sustainable practices within the realm of nanotechnology offers innovative solutions to multifaceted global challenges. This paper delves into the transformative potential of sustainable nanotechnology across critical domains such as energy, medical science, water and sanitation, and the petroleum sector, with a particular focus on Mozambique's unique context. By intertwining nanotechnology with an eco-friendly ethos, this study underscores the significance of aligning technological advancements with sustainable practices. The narrative navigates through Mozambique's vulnerability to extreme weather events, exemplified by the impact of cyclones, and explores global strategies aimed at mitigating climate change effects, including the United Nations Sustainable Development Goals (SDGs). The pivotal role of nanotechnology in addressing pressing challenges within the energy sector is elucidated, emphasizing advancements in renewable energy, energy storage, and efficiency. Similarly, nanotechnology's impact on healthcare delivery, water purification, and food security is examined, showcasing innovative solutions and potential avenues for future research. Furthermore, the paper outlines recent trends in nanotechnology within the oil and gas industry, highlighting advancements in enhanced oil recovery, data monitoring, and environmental sustainability. The exploration of nanotechnology's role in food security underscores its potential to revolutionize agricultural practices and mitigate global food scarcity challenges. By synthesizing historical insights, current trends, and future prospects, this paper provides a comprehensive overview of the transformative role of sustainable nanotechnology in advancing science, technology, and engineering towards a more sustainable and resilient future.

Keywords

Sustainable nanotechnology, Energy, Medical, Water purification and environment

Introduction

Sustainable nanotechnology provide innovative solutions through the adoption of sustainable practices. The exploration encompasses the multifaceted relevance of nanotechnology, extending its influence across critical domains, including energy, medical science, water and sanitation, and the petroleum sector. Notably, it's underscored within the context of mozambique, a region endowed with abundant raw materials. A strategic decision is made to approach nanotechnology from a physics perspective, intertwining it with an overarching eco-friendly ethos. This decision is thoroughly substantiated, emphasizing the importance of aligning nanotechnological advancements with sustainable practices. The chapter reaches its end with the elucidation of the thesis structure, providing a comprehensive and insightful overview of the organizational framework that underpins the entire research endeavor, followed by a meticulous referencing of consulted sources.

Why Sustainable Nanotechnology?

Currently, the planet is affected by climate change, as evidenced by extreme weather events, global warming, water scarcity, irregular rainfall, biodiversity loss, and global health issues. Conversely, human endeavors equally accelerate the planet's degradation, manifested by environmental pollution, industrialization, excessive mineral extraction, and overconsumption [1].

In many parts of the planet, with more incidence in the global south, the effects of extreme weather events have caused poverty, a high level of vulnerability, and fatalities within the communities, and still recovering from the effects. In Mozambique, for example, in the past 5 years, more than

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15 cyclones have hit the country, and the most significant cyclonic events are known to be IDAI, kenneth, eloise, and freddy [2].

The Idai cyclone is considered the strongest cyclone in the Global South, struck on 14th-15th March 2019 affecting mozambique, zimbabwe, madagascar, and malawi with huge consequences in terms of widespread devastation, floods, destruction of infrastructure, deaths, and humanitarian assistance to many families, infrastructure and the industrial sector in the affected regions [3].

Kenneth cyclone also formed in the indian ocean on the 21st of April and hit the northern part of mozambique (cabo-delgado), tanzania, including madagascar on April 29th, 2019 with gusts of around 230 km/h [3,4].

Eloise Cyclone also hit mozambique, south africa, eswatini, and zimbabwe on january 23rd, 2021 soon after being formed on January 15th affecting thousands of people, houses, and dozens of deaths [5].

Freddy was considered a long-lasting and severe cyclone that affected mascarene irelands, mozambique, zimbabwe, malawi, and eswatini. In mozambique, this cyclone hit twice, first on 23th february in vilanculo and second in quelimane on march 11th, 2023 with an overall wind speed ranging between 230 km/h to 270 km/h causing thousands of reported deaths and missing as well as the destruction of infrastructure and resettlement [6].

Considering the effects of climate change, different stock holders are engaged worldwide in mitigation and designing policies to slow down this paraphernalia, including the United Nations Framework Convention on Climate Change (UNFCCC) [7], the Intergovernmental Panel for Climate Change (IPCC) [8], Green Climate Fund (GCF) [9], World Meteorological Organization, the World Bank Climate Group (WBCG), the Global Environment Facility (GEF), the Climate Action Network (CAN) [10], Paris Agreement Sustainable Development Goals (SDG), and Conference of Parties (COP) [11-13].

The 17 Sustainable Development Goals are regarded as the vector and driving force for the planet's recovery in terms of poverty, hunger, health, education, gender equality, clean water, accessible energy, decent work, sanitation, reduced inequalities, innovation, peace, and justice, as well as a partnership to be achieved by 2030 [14,15] (Figure 1).

Different areas of research in science, engineering, technology, and the humanities are hardly engaged in other to recovering, preventing, and mitigating the damages caused to our planet and the environment by introducing the concepts of sustainability and resilience, which are eco-friendly approaches [16].

Physics Science, Material Science, and Nanotechnology are the central points of this thesis and are also involved in addressing suitable contributions related to sustainability and resilience to enhance global well-being, with a focus on finding materials that are less harmful to the environment and planet. These routes are also called as green and eco-friendly, consisting of balancing environmental impacts and desired products [17].

These study in Physics Science, Material Science, and Nanotechnology offer innumerous advantages in contributing to the solutions to the current problems affecting the global world in the sectors of energy, water and sanitation, food security, pollution, and health.

In sustainable nanotechnology, natural materials, often

Figure 1: SDG-Sustainable Development Goals [14,15].

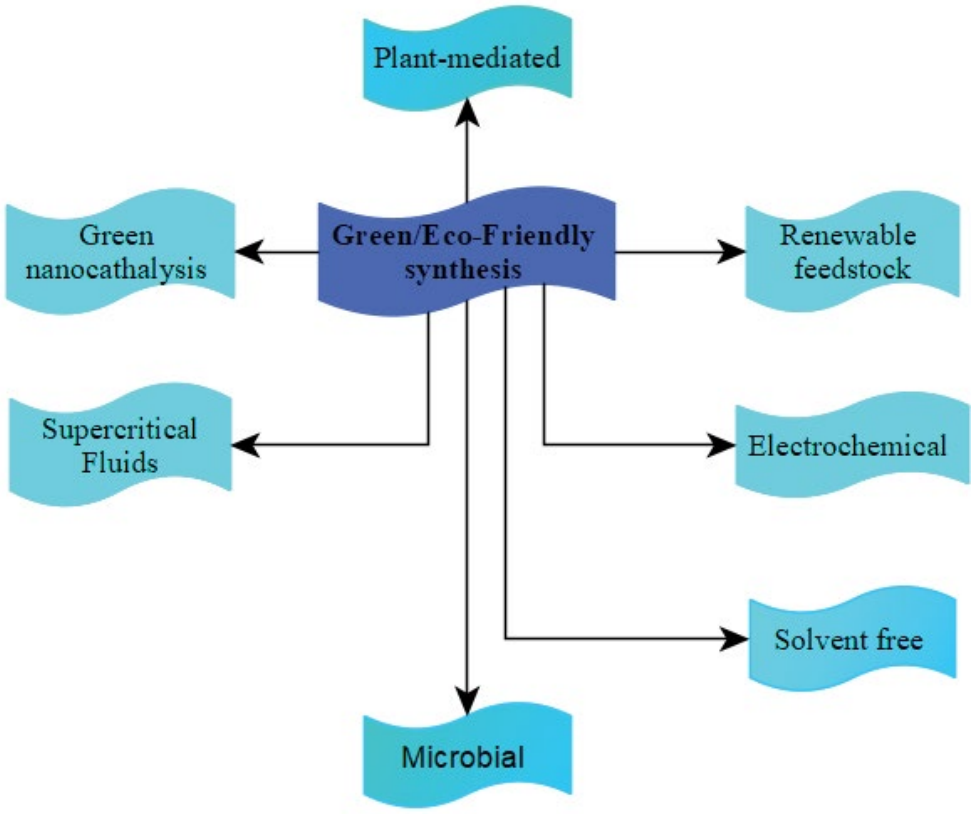

Figure 2: Green/Eco-friendly synthesis of nanoparticles [18].

discarded as waste, are carefully chosen to produce advanced materials, thereby mitigating environmental hazards [18]. The method's cost-effectiveness, with the potential to be executed in a single pot, requires minimal machinery, energy, and lacks expensive environmental prerequisites. Figure 2 illustrates various approaches in sustainable nanotechnology [19].

The Role of Nanotechnology in Enhancing Energy Domain

Regarding energy, globally, the consumption of electricity is continuously rising. According to the World in Data platform, global electricity demand has surged from 15,000 TWh to 28.661 TWh between 2020 and 2022, reflecting an almost twofold increase in just two years [20,21]. This substantial, nearly twofold increase within a span of only two years raises concerns about sustainability and environmental footprint, particularly in light of a significant portion of this heightened demand is attributed to fossil fuel sources (Figure 3). The investigation of more efficient solutions in the fields of renewable energies, storage, and energy efficiency has been an alternative to keep up with growth and avoid a possible power outage. Nanotechnology can manipulate matter at the nanoscale level, aiming to create new materials, products, and services with technological applications. In nano, there is potential for optimizing the electrical materials currently in use, aiming to reduce electrical technical losses related to the inefficiency of material Joule and Corona effects through the development of smart materials.

Quantum dots, nanowires, and nanotubes of different elements have been used to improve the efficiency of solar cells by their properties of boosting light absorption, electron transport, and reducing energy leakage in solar industry technology [22].

To respond to the demand for energy backups, selected materials and morphologies, including graphene and nanotubes, considering their good conductivity and ability to increase surface area, have gained attention in nanotechnology to improve battery efficiency by fast charging and extended cycles [23].

The process of converting chemical energy into electrical energy in battery cells was enhanced in nanotechnology, with an emphasis on platinum in terms of catalytic activity [24].

Lighting technology with all side effects since incandescent bulbs and fluorescent bulbs were effectively improved by nanotechnology light emission diodes (LEDs) with more efficiency and color control, emphasizing quantum dots for this purpose. Also, through nanotechnology, it is possible to transform thermal energy into electrical energy by using nanothermoelectric devices [25].

A hurdle in wind energy resides in the weight of turbines where more wind is needed to move the system. Through nanocomposites, it is possible to produce light-weight and long-lasting blades, improving their efficiency.

Hydrogen from water represents a burgeoning avenue within the realm of emerging renewable energy through

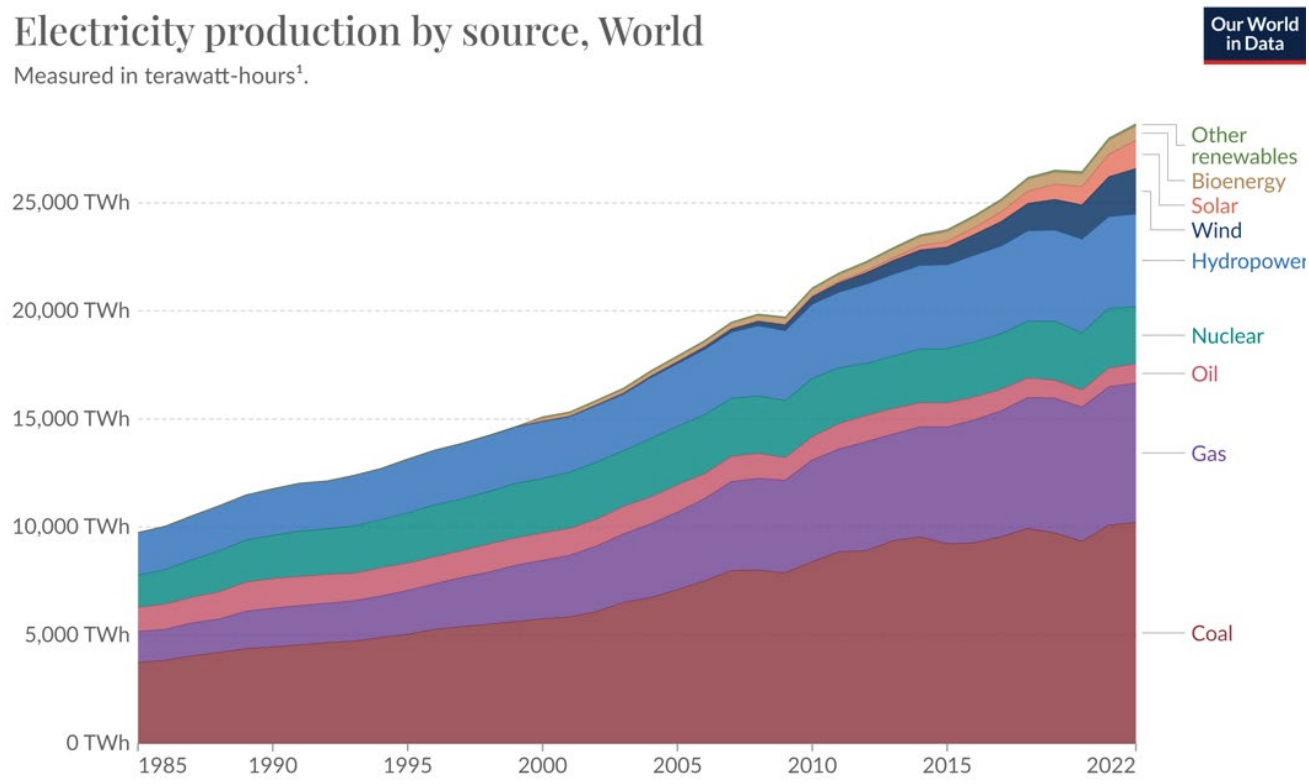

Figure 3: Electricity production by source [20].

nanocomposites. Consequently, it is possible to prepare more efficient water splitting and enhance the spread of production for clean fuel assembly.

The advancement of materials of high surface area with adjustable properties as nanocomposite-based, allows the capture and storage of carbon dioxide from the atmosphere, and industrial activities keep the environment clean.

One of the current challenges in the energy sector is energy efficiency, also considered a virtual source of energy (VSE) or virtual power plant (VPP). In this regard, nanoscale sensors have been developed and used to command and monitor the grids, managing efficiently the distribution of electricity, also called smart grid systems. High-fluorescent and thermal-enhanced nanocomposite materials are developed and integrated into buildings and building technology [26].

The Role if Nanotechnology in Enhancing Medical Sector

In terms of health sciences, nanotechnology has developed numerous techniques to improve health systems including drug delivery to target specific tissues or cells with minimum side effects and high efficiency. Also, polymer-based materials automate the administration of drugs to patients. It is now possible through nanoprobes that carry imaging agents as enhanced versions of tomography as well as magnetic resonance and quantum dots (QD) to carry images that detect multiple biological parameters simultaneously.

In health science, through nanotechnology in sensor technology, it is possible to produce detectors of disease makers, pathogens, and point-to-point care diagnoses through nanobiosensors and lab in a chip device.

Nanotechnology exhibits prospects for cancer treatment though the advancement of selective and noninvasive devices directly for tumors, also known as nanoparticle-based therapy and cancer hyperthermia devices, which destroy the cells through the heat of magnetic nature.

It is currently possible, through the development of nanotechnology, to develop biomaterials with regenerative properties for repairing tissues and nanocomposites that can mimic extracellular matrix that can allow the growth of cells and adhesion.

With the outbreak of the SARS-CoV-2 virus, also known as COVID-19, the pharmaceutical industry had to self-adapt through nanotechnology to meet the demands of patients as well as possible outbreaks by developing nanoparticle-based vaccines responsible for carrying antigens and adjuvants to boost immunity responses for vaccines [27].

In the field of nanomedicine, silver nanoparticles are widely applied as antimicrobial agents for infection prevention as well as wound treatment and coating [28].

Implants are also considered other evidence of applications of nanotechnology and material science in medicine, used for insight into biocompatibility to reduce the rejection effect of the immunologic system.

Further, in nanomedicine, nanotechnology and materials science have developed to the levels of diagnosis, treatment, prevention, and prediction of patients' needs and gained

the ability to advance the process of sequencing DNA, which will allow the creation of personalized medicine through the survey of genetic information.

The Role of Nanotechnology in Enhancing Water and Sanitation

Access to clean water remains a global challenge, with only a small fraction of the total water (2.5%) being potable, and another portion existing in forms such as saltwater, ice, and residual water and aquifers, which are not easily accessible. While seawater is abundant in coastal areas, it is unsuitable for consumption due to impurities [29].

Nanotechnology offers potential solutions to water scarcity, particularly in the desalination process. Utilizing nanoporous materials, such as graphene and single-layer carbon molecules arranged in a hexagonal structure, can effectively block salt ions, allowing only water molecules to pass through. Additionally, nanostructured filters containing silver and graphene oxide nanoparticles show promise in removing impurities, inhibiting bacteria, and filtering out viruses during water treatment [30].

Nanotechnology has also contributed to the development of sensors that monitor water purification processes, enabling the detection of harmful contaminants. In addressing wastewater treatment Zinc oxide nanocomposites enhance catalytic processes. These advancements align with Sustainable Development Goal 6 (SDG6) for clean water and sanitation, ultimately improving the availability of water on a global scale [31].

Recent Trends of Nanotechnology in Oil and Gas Industry

The oil and gas industry stands out as one of the most lucrative businesses globally, playing a pivotal role in supplying energy to diverse economies. Significant efforts have been directed towards modernizing this sector, incorporating advancements such as the use of nanofluids for enhanced oil recovery and lubrication in the drilling process, nanocatalysis to save energy and accelerate reaction rates in refineries, and nanosensors for real-time data collection and well or plant monitoring [32].

Furthermore, anticorrosion measures employing various metal oxide nanoparticles, particularly ZnO and TiO_2, are implemented in pipelines, enhancing material resistance. The deployment of different nanoparticles extends to Si, Al_2O_3, and Fe_2O_3 for enhanced oil recovery; Pd, Pt, and Ze for refining processes, and CNTs, graphene (Cn), and QDs sensors for real-time well monitoring and data collection. MOFs and amine, functionalized nanoparticles contribute to environmental monitoring and carbon capture, while clay and graphene oxides streamline drilling processes, improving efficiency.

Additionally, in the Mozambican context, an emerging competitor in oil and gas exploration with a specific focus on Cabo Delgado, Sofala, and Inhambane provinces, research in this domain is currently scarce.

Given the nation's status as an emerging player, there is a keen interest in various investigations and approaches to enhance the efficiency and production chain of oil and gas processes in the region, which is still open for further development. The author's connection to Mozambique adds particular weight to nanotechnology investigations in the oil and gas industry, underscoring the crucial significance of advancing research efforts within the country.

Nanotechnology's Role in Enhancing Food Security

Given the current challenges posed by global population growth, the imperative to increase food production and storage efficiency to minimize avoidable losses is paramount. This not only aligns with the objectives of Sustainable Development Goals 2, 3, and 12 but also addresses the pressing need for sustainable agricultural practices.

Never the less, nanotechnology emerges as a pivotal tool by contributing to the development of highly efficient fertilizers, improve food, innovative food packaging frameworks, and intelligent drip technologies. These advancements underscore the potential of nanotechnology in promoting food security, reducing waste, and supporting sustainable development objectives [33].

Zinc oxide nanoparticles (ZnO NPs) play a pivotal role in this context due to their antifungal and antibacterial properties in food packaging. These properties enable the inhibition of microbial growth, consequently enhancing the shelf life of packaged goods. To further illustrate the diverse applications of nanomaterials in bolstering food security, Table 1 delineates the contributions of various nanomaterials in this domain.

Conclusions

In conclusion, this paper has underscored the pivotal role of sustainable nanotechnology in addressing pressing global challenges, particularly in the context of climate change. By exploring the multifaceted applications of nanotechnology across various sectors such as energy, healthcare, water purification, and food security, we have elucidated its transformative potential in mitigating environmental degradation and fostering sustainable development.

Through a nuanced examination of Mozambique's vulnerability to extreme weather events, exemplified by the impact of cyclones, we have highlighted the urgent need for innovative solutions to enhance resilience and adaptation. Nanotechnology emerges as a promising avenue for achieving these goals, offering efficient and eco-friendly approaches to address complex environmental issues.

Furthermore, by aligning nanotechnological advancements with the United Nations Sustainable Development Goals (SDGs), we have outlined a pathway towards a more sustainable and resilient future. From enhancing renewable energy technologies to revolutionizing healthcare delivery and improving access to clean water, nanotechnology holds promise as a powerful tool for positive global change.

Table 1: Nanomaterials and their role in food security [6-9].

Nanomaterials	Role in Food Security
ZnO NPs	Antifungal, antibacterial protection in food packaging, fertilizer and seed treatment.
TiO_2 NPs	Antimicrobial activity and UV blocking.
Si NPs	Improve nutrients delivery, absorption and fertility of soil.
Fe_2O_3 NPs	Optimize the precision of nutrients delivery.
CuO NPs	Improve harvest and protect from fungal diseases on crops.
Ag NPs	Antimicrobial activity and reduce risk of contamination of food packaged.
CNTs	Sensor to monitor soil condition and detect contaminants.
Graphene (C_n)	High quality of sensors to monitor food safety from contaminants.
QDs	Sensor to monitor real-time the condition of crop with high precision.

As we navigate the challenges posed by climate change and strive for a more sustainable world, it is imperative that we continue to harness the potential of sustainable nanotechnology through interdisciplinary collaboration, innovative research, and responsible stewardship. By doing so, we can pave the way towards a brighter and more sustainable future for generations to come.

Disclosure Statement

The authors assert their research integrity, emphasizing a purpose-driven path devoid of conflicting interests.

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