

Review

# An Overview on the Role of Government Initiatives in Nanotechnology Innovation for Sustainable Economic Development and Research Progress

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**Abstract:** Nanoparticle technology has emerged as a fundamental component across various industries, including electronics, renewable energy, textiles, and medical biotechnology, particularly for targeted drug delivery applications. Commercialization has profoundly impacted economic growth, especially in the pharmaceutical and electronics industries. Moreover, it has improved workforce education and training, generating millions of employment prospects associated with nanotechnology development. By 2024, the Organisation for Economic Co-operation and Development anticipates that the global market for nanotechnology products will attain a value of United States Dollar (USD) 1 trillion to USD 3 trillion, resulting in the creation of over 2 million new employments globally. The swift progression of nanoparticle technology from 2000 to 2024 is primarily propelled by substantial industrial investment in research and development, alongside collaborations with academic institutions. The National Nanotechnology Initiative in the United States (US) has significantly contributed to these developments, with federal funding exceeding USD 30 billion by 2024 since its establishment in 2001. This funding has catalyzed significant advancements in both commercial and research applications of nanotechnology. Patent data highlights this expansion, with China establishing itself as the preeminent nation in nanotechnology patents. From 2000 to 2024, China steadily raised its proportion of nanotechnology patents, accounting for almost 40% of the global total by 2024. The US, Japan, Germany, and the Republic of Korea continued to be significant contributors, together advancing the frontiers of innovation in nanotechnology. In this timeframe, the quantity of nanotechnology-related patents increased by more than 150%, demonstrating the swift growth of the sector. The regulation of nanotechnology in the US is primarily managed by the Food and Drug Administration, particularly about healthcare and biotechnology applications. As the scope of nanotechnology uses has expanded, there is an increasing demand for more extensive regulations concerning potential long-term environmental and health effects. The future trajectory of nanotechnology, both in the US and worldwide, will hinge on continuous invention, economic advancement, and the progression of governmental policy. By upholding a robust regulatory framework and promoting ongoing collaboration between academics and industry, the complete potential of nanotechnology in advancing industrial and societal progress can be actualized.

**Keywords:** economic development; government initiatives; nanomaterials; nanotechnology



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## 1. Introduction

Nanoparticle technology has emerged as a revolutionary influence across various industries, owing to its capacity to modify material properties at the nanoscale, hence facilitating novel commercial applications. Nanoparticle materials are utilized in various applications, including fabrics, athletic gear, helmets, cosmetics, and electronic gadgets. In addition to industrial applications, nanoparticles are essential in medicinal fields, particularly in targeted drug delivery [1,2]. The National Nanotechnology Initiative (NNI) characterizes nanotechnology as the manipulation of matter within dimensions ranging from 1 to 100 nm, influencing attributes at atomic, molecular, and macromolecular levels [3]. The distinctive characteristics of nanoparticles, encompassing structural, thermal, quantum, and electromagnetic properties, render them essential for applications in several domains [3]. Their diminutive size enables them to traverse biological membranes, rendering them suitable for medicinal applications including medication administration. At the nanoscale, the thermal characteristics of materials differ from those of their bulk forms, rendering nanoparticles advantageous for applications such as altering melting points and enhancing the performance of materials like ceramics. The electronic characteristics of nanoparticles, along with their diminutive size, have enabled the creation of compact, high-performance electronic devices. Quantum effects augment the performance of materials in sectors like electronics, energy, and healthcare [4,5].

Since its inception in 2000, the NNI has been a catalyst for the swift advancement of nanotechnology in the United States (US). As of 2024, the total federal investment in nanotechnology via the NNI exceeded \$43 billion [6], with yearly federal funding continuously surpassing United States Dollar (USD) 1.5 billion since 2015. This financing has catalyzed pioneering research and innovation across various domains, including electronics, energy, agriculture, healthcare, infrastructure, and nanobiology. A significant initiative endorsed by the NNI entailed the creation of nano-assisted intraoperative brain tumor therapy, utilizing a non-toxic two-photon photodynamic nanoparticle to precisely identify tumors during surgical procedures. In the last twenty years, nanotechnology has progressed through various unique phases. The initial five years following the founding of the NNI witnessed the emergence of passive nanostructures, such as coatings and nanoparticles. In the subsequent decade, emphasis transitioned to active nanostructures, including amplifiers and targeted drug delivery devices. By 2024, the domain is advancing toward nanosystems applicable in robotics, molecular devices, and next-generation materials [7].

The worldwide proliferation of nanotechnology is demonstrated by a significant surge in patent applications, with China establishing itself as the preeminent leader [7]. Between 2000 and 2024, the number of patents about nanotechnology increased significantly, especially in nations such as China and the US, which are at the forefront of research and commercialization. In 2024, China singularly represented a substantial share of nanotechnology patents, reinforcing its preeminent status in this domain [8,9].

The influence of nanotechnology on the economy is significant, with the Organisation for Economic Co-operation and Development (OECD) estimating that by 2024 it may represent a global market value ranging from USD 1 trillion to USD 3 trillion, leading to the generation of more than 2 million new jobs globally [10]. The future of nanotechnology will be influenced by ongoing collaboration among academic institutions, industry leaders, and governments, with innovation and regulatory policies being essential for promoting sustainable growth and addressing safety and long-term environmental concerns.

Nanotechnology is set to remain a fundamental element of industrial and economic advancement, offering solutions to contemporary difficulties across several industries while adapting to economic, technological, and regulatory factors (Table 1). The inception of nanoscale science and engineering in the US occurred in 1998 with the establishment of

the Interagency Working Group on Nanoscience, Engineering, and Technology under the National Science and Technology Council [10]. This program established the foundation for the NNI, which was officially inaugurated in 2000. The NNI designated a substantial amount of federal financing, primarily concentrating on long-term research, technical advancement, education, and the comprehension of societal effects [11].

**Table 1.** Top 20 companies with nanotechnology-based products. Data were extracted from the STATNANO database [12].

Company	Country	Total Products	Area
Amphenol Corporation	United States	206	Electronics
NanoWorld	Switzerland	197	Electronics
Intel	United States	189	Electronics
Analog Devices, Inc.	United States	186	Electronics
Alpes Lasers	Switzerland	148	Electronics
Samsung Electronics Co., Ltd.	Republic of Korea	138	Home Appliance, Environment, Electronics
OMRON Corporation	Japan	135	Electronics
Donaldson Company Inc.	United States	100	Automotive, Cosmetics
Merit Medical Systems, Inc	United States	87	Electronics
Sensor Electronic Technology, Inc.	United States	70	Electronics
Texas Instruments Inc.	United States	60	Electronics
Nuvoton Technology Corporation	Taiwan	57	Electronics
Shanghai Huzheng Nanotechnology Co., Ltd.	China	50	Construction, Textile, Medicine
BaByliss PRO	France	50	Cosmetics
Beiersdorf AG	Germany	43	Cosmetics, Medicine
Hitachi Ltd.	Japan	38	Home Appliance, Environment, Renewable Energies
NANOSKIN Car Care	United States	38	Automotive
QD Laser Inc.	Japan	35	Electronics
Pfizer Inc.	United States	35	Medicine
Nanogist Co., Ltd.	Republic of Korea	35	Cosmetics, Medicine, Home Appliance

## 2. Global Nanotechnology Initiatives

Nanotechnology initiatives worldwide are pivotal in addressing sustainable development challenges through innovative solutions in energy, healthcare, agriculture, and environmental protection. Governments have recognized its transformative potential and are investing in research and development to foster economic growth while promoting sustainability. Countries like the US, China, and members of the European Union (EU) have integrated nanotechnology into their national strategies, focusing on renewable energy systems, efficient water purification methods, and reducing carbon footprints (Table 2) [13,14]. These efforts align with global goals such as the United Nations Sustainable Development Goals (SDGs) [15].

**Table 2.** Overview of initiatives and the roles of the organizations associated in different countries [14,16].

Country	Overview	Initiative(s)	Key Organization(s)	Objective	Impact
United States (US)	To establish the as a leader in nanotechnology research and applications.	National Nanotechnology Initiative (NNI) launched in 2000	National Science Foundation (NSF)	Funds basic research in nanotechnology.	The initiative has enhanced the US's global standing in nanotech research, contributing to advanced manufacturing and medical applications.
			National Nanotechnology Coordination Office (NNCO)	Coordinates NNI activities and monitors societal implications.	
			Department of Energy (DoE)	Focus on energy.	
			Department of Defence (DoD)	Focus on defence applications.	
China	Prioritizes nanotechnology through state-led initiatives like the National High-Tech R&D Program.	863 Program launched in 1986	Chinese Academy of Sciences (CAS)	Leads fundamental research.	China has rapidly become a global leader, with significant advancements in materials, electronics, and medicine
			National Center for Nanoscience and Technology (NCNT)	Fundamental and applied researches in the field of nanoscience and technology.	
			Suzhou Institute of Nano-Tech and Nano-Bionics	Key research areas such as electronic information, biomedical and functional materials.	
European Union (EU)	EU's Framework Programs emphasize nanotechnology as a key enabling technology.	Framework Programs in 2004 (European Green Deal and the Chemicals Strategy for Sustainability)	European Technology Platform for Nanomedicine (ETPN)	Focuses on healthcare innovations.	EU has fostered collaboration across member states, leading to breakthroughs in renewable energy and sustainable materials.
			Horizon Europe	Supports interdisciplinary nanotech research.	
India	To position the country as a significant global player.	Nano Mission launched in 2007	Indian Institute of Technology (IIT) and Indian Institute of Science (IISc)	Centres of excellence in nanotechnology.	Focus on affordable healthcare, clean energy, and water purification technologies.
			NanoScience and Technology Consortium (NSTC)	Facilitates academia–industry linkages.	
Brazil	Emphasizes integrating nanotechnology with industrial sectors.	National Nanotechnology Program in 2005	National Laboratory for Nanotechnology (LNNano)	Central for innovation.	Program has significantly advanced agriculture and health technologies.
			Ministry of Science, Technology, and Innovations (MCTI)	Provides strategic oversight.	
South Africa	Programs emphasizing sustainable development.	South African National Nanotechnology Strategy in 2005	South African Nanotechnology Initiative (SANi)	Promotes collaboration and funding.	Progress in water purification and renewable energy highlights nanotechnology's role in addressing local challenges.
			African Union	Encourages regional cooperation.	
Japan	Integrating nanotechnology into existing high-tech industries.	NanoTech Japan in 2001	Japan Science and Technology Agency (JST)	Supports basic and applied research.	Japan excels in semiconductors and electronics using nanotechnology.
			Nanotechnology Business Creation Initiative (NBCI)	Bridges research and commercialization.	
			National Institute of Advanced Industrial Science and Technology (AIST)	Develops next-gen nanomaterials.	

Table 2. Cont.

Country	Overview	Initiative(s)	Key Organization(s)	Objective	Impact
Russia	Emphasizes nanotechnology through its Strategy for Development of Nanotechnology in Russia.	NanoTechnology Development Program in 2007	RUSNANO	Focuses on funding and commercializing nanotechnology projects.	Focus on energy, aerospace, and medical devices.
			Kurchatov Institute	A research hub for nanotechnology.	
Republic of Korea	R&D and commercializing nanotechnology applications in semiconductors and biomedicine.	Nano 2020 Program	National NanoFab Center (NNFC)	Supports nanotechnology research	Nanotechnology applications in the electronics sector.
			Ministry of Science and ICT	Oversees strategic planning.	
Germany	Integrating nanotechnology into its industrial and innovation strategies.	Nanotechnology Action Plan in 2010	Federal Ministry of Education and Research (BMBF)	Focus on basic research.	Contributions to automotive, healthcare, and environmental technologies.
			Fraunhofer Institutes	Focuses on applied research in nanotechnology.	
Canada	Coordinates research and innovation through collaborations across academia, government, and industry.	NanoCanada in 2012	NanoCanada	Hub for nanotechnology.	Advances in quantum computing, nanomedicine, and materials science.
			National Research Council of Canada (NRC)	Funding for nano based research.	
Australia	Towards environmental sustainability and healthcare innovations.	Nanotechnology Strategy in 2012	Australian Research Council (ARC)	Funds nanotech research.	Progress in energy-efficient solutions and drug delivery systems.
			Australian National Fabrication Facility (ANFF)	Supports prototyping and innovation.	
Israel	Focus on defence, agriculture, and medicine.	Nanotechnology Leadership in 2007	Israel National Nanotechnology Initiative (INNI)	Promotes research and innovation	Breakthroughs in nanomedicine and smart materials.
			Technion–Israel Institute of Technology	Nanotechnology education and R&D.	
Singapore	Integrate nanotechnology into its vision of a smart nation.	Nano Singapore Initiative in 2000	Agency for Science, Technology, and Research (A*STAR)	Leads R&D in applied nano based research.	Advancements in clean energy and smart materials.
			Institute of Materials Research and Engineering (IMRE)	A leading research institution.	
Malaysia	Focus on research, industrial applications, and sustainable development	NanoMalaysia Program in 2011	NanoMalaysia Berhad	Coordinates nanotechnology projects and promotes industrialization.	Integrating nanotechnology into key industries, including healthcare, energy, electronics, and agriculture.
			National Nanotechnology Centre (NNC)	Oversees R&D and policy implementation.	
			NanoVerify	Provides certification for nanotech products to ensure quality and safety.	

Looking to the future, nanotechnology holds the promise of creating greener industries and addressing pressing societal needs. Governments are prioritizing ethical considerations and safety in nanotech development through stringent regulatory frameworks. Programs like the US's NNI and Japan's NanoTech Framework focus on multidisciplinary research and commercialization, ensuring that advances benefit both the economy and the environment [17]. By fostering international collaboration and public–private partnerships,

these initiatives aim to position nanotechnology as a cornerstone of sustainable global development [18].

Nanotechnology also plays a transformative role in agriculture and food security, with governments supporting innovations to enhance crop yields and reduce environmental impact. Nanofertilizers and nanopesticides, which deliver nutrients and protection at the nanoscale, are being developed to improve efficiency and minimize ecological harm [19]. Countries like Brazil and Malaysia are investing in nanotech for agricultural sustainability, focusing on applications such as smart sensors for soil health monitoring and nanomaterials for controlled-release fertilizers [20]. These innovations align with sustainable farming practices, reducing resource consumption while increasing productivity.

In the energy sector, nanotechnology has revolutionized solar cell efficiency, energy storage, and hydrogen production. Governments are funding research on nanomaterials like graphene and quantum dots to create more efficient photovoltaic cells and next-generation batteries [21]. For instance, the EU's Horizon Europe program [22] and China's state-led initiatives [23] emphasize clean energy technologies powered by nanoscale innovations. Similarly, water purification systems leveraging nanomaterials such as titanium dioxide and carbon nanotubes are being developed in countries like India and South Africa, offering cost-effective and scalable solutions to water scarcity [24,25].

Furthermore, healthcare and medicine are significant beneficiaries of nanotechnology initiatives, with governments funding research into nanodrugs, nanoscale diagnostics, and nanostructured implants. For instance, the EU's nanomedicine projects under Horizon Europe [26] and India's Nano Mission [27] have led to advancements in targeted drug delivery systems, reducing side effects and improving treatment outcomes. Nanotechnology-based diagnostics are enabling early disease detection, offering potential breakthroughs in managing global health challenges like cancer, infectious diseases, and neurological disorders. As countries integrate nanotech into their healthcare strategies, the focus remains on affordability and accessibility to ensure equitable benefits [28].

In summary, countries globally have embraced nanotechnology as a strategic domain, deploying dedicated organizations to drive research, innovation, and commercialization. Collaboration among academia, industry, and government remains a cornerstone of these initiatives, ensuring the ethical and responsible use of nanotechnology.

### **3. Nanotechnology and Its Role in Achieving Sustainable Development Goals**

The United Nations SDGs represent a universal blueprint to address pressing global challenges by 2030, encompassing 17 interconnected goals targeting economic growth, social inclusion, and environmental sustainability. The SDGs aim to eradicate poverty, ensure equitable access to healthcare and education, promote sustainable industrial practices, and mitigate climate change, fostering a better future for humanity. Achieving these goals requires innovative, scalable solutions that address complex challenges efficiently and equitably [15].

Technology and innovation play a critical role in bridging the gap between existing limitations and the ambitious targets of the SDGs. Among these, nanotechnology stands out as a transformative tool due to its capacity to manipulate matter at the atomic and molecular levels, enabling breakthroughs in energy, water purification, healthcare, agriculture, and environmental management. By leveraging nanotechnology, governments, industries, and researchers can develop affordable, sustainable, and high-performance solutions tailored to specific SDG objectives (Table 3) [14].

**Table 3.** Summarizing each SDG, its purpose, current limitations, and the role of nanotechnology in addressing those limitations [14]. Icons included were used from the United Nations' Sustainable Development Goals website [15].

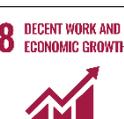
SDG [15]	Purpose	Current Limitations	Role of Nanotechnology
 <p><b>1</b> NO POVERTY</p>	Eradicate extreme poverty for all people everywhere.	Lack of access to basic resources, energy, and economic opportunities.	Enables affordable solutions like low-cost solar panels, improving energy access and fostering economic development in remote areas [29].
 <p><b>2</b> ZERO HUNGER</p>	End hunger, achieve food security, and promote sustainable agriculture.	Inefficient agricultural practices, resource wastage, and soil degradation.	Smart delivery systems for fertilizers and pesticides reduce wastage. Nanosensors monitor crop health, improving yields and minimizing environmental impact [30].
 <p><b>3</b> GOOD HEALTH AND WELL-BEING</p>	Ensure healthy lives and promote well-being for all at all ages.	Limited access to affordable healthcare, diagnostics, and targeted treatments.	Advances in nanomedicine enable precise drug delivery, early disease detection with nanosensors, and affordable nanostructured implants for healthcare improvement [31].
 <p><b>4</b> QUALITY EDUCATION</p>	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.	Limited access to educational tools, especially in rural or underprivileged areas.	Nano-enabled e-learning devices improve accessibility and durability. Nano-based materials lower production costs of educational devices and tools [32].
 <p><b>5</b> GENDER EQUALITY</p>	Achieve gender equality and empower all women and girls.	Inadequate access to healthcare, clean water, and sanitation disproportionately affects women.	Nanotechnology innovations like portable water purifiers and nanosensors for sanitation systems benefit women and children, reducing their workload in resource-scarce regions [33].
 <p><b>6</b> CLEAN WATER AND SANITATION</p>	Ensure availability and sustainable management of water and sanitation for all.	Water scarcity, contamination, and inefficient purification systems.	Nanomaterials like graphene oxide and carbon nanotubes enable efficient water purification, desalination, and pollutant removal [34].
 <p><b>7</b> AFFORDABLE AND CLEAN ENERGY</p>	Ensure access to affordable, reliable, sustainable, and modern energy for all.	High costs and inefficiencies in renewable energy technologies.	Quantum dots and perovskite nanomaterials improve solar cell efficiency. Nanomaterials in batteries enhance energy storage, reducing costs and increasing scalability [35].
 <p><b>8</b> DECENT WORK AND ECONOMIC GROWTH</p>	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all.	Limited job creation in emerging industries and resource inefficiencies.	Nanotechnology fosters innovation in green jobs, such as manufacturing nano-enabled energy devices, creating a sustainable workforce [1].
 <p><b>9</b> INDUSTRY, INNOVATION AND INFRASTRUCTURE</p>	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.	Aging infrastructure, limited adoption of advanced technologies, and inefficiency in resource utilization.	Nanocomposites improve material strength and durability. Nanosensors monitor structural health, reducing maintenance costs and enhancing infrastructure longevity [36].
 <p><b>10</b> REDUCED INEQUALITIES</p>	Reduce inequality within and among countries.	Limited access to technology and healthcare for disadvantaged communities.	Nano-enabled affordable medical devices and energy solutions bridge the gap in underserved areas [35].
 <p><b>11</b> SUSTAINABLE CITIES AND COMMUNITIES</p>	Make cities and human settlements inclusive, safe, resilient, and sustainable.	Urban pollution, inefficient waste management, and inadequate housing materials.	Nanotechnology offers air and water purification solutions, and nano-enhanced construction materials improve energy efficiency and reduce environmental impact [37].

Table 3. Cont.

SDG [15]	Purpose	Current Limitations	Role of Nanotechnology
 <p>12 RESPONSIBLE CONSUMPTION AND PRODUCTION</p>	Ensure sustainable consumption and production patterns.	Excessive waste generation, low recycling rates, and reliance on non-biodegradable materials.	Nano-enabled recyclable materials and nano-barriers in packaging reduce food waste. Nanotechnology supports efficient recycling of critical materials like rare earth metals [38].
 <p>13 CLIMATE ACTION</p>	Take urgent action to combat climate change and its impacts.	High greenhouse gas emissions and inefficiencies in renewable energy adoption.	Nanotechnology-based catalysts (e.g., MOFs) enhance carbon capture and storage. Nanomaterials in clean energy solutions reduce carbon footprints [39].
 <p>14 LIFE BELOW WATER</p>	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development.	Marine pollution, overfishing, and degradation of aquatic ecosystems.	Nanomaterials are used in sensors for monitoring water quality and in remediation techniques for cleaning up oil spills and microplastics [40].
 <p>15 LIFE ON LAND</p>	Protect, restore, and promote sustainable use of terrestrial ecosystems, manage forests, combat desertification, and halt biodiversity loss.	Deforestation, soil contamination, and habitat destruction.	Nanotechnology enables soil remediation using iron oxide nanoparticles and promotes sustainable land management through precision agriculture techniques [41].
 <p>16 PEACE, JUSTICE AND STRONG INSTITUTIONS</p>	Promote peaceful and inclusive societies, provide access to justice for all, and build effective, accountable institutions.	Inequalities in access to technology and transparency in governance.	Nano-enabled secure data storage and blockchain integration strengthen institutional transparency and accountability [42].
 <p>17 PARTNERSHIPS FOR THE GOALS</p>	Strengthen the means of implementation and revitalize the global partnership for sustainable development.	Limited collaboration and technology transfer between nations and sectors.	Nanotechnology promotes interdisciplinary and international collaboration in research, fostering partnerships for developing affordable and scalable innovations [43].

Nanotechnology addresses key sustainability challenges by improving efficiency and reducing waste. For instance, in energy, nanotechnology enhances the efficiency of renewable energy systems such as solar panels and batteries, reducing dependency on fossil fuels [36]. In healthcare, nanomedicine facilitates targeted drug delivery systems and early diagnostics, increasing treatment efficacy while minimizing costs [31]. Furthermore, nanomaterials are pivotal in environmental remediation, such as water purification systems using graphene oxide and soil remediation through nanoparticles, directly contributing to sustainable development.

The interdisciplinary nature of nanotechnology fosters global collaboration across academia, industry, and governments, promoting partnerships essential for achieving the SDGs. These collaborations accelerate the deployment of nano-enabled solutions in developing regions, ensuring equitable access to critical resources like clean water, affordable energy, and healthcare. As nanotechnology continues to evolve, its ethical and responsible development will be key to maximizing its potential while addressing concerns like environmental safety and equitable access, ensuring it remains a catalyst for sustainable global progress [29,43].

In summary nanotechnology's ability to address complex challenges makes it a powerful tool for achieving the SDGs. From ensuring food security and improving health outcomes to advancing clean energy and environmental conservation, nanotechnology is paving the way for a sustainable future. By integrating nanotech innovations into global strategies, nations can accelerate progress toward achieving these goals. Continuous in-

vestment, interdisciplinary collaboration, and ethical considerations will ensure that the benefits of nanotechnology are equitably shared across the globe.

#### 4. Confronting the “Valley of Death” in Nanotechnology

The “Valley of Death” refers to the critical gap between research and commercialization where promising scientific discoveries fail to transition into market-ready technologies [44]. In nanotechnology, this challenge is particularly pronounced due to the high costs of scaling up production, regulatory hurdles, and the complexity of integrating nanomaterials into existing industrial systems. Despite substantial advancements in nanoscale science, many innovations struggle to move beyond the laboratory, delaying their potential societal and economic impacts [45,46].

Nanotechnology faces unique obstacles in crossing the “Valley of Death”. These include the need for specialized infrastructure, such as cleanrooms and advanced fabrication facilities, which are expensive to establish and maintain. Additionally, nanotechnology’s interdisciplinary nature requires collaboration among diverse fields, complicating the coordination necessary for commercialization. Regulatory uncertainties regarding the safety and environmental impacts of nanomaterials further deter private investment, prolonging the development cycle [45,46].

Addressing this gap requires a multi-faceted approach involving funding, infrastructure, and policy support (Table 4). Governments and private sectors can establish public–private partnerships to de-risk investment in nanotechnology startups. Dedicated incubators and accelerators, such as the US NNI’s commercialization programs, offer platforms for transitioning research into products. Standardization and clear regulatory frameworks are also essential to alleviate concerns about nanomaterial safety, fostering greater investor confidence.

**Table 4.** Strategies for overcoming the “Valley of Death” and achieving sustainable commercialization in the field of nanotechnology [47].

Strategy	Description	Approaches
Early-Stage Funding and Grants [48]	Secure early-stage funding to bridge the gap between nanotechnology research and commercialization.	<ul style="list-style-type: none"> <li>Government grants (e.g., National Science Foundation SBIR/STTR).</li> <li>Angel investors.</li> <li>Crowdfunding platforms like Kickstarter or Indiegogo for nanotech products.</li> </ul>
Strategic Partnerships [49]	Collaborate with industry leaders, research institutions, and investors to reduce risks.	<ul style="list-style-type: none"> <li>Partner with established companies in the electronics, healthcare, or materials industries.</li> <li>Collaborate with academic institutions for advanced research.</li> </ul>
Proof of Concept and Pilots [50]	Develop and validate prototypes or pilot projects to demonstrate the feasibility of nanotech.	<ul style="list-style-type: none"> <li>Pilot projects with nanomaterials in industrial applications.</li> <li>Conduct lab-based simulations to test product viability (e.g., nanocoatings, drug delivery systems).</li> </ul>
Incremental Development and Scaling [51]	Gradually scale up from research and development (R&D) to full commercial production.	<ul style="list-style-type: none"> <li>Start small with targeted markets, such as consumer electronics, and scale up production.</li> <li>Focus on niche applications like nanotechnology in clean energy, sensors, or medicine.</li> </ul>

Table 4. Cont.

Strategy	Description	Approaches
Diversified Funding Sources [52]	Leverage multiple funding avenues to minimize financial risk in scaling nanotech ventures.	<ul style="list-style-type: none"> <li>• Venture capital firms with an interest in advanced materials.</li> <li>• Strategic partnerships with large multinational corporations.</li> <li>• Corporate research sponsorships.</li> </ul>
De-risking Technology [53]	Minimize technical uncertainties by conducting extensive testing and validation.	<ul style="list-style-type: none"> <li>• Extensive testing of nanomaterial properties (e.g., strength, conductivity).</li> <li>• Regulatory approval processes for nanotech-based medical devices or therapies.</li> </ul>
Robust Business Model Development [54]	Develop a solid business plan with clear revenue streams and a pathway to profitability.	<ul style="list-style-type: none"> <li>• Identify early commercial applications for nanotech (e.g., drug delivery, water filtration).</li> <li>• Establish business models based on licensing IP or direct product sales.</li> </ul>
Effective Intellectual Property Protection [55]	Protect intellectual property to maintain competitive edge and attract investors	<ul style="list-style-type: none"> <li>• File patents for novel nanomaterials and processes.</li> <li>• Create licensing agreements for patented nanotech innovations.</li> <li>• Trademark branded nanotech products or solutions.</li> </ul>
Market Readiness and Customer Focus [56]	Ensure technology aligns with market needs, and gather customer feedback for refinement.	<ul style="list-style-type: none"> <li>• Conduct market research to understand demand in industries like electronics, healthcare, or energy.</li> <li>• Develop customer personas and focus groups for nanotech-based products.</li> </ul>
Government and Regulatory Engagement [57]	Navigate complex regulations and ensure compliance with nanotechnology-related laws.	<ul style="list-style-type: none"> <li>• Work with regulatory bodies (e.g., FDA, EPA) for approval of nanotech in pharmaceuticals or consumer goods.</li> <li>• Stay updated on emerging global regulations for nanotechnology.</li> </ul>
Business Development and Sales [58]	Build a comprehensive sales strategy and marketing plan for nanotech products.	<ul style="list-style-type: none"> <li>• Develop go-to-market strategies for nanotech products (e.g., nanoelectronics, nanomaterials).</li> <li>• Leverage partnerships with industry leaders for distribution.</li> </ul>
Talent Acquisition and Retention [59]	Hire and retain a skilled workforce capable of advancing nanotech commercialization.	<ul style="list-style-type: none"> <li>• Recruit experts in nanomaterials, chemistry, and engineering.</li> <li>• Offer equity or profit-sharing to incentivize key team members.</li> </ul>
Financial Management and Metrics [60]	Maintain robust financial oversight and establish clear KPIs to monitor progress.	<ul style="list-style-type: none"> <li>• Develop financial models that account for the high initial investment in nanotechnology.</li> <li>• Track metrics such as product development costs, commercialization timelines, and ROI.</li> </ul>
Post-Launch Support and Iteration [61]	Continuously improve and support products post-launch to ensure long-term success.	<ul style="list-style-type: none"> <li>• Establish customer support channels for nanotech products.</li> <li>• Update and refine products based on user feedback and advancements in nanotechnology research.</li> </ul>

To confront the “Valley of Death” in nanotechnology effectively, fostering collaboration across academia, industry, and policy is critical. Encouraging international partnerships and sharing best practices can reduce costs and accelerate the commercialization timeline. Additionally, focusing on scalable, high-impact applications—such as energy-efficient

nanomaterials or nano-enabled medical devices—can build early successes that attract further investment. Bridging this gap will ensure that nanotechnology reaches its full potential, driving innovation and contributing to global sustainability.

## 5. Worldwide Investment in Nanotechnology

From 2000 to 2024, there was a significant increase in global investment in nanotechnology. The US government consistently maintained a leadership role in funding, contributing significantly by 2024. The European Commission invested €1.3 billion in nanotechnology research in Europe from 2004 to 2006 [62], with ongoing investment in subsequent years. Japan, the Republic of Korea, and Germany emerged as significant contributors to nanotechnology funding, with Japan's private sector accounting for more than two-thirds of overall investments.

### 5.1. Global Investment Landscape in Nanotechnology

Nanotechnology is one of the most exciting and transformative fields of research, leading to rapid advancements across industries like healthcare, energy, electronics, and materials science. The global investment landscape in nanotechnology has evolved significantly over the past two decades, as governments, corporations, and private investors have recognized the field's potential to drive innovation and economic growth. As of recent estimates, the global nanotechnology market is projected to exceed USD 125 billion by mid-2024 [63]. The increasing recognition of its ability to revolutionize industries has led to a surge in funding for nanotech R&D and commercialization. Governments around the world have been allocating substantial resources to fund this sector, while venture capital and corporate investments have helped bridge the gap between research and practical application.

### 5.2. Government Funding and National Initiatives

Governments play a significant role in funding nanotechnology research, offering financial support through grants, dedicated research programs, and national initiatives aimed at fostering innovation. The US has been one of the leading investors in nanotechnology, with the NNI established in 2000 [64]. The NNI has allocated over USD 1.5 billion annually for nanotechnology research and development, supporting more than 20 federal agencies, including the Department of Energy and the National Institutes of Health. China, the largest global investor in nanotechnology, has committed billions of dollars to nanoscience research as part of its national 5-year plans [64]. As of 2020, China's annual investment in nanotechnology research surpassed USD 1.5 billion, and the country is actively investing in projects involving nanomaterials, nanomedicine, and energy applications [65]. In Europe, the EU funds nanotechnology under the Horizon 2020 program, with more than €2.7 billion allocated to nanotechnology-related projects from 2014 to 2020. This collaborative investment model has been crucial for advancing nanotechnology research and its applications.

### 5.3. Venture Capital Investment

Venture capital investment has been pivotal in advancing the commercialization of nanotechnology, particularly in sectors like healthcare, materials, and energy. Venture capital firms are attracted to the potential of nanotechnology to disrupt traditional industries and provide breakthrough solutions. In 2020 alone, global venture capital funding for nanotechnology startups reached over USD 1.9 billion, with significant investments directed towards companies working on nanomedicine, nanoelectronics, and clean energy [66]. A notable example is Nanobiotix, a nanomedicine company focused on developing radiotherapy treatments, which raised USD 70 million in a series D funding round [67]. Similarly,

Nanosys, a leader in quantum dot technology for display applications, secured funding from top investors, including Samsung and Intel [68]. While venture capital investments continue to pour in, they are often targeted toward companies that are addressing immediate market needs and have a clear path toward scaling their technologies, such as those developing nanomaterials for batteries, energy storage, and smart sensors.

#### *5.4. Corporate Investments and Industry-Specific Funding*

Large multinational corporations have been key players in funding nanotechnology innovation, as they look to leverage nanotech to enhance their product offerings and maintain competitive advantages. Corporations in sectors like electronics, pharmaceuticals, and materials have invested heavily in nanotechnology. For instance, IBM and Intel have invested in nanotechnology for the development of smaller, more powerful semiconductors. In 2019, Intel announced an investment of over USD 1 billion in the development of new nanotechnology-based chip technologies [69]. In the pharmaceutical industry, companies like Pfizer and Novartis have invested in nanomedicine to develop drug delivery systems and targeted therapies, with Pfizer investing USD 100 million in nanotechnology research through collaborations with universities and startups [70]. Moreover, in the energy sector, Shell and ExxonMobil have supported projects that explore the use of nanomaterials for more efficient solar cells, batteries, and fuel cells, with ongoing investments of hundreds of millions of dollars [71].

#### *5.5. Collaborative Funding Models and International Cooperation*

International collaboration has become an increasingly important source of funding in nanotechnology, enabling research institutions and companies across borders to pool resources and knowledge. Programs such as the EU-China Nanotechnology Cooperation Program have been instrumental in facilitating joint research projects between European and Chinese entities. Additionally, the United Nations Industrial Development Organization and the World Intellectual Property Organization have supported funding initiatives that promote nanotechnology for sustainable development in emerging economies [14]. Such collaborations allow for the sharing of costs and expertise, accelerating the pace of nanotechnology research and development. In 2021, the EU allocated €1 billion under the Horizon Europe program for nanotechnology, with a focus on sustainability and healthcare applications, and international partnerships are expected to play an increasingly central role in advancing nanotech's global impact [14].

#### *5.6. Challenges and Future Outlook for Investment*

Despite the significant increase in investment, there are still challenges that could affect the growth of nanotechnology, especially in terms of commercialization and public acceptance. High production costs, technical hurdles, and regulatory uncertainty remain obstacles for scaling up nanotech applications. Moreover, concerns about the environmental and health safety of nanomaterials have led to calls for more stringent regulations, which could increase development costs. However, the growing global awareness of nanotechnology's potential benefits means that investment in nanotechnology is likely to continue increasing, with a focus on de-risking technological challenges and ensuring safety standards. As of 2024, experts predict that investments in nanotechnology will continue to rise, with a special emphasis on green nanotechnology and its potential to address global challenges such as climate change, energy efficiency, and healthcare [72]. The combined efforts of governments, private investors, and international collaborations will be crucial in driving the sustainable growth of the nanotechnology market in the years to come.

## 6. Cooperation Between Public and Private Sectors

The progression of nanotechnology has been propelled by partnerships among federal agencies, corporations, and academic institutions. In the US, the private sector constituted 60% of nanotechnology spending, whereas in Japan, private investment represented more than two-thirds of total funding. The amalgamation of public and private funding has enabled the US and Japan to sustain their pre-eminence in nanotechnology, fostering advancements in nanobiotechnology, nanomaterials, and nanodevices.

### 6.1. Importance of Public–Private Cooperation in Nanotechnology

The development of nanotechnology has been greatly influenced by collaboration between the public and private sectors, especially in countries with significant investments in high-tech research and development [73]. The unique challenges and opportunities in nanotech—ranging from basic scientific discovery to scaling up production and commercialization—require a combination of government funding, policy support, and private sector innovation. Governments often provide the necessary infrastructure, regulatory frameworks, and initial funding for basic research, while private companies bring in the technological expertise and capital required to bring innovations to market [74]. Such cooperation is vital for advancing nanotech solutions that can transform industries like healthcare, energy, and electronics, and address global challenges such as environmental sustainability and climate change.

### 6.2. United States: National Nanotechnology Initiative

In the US, the NNI has served as a key platform for fostering public–private partnerships in nanotechnology. The initiative involves over 20 federal agencies, such as the DOE, National Institutes of Health, and the NSF, that fund both basic and applied nanotech research [64]. The NNI has allocated billions of dollars to support nanotechnology projects, some of which involve collaborations with private companies to commercialize breakthroughs. A notable example is Nanosys, a nanomaterial company that develops quantum dots for electronics and displays. Nanosys has received federal funding through the NNI and partnered with companies like Samsung [68] and LG Electronics [75] to bring their nanomaterial-based display technologies to market. Such partnerships are vital for translating government-funded research into commercially viable products, enabling private companies to scale up production and reach global markets.

### 6.3. China: Government-Driven Nanotech Innovations

China has become a global leader in nanotechnology due to significant public investments and strong public–private cooperation. The Chinese government has included nanotechnology in its five-year plans and committed substantial resources to its development. In 2019 alone, China invested over USD 1.5 billion in nanotech R&D, which includes research in areas like nanomaterials, nanoelectronics, and nanomedicine [65]. The government works closely with private companies, including tech giants like Huawei and Tencent, to accelerate the commercialization of nanotech innovations. For example, Huawei collaborates with Chinese universities and government research institutes to develop advanced materials for use in telecommunications and electronics [76]. In the medical field, companies like Biosino are working with the government to develop nanotechnology-based diagnostic tools [77]. These collaborations have enabled China to rapidly advance its nanotech industry and commercialize cutting-edge products on a global scale.

#### 6.4. European Union: Horizon Europe and Industry Collaboration

In Europe, the Horizon Europe program is a key vehicle for public–private cooperation in advancing nanotechnology. With a budget of over €5.4 billion for the 2021–2027 period, Horizon Europe funds a wide range of R&D projects, many of which focus on nanotech and its applications in industries like healthcare, energy, and manufacturing [78]. A notable example is the Graphene Flagship, a European research initiative aimed at developing graphene-based technologies. The project is a collaboration between academic institutions, research organizations, and private companies such as Bosch, Airbus, and Siemens, which bring their industry expertise and funding to the table [79]. These partnerships have already resulted in several commercial applications of graphene in electronics, automotive, and aerospace industries. The EU’s emphasis on public–private collaboration helps ensure that nanotech research moves quickly from the lab to the marketplace, benefiting both European industries and global consumers.

#### 6.5. India: Public–Private Partnerships in Nanotech for Healthcare

India is rapidly emerging as a key player in the global nanotechnology landscape, particularly in the field of healthcare. The Indian government has established the NanoMission under the Department of Science and Technology to support nanotech research and commercialization, with a ten-year investment of ₹1000 crore (about USD 140 million) [80]. This initiative encourages partnerships between public research organizations and private companies. These collaborations not only advance nanotech solutions for healthcare but also help India build a competitive edge in global nanotech markets. The public sector’s funding and regulatory support are crucial for enabling such innovative healthcare solutions.

#### 6.6. Japan: Bridging the Gap Between Research and Commercialization

Japan has a long history of government and private sector collaboration in advanced technologies, including nanotechnology. The Japan Science and Technology Agency plays a central role in funding nanotech research through initiatives such as the World Premier International Research Center Initiative. Japan’s private sector, including global corporations like Sony, Hitachi, and Toyota, actively participates in these initiatives, turning academic research into marketable products [81]. The partnership aims to commercialize next-generation battery technologies that can significantly improve energy storage efficiency, which is critical for the electric vehicle and renewable energy industries. These joint efforts in Japan exemplify how public and private entities can work together to transform scientific discoveries into tangible products that meet global market demands.

#### 6.7. Saudi Arabia: Public–Private Cooperation

Saudi Arabia has been making significant strides in advancing nanotechnology, primarily through collaboration between the public and private sectors. The Saudi government has recognized nanotechnology as a key driver for future innovation, economic diversification, and sustainable development, in line with its Vision 2030 initiative. The King Abdulaziz City for Science and Technology (KACST) is the leading government organization driving nanotech innovation in Saudi Arabia [82]. KACST supports both fundamental research and applied nanotechnology projects, with a focus on areas such as nanomaterials, energy, water desalination, and healthcare. The Saudi National Science, Technology, and Innovation Plan has also allocated resources to enhance the country’s capabilities in nanotechnology. In addition, the King Abdullah University of Science and Technology (KAUST) is playing a major role in advancing nanotech research, providing state-of-the-art labs and fostering collaboration with international institutions. KAUST has been instrumental in facilitating partnerships between the public and private sectors to commercialize nanotechnology

innovations, such as advanced nanomaterials for energy storage and medical applications. Saudi Aramco, the world's largest oil company, is one of the key private players investing in nanotechnology research, especially for energy applications [83]. Saudi Aramco has been working on developing nanomaterials for improving the efficiency of energy storage, as well as for advanced oil recovery techniques. Additionally, private companies are working with government-funded institutions like KACST to develop water purification technologies using nanomaterials, a critical need for a country that faces water scarcity challenges. These collaborations are key to scaling up nanotech innovations and integrating them into industries that are critical to Saudi Arabia's economy.

In summary, these examples across different countries demonstrate that effective public–private cooperation is essential for advancing the field of nanotechnology. By combining government support with private sector expertise and investment, nations can accelerate the transition from research to commercialization, driving innovation and economic growth in nanotech-related industries. As the global nanotechnology market continues to grow, these partnerships will remain crucial for addressing the technological, regulatory, and financial challenges involved in scaling up nanotech applications.

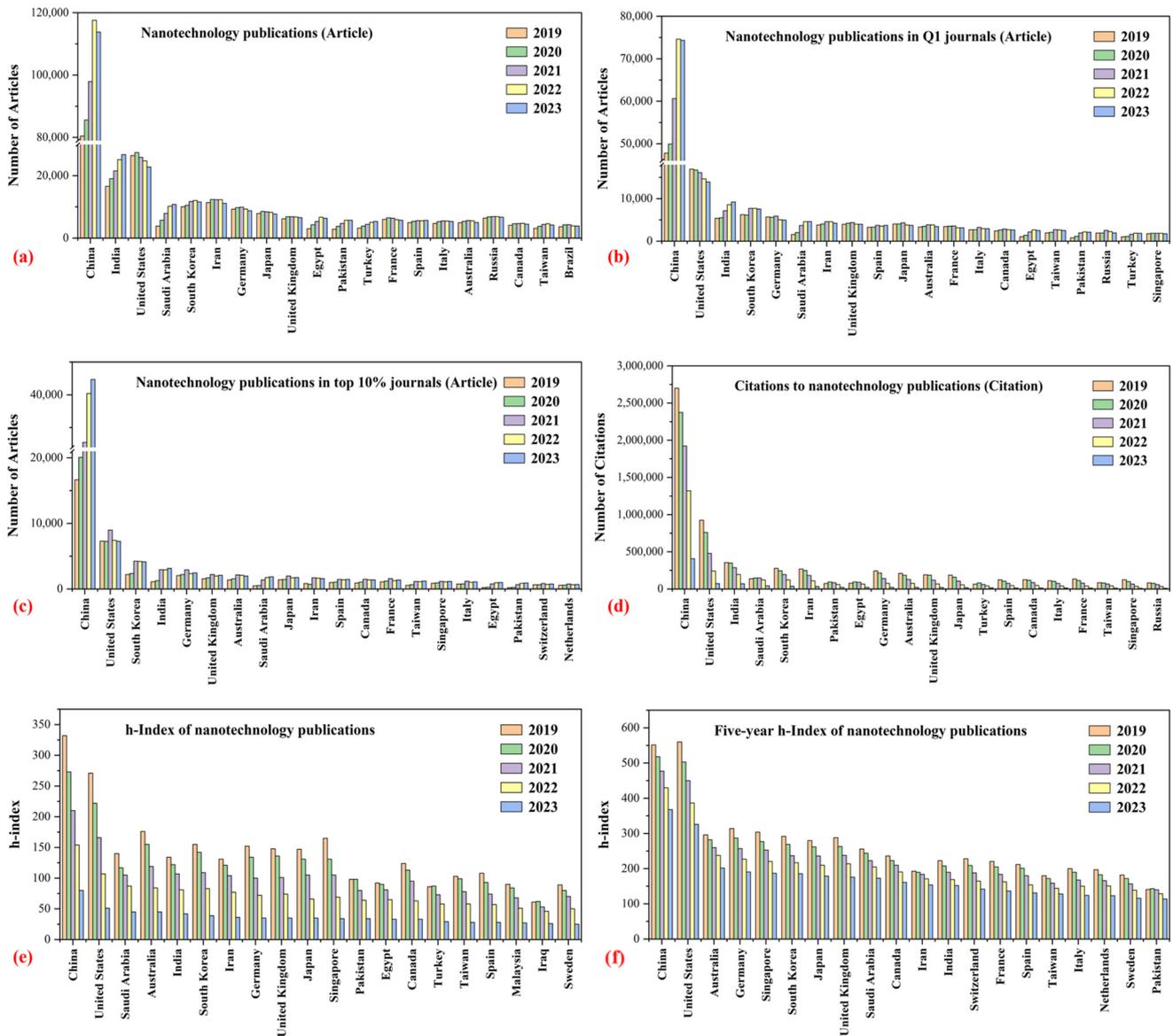
## 7. Evaluation of Advancements in Nanotechnology

The improvement in nanotechnology can be evaluated through a Techno-Economic Network framework, which assesses developments in research, technology, and market applications. Scientific advancement is quantified through publications, technological breakthroughs through patents, and market expansion through the commercialization of nanotechnology products. An analysis of these three pillars reveals that nanotechnology has achieved considerable advancements in both research and practical applications from 2000 to 2024.

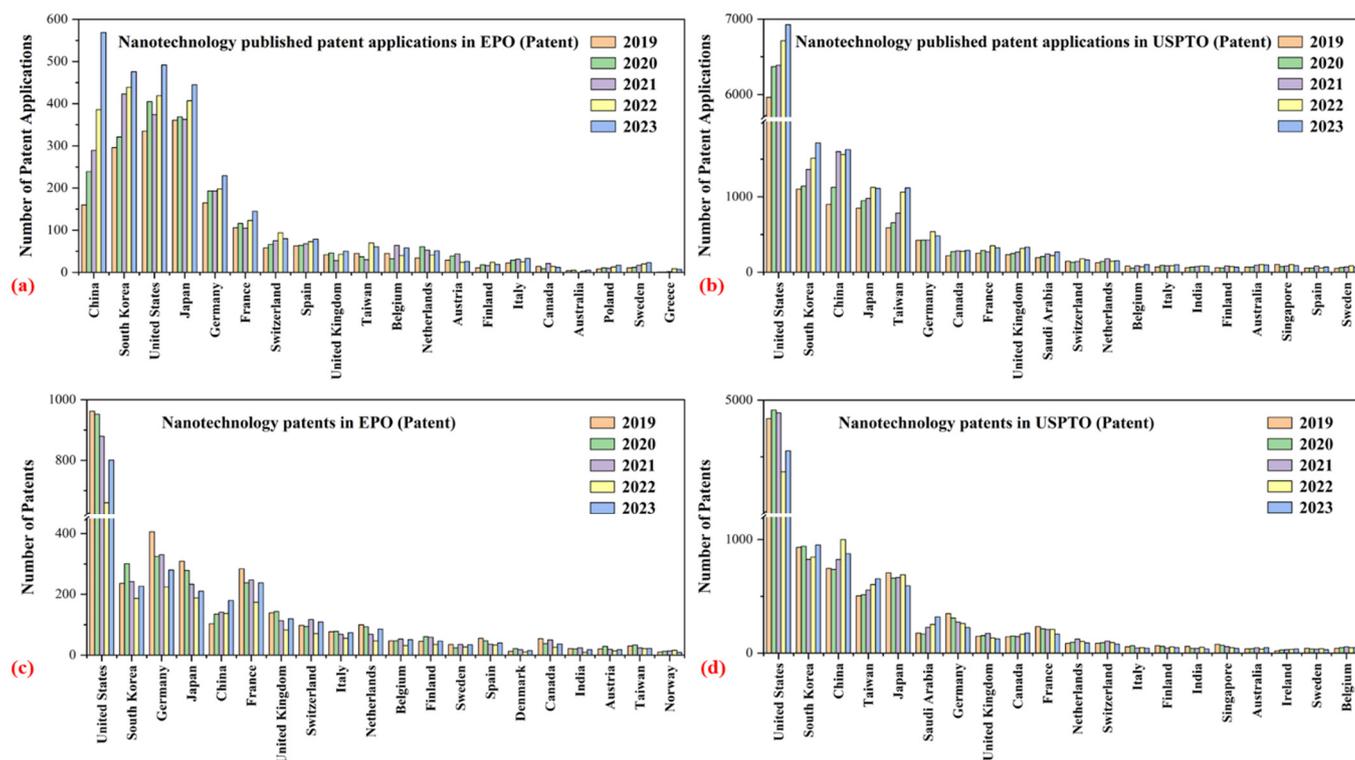
The scientific aspect of nanotechnology innovation has predominantly been propelled by research undertaken in industrial and academic laboratories, with publications acting as a crucial indicator of scientific productivity. The quantity of publications is a significant metric, but their quality—frequently signified by citation frequency—is essential for assessing their impact on the discipline. The cumulative expansion of nanotechnology-related publications has been consistent, with significant rises observed in countries such as China and India (Figure 1).

The technological aspect of nanotechnology innovation is most effectively assessed by patent filings, which indicate the ability to convert scientific findings into technological applications and commercial goods. Patents act as a conduit between research and commercialization. Data from the European Patent Office reveal a consistent increase in nanotechnology patent families from 2019 to 2024 (Figure 2). The initial expansion in patent filings until 2006 was slow; nevertheless, a significant increase in patents has been noted since 2019, largely attributable to improved collaborations between research institutions and worldwide industries.

This expansion is reflected in the increase in nanotechnology papers and patents. The quantity of articles about nanotechnology has significantly risen, particularly in nations such as China, US, Japan, and the Republic of Korea. China, notably, dominates the worldwide landscape with the highest volume of patents and publications, accounting for nearly 40% of all nanotechnology-related patents by 2023.



**Figure 1.** Top 20 countries for (a) nanotechnology publications (articles), (b) nanotechnology publications in Q1 journals (articles), (c) nanotechnology publications in top 10% journals (articles), (d) citations to nanotechnology publications, (e) h-index of nanotechnology publications, and (f) five-year h-index of nanotechnology publications from 2019 to 2023. Raw data used to generate graphs were extracted from the STATNANO database [84].



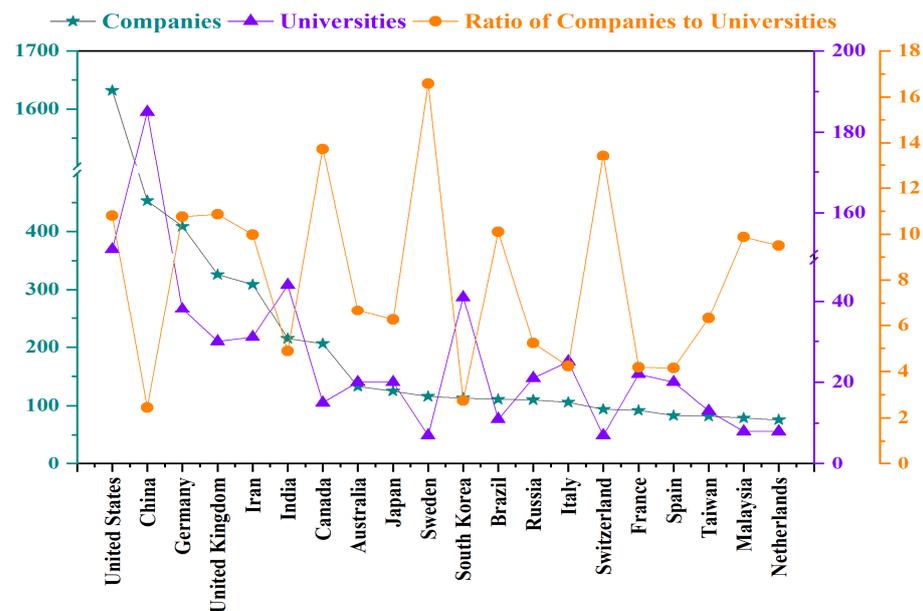
**Figure 2.** Top 20 countries for (a) patent applications in EPO, (b) patent applications in USPTO, (c) patents in EPO, and (d) patents in USPTO from 2019 to 2023. Raw data used to generate graphs were extracted from the STATNANO database [84].

## 8. Role of Partnership Between Companies and Universities

Partnerships between companies and universities play a pivotal role in advancing nanotechnology applications by fostering innovation, bridging theoretical research with practical implementation, and accelerating commercialization. These collaborations enable universities to focus on fundamental research while industries guide the application of these findings to market-ready products (Figure 3). According to a 2023 report by the NNI, approximately 65% of nanotechnology advancements stem from academia–industry collaborations. This synergy ensures that groundbreaking technologies, such as carbon nanotubes and quantum dots, transition effectively from laboratories to sectors like healthcare, electronics, and renewable energy.

One prominent example is the partnership between IBM and the Massachusetts Institute of Technology. Their joint research on nanoscale devices has significantly improved the efficiency of transistors and microprocessors, impacting the semiconductor industry [85,86]. Similarly, the collaboration between Rice University and Shell has led to enhanced methods for carbon capture using nanomaterials, aiding global efforts against climate change [87]. These underscore the critical role of shared expertise and resources.

Furthermore, partnerships facilitate workforce development and knowledge transfer. Companies often support university programs by funding scholarships and research facilities, preparing a skilled workforce adept in nanotechnology. For instance, the University of Manchester’s collaboration with Graphene Flagship has not only advanced graphene-based technologies but also trained thousands of researchers in nanoscience applications [88]. This mutual benefit ensures that both academic and corporate entities maintain competitive edges, propelling industries such as drug delivery and energy storage toward revolutionary breakthroughs.



**Figure 3.** Top 20 countries by companies and universities associated with nanotechnology. Raw data used to generate graph were extracted from the STATNANO database [84].

Collaborative partnerships between companies and universities in nanotechnology also play a vital role in addressing global challenges such as healthcare, energy sustainability, and environmental protection. For instance, the California NanoSystems Institute at University of California, Los Angeles has partnered with NanoPacific Holdings Inc. to commercialize nanoparticle-based technologies aimed at enhancing cancer treatment. This collaboration focuses on creating mechanized nanoparticles capable of targeted drug delivery, potentially improving the efficacy and reducing the side effects of chemotherapy [89]. According to the Global Nanotechnology Market Report 2023, healthcare accounts for over 30% of nanotechnology investments, with significant contributions from academic–industry collaborations [90]. These joint ventures ensure that research outcomes meet regulatory standards and are optimized for practical use.

Another critical impact of these partnerships is their contribution to the rapid prototyping and commercialization of nanotechnology-based products. Universities often provide the foundational research and experimental facilities, while companies contribute expertise in scaling up production and navigating market dynamics. For example, the collaboration between Stanford University and Intel has resulted in the commercialization of nanoscale computing technologies that enhance the performance and energy efficiency of processors [91]. This has enabled the tech industry to meet growing demands for smaller, faster, and more sustainable devices. Reports suggest that nanotechnology-based products generated from over USD 67 billion to USD 83 billion in economic value in 2022, much of which was driven by collaborative initiatives [10].

Regional economic development also benefits significantly from such partnerships, as they attract investment, create jobs, and build innovation hubs. Research parks and incubators, often formed through academia–industry collaborations, provide the ecosystem necessary for startups to thrive. The Nano-Bio Manufacturing Consortium, a collaboration among academic institutions, private companies, and government agencies in the US, is an example of how partnerships can drive local innovation [92]. By focusing on flexible electronics and wearable sensors, the Nano-Bio Manufacturing Consortium has not only advanced nanotechnology applications but also bolstered regional economies through job creation and infrastructure development.

Lastly, partnerships foster global competitiveness by ensuring that national industries stay at the forefront of technological advancements. Countries like Germany, Japan, and the US lead in nanotechnology innovation largely due to strong collaborations between universities and industry. In Germany, Fraunhofer Institutes work closely with companies like BASF to innovate in fields such as nanomaterials and coatings [93]. Similarly, Japan's University of Tokyo collaborates with Toyota to develop next-generation battery technologies using nanomaterials [94]. These collaborations ensure that nations maintain leadership in high-tech sectors while addressing pressing challenges in energy, environment, and medicine. As global competition intensifies, the integration of academic and industrial expertise remains a cornerstone of success in the nanotechnology landscape.

## 9. Innovation and Transition to Industrial Manufacturing

Nanotechnology has sparked a new era of innovation, especially in manufacturing processes and product design. By manipulating matter at the atomic and molecular scale, nanotechnology can enhance material properties like strength, conductivity, and reactivity, making it applicable across a wide range of industries, from electronics to healthcare. However, translating these innovations from small-scale research to large-scale industrial manufacturing is a significant challenge [95]. Real-world examples demonstrate how the transition is taking place through advancements in material science, process engineering, and production techniques, turning scientific breakthroughs into commercially viable products.

The shift from research and development to industrial production is a critical component of nanotechnology's progress. The economic importance of nanotechnology can be assessed through market size and shares; however, this is difficult due to its extensive application across multiple sectors (Figure 4). Since the early 2000s, various projections regarding the market size of nanotechnology have been formulated, yielding diverse results. The NSF anticipated a more cautious estimate of approximately USD 1 trillion by 2020 [96]. Both forecasts highlight the significant market growth propelled by nanotechnology across various sectors, especially post-2020.

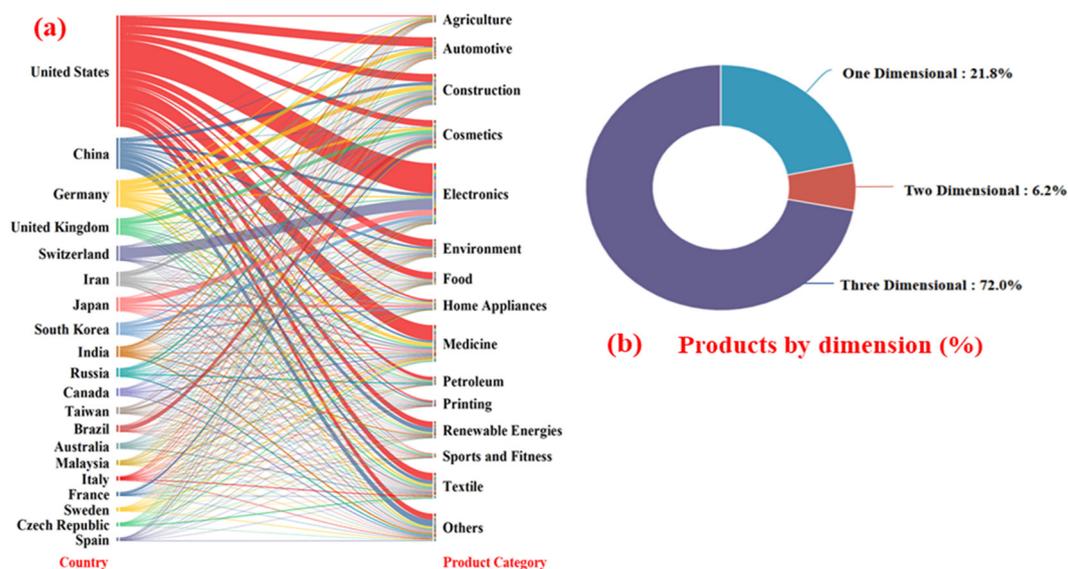
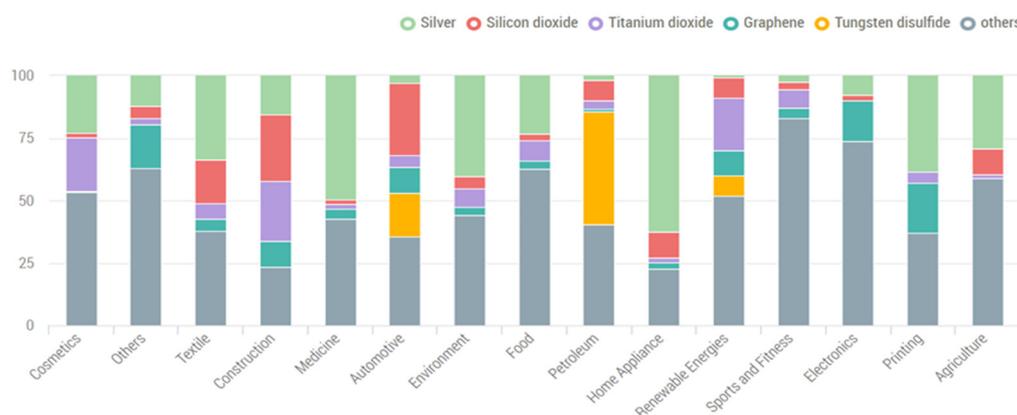


Figure 4. Cont.



(c) Nanomaterials used in products by industrial divisions (%)

**Figure 4.** (a) Top 20 countries with nanotechnology-based products in various categories, (b) percentage of nanotechnology products based on different nanomaterial dimension, (c) various nanomaterials used in products of different categories. Raw data used to generate (a) were extracted, whereas (b,c) were used directly from the STATNANO database [97].

### 9.1. Nanomaterials in Electronics: Quantum Dots and Flexible Displays

One of the most successful transitions from innovation to industrial manufacturing has been in quantum dots for electronics. These semiconductor nanocrystals have unique optical properties that are ideal for display technologies. Nanosys, a leading company in this field, has worked closely with industry giants like Samsung and LG Electronics to incorporate quantum dots into QLED (Quantum Dot LED) displays [68,75]. The shift from laboratory research to mass production involved overcoming challenges related to controlling the size and uniformity of the quantum dots to ensure consistent performance in large-screen displays. The industrialization process used scalable production techniques like chemical vapor deposition and hot-injection methods, which allow for large-scale production of high-quality quantum dots [98]. These displays are now commercially available worldwide, representing a successful application of nanotechnology in consumer electronics.

### 9.2. Carbon Nanotubes in Aerospace and Automotive Manufacturing

Another example of nanotechnology making the leap to industrial manufacturing is carbon nanotubes (CNTs), which are used in the aerospace and automotive industries for making lightweight, high-strength composites [99]. CNTs have remarkable mechanical properties, such as high tensile strength and excellent electrical conductivity [100]. In the aerospace sector, companies like Boeing and Airbus have begun integrating CNTs into composite materials used in aircraft structures, reducing weight and improving fuel efficiency [101]. The nano-enhanced composites have been manufactured using techniques like melt compounding and polymer matrix infiltration, which enable scalable production. These composites are also used in automotive parts to improve performance, durability, and fuel efficiency [101]. The successful incorporation of CNTs into these industries demonstrates how nanomaterials, once confined to the laboratory, are now integral to critical industrial applications.

### 9.3. Nanocoatings for Enhanced Durability and Corrosion Resistance

Nanocoatings have gained widespread use in various industries, particularly in aerospace, automotive, and electronics, due to their ability to impart unique properties like anti-corrosion, scratch resistance, and self-cleaning abilities [102]. P2i, a company specializing in nanocoating technologies, has developed liquid-repellent coatings that

protect electronics and textiles. These coatings are created using atomic layer deposition or plasma-enhanced chemical vapor deposition techniques [103]. For instance, Apple has applied these nanocoatings to its smartphones to make them resistant to water and dirt, ensuring greater durability [104]. The industrialization of nanocoatings involves overcoming challenges related to uniform application and cost efficiency, but as production processes like spray coating and dip coating are refined, these technologies are being scaled up for use in mass production.

#### *9.4. Nanomedicine: Nanoparticles for Drug Delivery Systems*

Nanotechnology's impact on healthcare and pharmaceuticals is exemplified by the development of nanoparticles for drug delivery systems. One of the most notable real-time examples is the transition of lipid nanoparticles used in mRNA vaccines like those developed for COVID-19 [105]. Companies such as Moderna and Pfizer-BioNTech utilized lipid nanoparticles to encapsulate mRNA and deliver it effectively to cells [106,107]. The successful large-scale production of these vaccines required overcoming significant manufacturing challenges, including ensuring the stability of the nanoparticles during production and distribution. The lipid nanoparticle formulations are created using techniques like high-pressure homogenization, which are scalable and can be applied in the mass production of mRNA vaccines and other therapeutics [108]. This breakthrough represents a significant example of how nanotechnology has revolutionized drug delivery systems, transitioning from experimental laboratory concepts to lifesaving products used on a global scale.

#### *9.5. Nanostructured Catalysts in Chemical Manufacturing*

In the field of chemical manufacturing, the transition of nanostructured catalysts from laboratory innovation to industrial-scale production has been a game changer. Nanocatalysts, made from metals like platinum, palladium, or gold, are known for their high surface area and improved efficiency in catalyzing chemical reactions [109]. In industries such as petrochemicals and pharmaceuticals, nanocatalysts have been used to improve reaction rates and reduce energy consumption. For example, Johnson Matthey, a leading catalyst manufacturer, has developed nanocatalysts for cleaner fuel production and efficient chemical reactions [110]. The shift to industrial-scale production has been made possible by processes like sol-gel synthesis and co-precipitation, which are scalable methods used to produce uniform nanoparticles [111]. These advancements in nanocatalysts are helping reduce the environmental impact of chemical manufacturing while also enhancing production efficiency.

#### *9.6. Future of Nanomanufacturing: Automation and Green Technologies*

Looking forward, the integration of automation and green nanomanufacturing will play an essential role in scaling nanotechnology for industrial applications. Innovations such as self-assembly processes, where nanoparticles spontaneously organize themselves into desired structures, promise to reduce manufacturing costs and energy usage [112]. Additionally, green manufacturing techniques, like aqueous synthesis methods and biotechnological approaches, aim to reduce the environmental footprint of nanotechnology production [113]. Companies are also exploring roll-to-roll processing, a method commonly used in flexible electronics, to produce nanomaterials efficiently on large scales. For example, Applied Materials, a leader in semiconductor equipment, is working on automated systems for the production of nanoelectronics that can significantly reduce production costs while maintaining precision and quality [114]. These advancements will not only streamline the industrialization of nanotechnology but also ensure that nanomanufacturing aligns with sustainable and eco-friendly production standards.

In summary, nanotechnology's transition from the laboratory to industrial manufacturing is marked by real-time examples where scientific innovation has led to the development of products that are now part of daily life. From nanomaterials in electronics and aerospace to nanomedicines and green manufacturing solutions, the progress in scaling up nanotech innovations demonstrates its potential to reshape industries. By overcoming challenges related to scalability, reproducibility, and cost efficiency, nanotechnology is set to drive the future of manufacturing and continue to open new frontiers in product development and industrial applications.

## 10. Economic Consequences of Nanotechnologies—A Balancing Act

The distinctiveness of nanoparticle technology arises from the properties of materials at the nanoscale (1 to 100 nm), which frequently diverge from those of bulk materials. These attributes facilitate a variety of applications across sectors including consumer goods, electronics, renewable energy, and medical technology [115]. Nanotechnology significantly enhances transistors, memory chips, and display technologies, while also contributing to the advancement of more efficient solar panels, batteries, and wind turbine blades [116]. The swift advancement of nanoparticles for medication administration and molecular imaging has transformed the medical sector [117].

By 2024, nanotechnology had become essential to multiple businesses, generating billions for worldwide markets. Innovations in nanomaterials for energy storage, particularly in battery technology, are anticipated to dramatically influence the electric vehicle and renewable energy sectors [118]. The global market for nanotechnology-based consumer products, including cosmetics and household goods, is expanding due to advancements in material design and manufacturing.

Nanotechnology has the potential to dramatically reshape economies by driving innovation, enhancing productivity, and creating new industries [119]. As nanotechnology continues to evolve, it promises to contribute significantly to economic growth, particularly in high-tech sectors such as electronics, energy, healthcare, and manufacturing [120]. However, while the economic potential is vast, it also comes with challenges, including investment risks, regulatory hurdles, and potential job displacement due to automation. The economic consequences of nanotechnologies will depend on how effectively governments, businesses, and research institutions collaborate to harness these innovations while addressing the associated risks (Table 5) [121].

**Table 5.** Highlights the dual-edged nature of nanotechnology's economic impact.

Category	Positive Economic Consequences	Negative Economic Consequences
Industry Growth	New markets in nanomedicine, nanoelectronics, and nanomaterials.	High R&D costs restrict access for small enterprises and startups.
Job Creation	Increased demand for skilled professionals in nanotech-related fields.	Potential job displacement in traditional industries.
Innovation	Advances in materials science and technology, boosting efficiency.	Innovations may concentrate in wealthier nations, exacerbating inequality.
Healthcare	Novel treatments and diagnostics, improving patient outcomes.	Higher costs for advanced nanotechnology-based medical solutions.
Sustainability	Development of energy-efficient and environmentally friendly technologies.	Environmental concerns from improper disposal of nanomaterials.
Manufacturing	Improved product quality and precision, reducing waste.	Significant costs to upgrade existing manufacturing processes.
Agriculture	Enhanced crop yields with nano-fertilizers and pesticides.	Potential long-term environmental effects of nano-agrochemicals.

Table 5. Cont.

Category	Positive Economic Consequences	Negative Economic Consequences
Energy Sector	Better renewable energy solutions like advanced batteries and solar cells.	Dependence on rare earth elements raises supply chain risks.
Consumer Products	Superior performance in goods like electronics, clothing, and cosmetics.	Increased costs may limit accessibility for average consumers.
Global Trade	Boosts export potential for nanotechnology-leading countries.	Risk of trade imbalances if adoption remains uneven across nations.
Economic Disparities	Opportunities for emerging markets to leapfrog in technological adoption.	Deepened divides between technologically advanced and lagging regions.
Regulatory Implications	Stimulates development of new policies and regulatory frameworks.	Costs of compliance can be burdensome for smaller companies.
Insurance and Liability	Growth of insurance markets for covering nanotech risks.	Unknown long-term effects may lead to liability issues and high premiums.

### 10.1. Economic Growth and Job Creation

Nanotechnologies offer a path to economic growth by spurring the development of new products and industries. The application of nanomaterials, for example, has led to advancements in electronics, where smaller, faster, and more efficient devices are being produced. This is evident in the semiconductor and consumer electronics sectors, which contribute billions of dollars to global economies [122]. Nanotechnology also has a transformative effect on industries like aerospace, automotive, and healthcare, where it enhances the performance of materials and enables the creation of next-generation devices [120]. As these industries grow, they create high-paying jobs in research, development, and manufacturing. According to estimates, the global nanotechnology market could reach nearly USD 125 billion by mid-2024, underscoring its potential to fuel economic expansion and employment opportunities in various sectors [63].

### 10.2. Innovation and Competitive Advantage

For businesses, the integration of nanotechnology into products can offer a significant competitive advantage. Companies that are early adopters of nanotech innovations can gain a first-mover advantage by developing unique products that meet new consumer demands. For example, in the pharmaceutical sector, the development of nanomedicines has revolutionized drug delivery systems, allowing for more effective treatments with fewer side effects [123]. Similarly, nanomaterials have enabled the production of lighter, stronger, and more durable components in sectors such as automotive and aerospace [124]. These technological advancements not only drive product differentiation but also reduce production costs and improve overall efficiency, further boosting profitability and global competitiveness. Countries and firms that invest early in nanotechnology are positioned to dominate these emerging markets, fostering economic leadership.

### 10.3. Disruption and Job Displacement

While nanotechnologies create new job opportunities, they also have the potential to disrupt existing industries and lead to job displacement. For instance, industries that rely on traditional manufacturing processes may face challenges as nanotechnologies allow for the production of more efficient and cost-effective products [125]. Automation and the use of nanotechnology in manufacturing can reduce the need for labor in certain sectors, leading to job losses in areas like assembly, quality control, and logistics [126]. Moreover, smaller companies that cannot afford to invest in nanotechnology may struggle to compete with larger firms that adopt these innovations, potentially causing a concentration of market

power. To mitigate these effects, there will be a need for upskilling programs to prepare workers for the changing demands of the labor market, ensuring that displaced workers can transition to new roles within emerging sectors [127].

#### *10.4. Environmental and Societal Impacts*

The economic consequences of nanotechnology are also influenced by its potential environmental and societal impacts. Nanotechnologies can help address global challenges such as energy efficiency, water purification, and sustainable agriculture [13]. For example, the use of nanomaterials in solar cells can significantly improve energy production, helping to reduce reliance on fossil fuels and mitigate climate change [128]. In healthcare, nanomedicines are transforming the treatment of diseases like cancer, potentially reducing healthcare costs in the long run [129]. However, the widespread use of nanotechnology also raises concerns about environmental health and safety, particularly regarding the potential toxicity of certain nanoparticles. Proper regulation, monitoring, and environmental risk assessments are crucial to ensuring that nanotechnology's economic benefits are not overshadowed by unforeseen ecological or societal consequences [130].

The economic consequences of nanotechnologies are multifaceted, offering both vast opportunities and significant challenges. On the one hand, nanotechnology can drive innovation, create new industries, and enhance the global competitiveness of nations and businesses. On the other hand, the rapid adoption of these technologies can disrupt existing markets, displace jobs, and present environmental risks. To maximize the positive economic impact, governments, businesses, and research institutions must work together to promote responsible development, ensure sustainable practices, and invest in education and workforce training. By doing so, nanotechnologies can become a cornerstone of future economic growth, while minimizing potential negative consequences.

## **11. Globalization and Spatial Distribution of Nanotechnology**

Nanotechnology is increasingly becoming a key driver of globalization, influencing economies, industries, and technological landscapes worldwide. By enabling innovations across sectors such as electronics, healthcare, energy, and materials science, nanotechnology is reshaping industries, creating new markets, and enhancing competitiveness [13]. As countries and companies invest in nanotech research and development, the spatial distribution of nanotechnology is evolving, with some regions emerging as global leaders, while others strive to catch up. The globalization of nanotechnology is marked by the movement of research, capital, and talent across borders, as well as the diffusion of nanotech innovations to both developed and developing economies [131].

### *11.1. Leading Regions in Nanotechnology Innovation*

The US, the EU, and China are the leading regions in the field of nanotechnology [6,7,13,14]. The US has long been at the forefront, with heavy investments from both the public and private sectors. Institutions like the NNI have helped foster collaboration among government agencies, academic institutions, and industry, ensuring that nanotechnology remains a central focus of US innovation. Similarly, Germany and other EU countries are heavily invested in nanotechnology, supported by frameworks like the EU's Horizon programs, which fund research and development (Table 2). China, on the other hand, has emerged as a major player in recent years, with a rapidly growing nanotech sector supported by significant government funding. China's emphasis on high-tech industries and strategic investments in research infrastructure has made it a key player in the global nanotechnology landscape.

The US has traditionally excelled in nanotechnology innovation, notably through the NNI, which has allocated more than USD 43 billion in federal funding since 2001 [6]. In recent years, China has ascended to the position of a global leader in nanotechnology patents and publications. This increase has been bolstered by substantial government funding in nanotechnology research and development. In 2024, China represented more than 40% of global nanotechnology patents, indicating the nation's increasing prominence in this domain [84]. Japan, the Republic of Korea, and Germany have significantly contributed to nanotechnology research and commercialization. Japan's emphasis on nanomaterials and energy has resulted in notable advancements in electronics and clean energy technologies [132], but the Republic of Korea has excelled in nanotechnology applications within consumer electronics, propelled by corporations such as Samsung and LG [133]. India and Taiwan have advanced in nanotechnology, with India emphasizing sustainable energy technologies and medical uses, while Taiwan invests significantly in nanomaterials for the electronics sector [134].

### *11.2. Emerging Nanotechnology Hubs in Asia*

Beyond China, other parts of Asia are also emerging as significant contributors to the global nanotechnology landscape. Countries like Japan, the Republic of Korea, and India have established themselves as key players in nanotech research and commercialization [135]. Japan has long been a leader in advanced materials and electronics, and its nanotechnology sector benefits from the close integration of academia and industry. Companies like NTT and Toyota are integrating nanotech innovations into products ranging from electronics to automotive components [136]. The Republic of Korea is another strong contender, with its government investing heavily in nanotech research and innovation, particularly in the fields of nanoelectronics and nanomaterials [137]. In India, nanotechnology is a growing field in both academic and commercial sectors, with a focus on applications in healthcare, energy, and agriculture [138]. The emergence of these countries as nanotech hubs reflects the broader trend of global competition in nanotechnology development and the diffusion of this technology across diverse regions.

### *11.3. Nanotechnology in the Developing World*

While developed regions dominate the nanotechnology field, developing countries are also beginning to make strides in adopting and adapting nanotechnologies. Brazil, Mexico, and several African nations are investing in nanotech for applications such as sustainable agriculture, clean water, and renewable energy. For instance, South Africa has made notable progress in nanomaterials research for water purification and solar energy solutions, areas critical to the country's development [139]. India is also a prominent example of a developing country using nanotechnology for social and economic benefits, particularly in healthcare and agriculture, where affordable and accessible nanotech solutions can help address critical challenges [138]. The Global South's adoption of nanotech highlights the potential for these technologies to support sustainable development and innovation in regions traditionally less equipped to access advanced technologies [140].

### *11.4. Regional Disparities and the Digital Divide*

Despite the growing interest in nanotechnology across the globe, there remain significant regional disparities in terms of investment, infrastructure, and innovation capacity. Countries in sub-Saharan Africa and central Asia face challenges in nanotech adoption due to limited access to funding, technological expertise, and research facilities [141]. This divide contributes to an emerging digital divide in the development and application of cutting-edge technologies like nanotechnology. While developed countries benefit from robust research ecosystems, developing nations often struggle to scale nanotechnology in-

novations due to these limitations [142]. The unequal distribution of nanotech research and commercialization opportunities also risks exacerbating existing global inequalities, with wealthier nations gaining greater access to the economic benefits and high-tech advantages offered by nanotechnology.

#### 11.5. Role of Global Collaboration in Nanotechnology

Global collaboration has played a crucial role in advancing the spatial distribution of nanotechnology. International partnerships and research initiatives enable countries to share knowledge, resources, and expertise, helping to bridge gaps between developed and developing regions (Table 6). For example, collaborations between universities and research institutions in the US, Europe, and Asia have led to breakthroughs in nanomaterial science, drug delivery, and renewable energy technologies [143]. Public–private partnerships and consortia like the Nanotechnology Industries Association facilitate cooperation between governments, industry, and academia, ensuring that innovations reach global markets [144]. Such collaboration not only promotes the global exchange of ideas but also helps distribute the benefits of nanotechnology to regions that might otherwise lack the resources to develop these technologies on their own [144].

**Table 6.** Purpose and limitations of global collaboration in nanotechnology [18].

Aspect	Description	Purpose	Limitation
Knowledge Sharing	Exchange of research findings, methods, and insights between countries and institutions.	To accelerate innovation and avoid duplication of effort.	Potential for intellectual property disputes and unequal sharing of benefits.
Resource Access	Sharing of specialized equipment, materials, and funding among global partners.	To leverage global resources for conducting high-quality research.	Dependence on external sources may hinder autonomy.
Interdisciplinary Research	Collaboration between diverse scientific disciplines globally.	To address complex problems that require a multifaceted approach.	Challenges in coordinating diverse teams and integrating different perspectives.
Standardization	Development of international standards for nanomaterials and processes.	To ensure safety, interoperability, and market compatibility.	Lengthy negotiations and delays in adoption across regions.
Economic Collaboration	Building global supply chains and partnerships in nanotechnology-driven industries.	To stimulate trade, economic growth, and industrial innovation.	Risk of over-reliance on international supply chains.
Addressing Global Challenges	Joint efforts to tackle issues like energy, healthcare, and climate change through nanotechnology solutions.	To create impactful solutions that benefit humanity worldwide.	Differing priorities and levels of commitment among partners.
Skill Development	International training programs, workshops, and academic exchanges.	To build a skilled global workforce in nanotechnology.	Limited accessibility for participants from underdeveloped regions.
Policy and Regulation	Harmonization of global regulations and ethical standards for nanotechnology applications.	To ensure safe and ethical use of nanotechnology worldwide.	Diverse legal and cultural frameworks may complicate agreement.
Innovation Hubs	Establishment of international research centers and collaborative projects.	To pool talent, resources, and ideas for groundbreaking research.	High costs and administrative challenges in managing joint ventures.
Risk Management	Global efforts to assess and mitigate environmental, health, and societal risks.	To responsibly advance nanotechnology without adverse effects.	Differences in risk perception and regulation across countries.

### 11.6. Future Prospects and the Global Spread of Nanotechnology

Looking ahead, the globalization of nanotechnology is expected to accelerate as technological advancements continue to lower the cost of research and development, making it more accessible to a wider array of countries. The spread of nanotechnology will likely be driven by cross-border investments, policy alignment, and increased access to affordable research tools [121]. As the barriers to entry for nanotech innovation continue to fall, smaller nations and emerging economies will have more opportunities to participate in the global nanotechnology ecosystem [145]. The future of nanotechnology lies in a more distributed model of innovation, where knowledge and technological capabilities are shared, and the benefits of nanotech reach a broader segment of the global population [146]. This will require international efforts to ensure equitable access to nanotechnology, support sustainable practices, and address challenges related to intellectual property, regulation, and safety concerns.

In summary, the spatial distribution of nanotechnology is evolving rapidly, with major hubs in the US, Europe, and Asia leading innovation, while developing countries are making strides in applying nanotechnology for local development. As the globalization of nanotechnology continues, global collaboration will be key in overcoming regional disparities and ensuring that the benefits of this transformative technology are shared more equitably around the world. The future of nanotechnology promises a more interconnected world, where innovation and knowledge flow freely across borders to address the pressing challenges of the 21st century.

## 12. Regulatory Framework

As nanotechnology continues to evolve and permeate various industries, the need for robust regulatory frameworks has become essential to ensure its safe development, commercialization, and use. Nanotechnology has vast potential to revolutionize sectors like healthcare, energy, manufacturing, and electronics, but its novel properties also introduce unique risks to human health and the environment [95]. Regulatory bodies worldwide are grappling with the challenge of crafting appropriate regulations that balance innovation with safety (Table 7). Given the rapidly advancing nature of nanotech, it is crucial for governments and international organizations to establish clear guidelines that can keep pace with scientific progress while addressing concerns related to toxicity, environmental impact, and ethical implications [147]. The growing commercialization of nanoparticles and nanomaterials necessitates the establishment of regulatory frameworks to handle possible environmental, health, and safety issues. The FDA regulates nanotechnology in medical applications in the US, whereas other industries, like consumer products and electronics, require more precise regulatory monitoring [148]. International entities like the OECD and the International Risk Governance Council have been instrumental in formulating criteria for the risk assessment of nanotechnology and public involvement [149,150]. These organizations seek to guarantee that the advancement of nanotechnology transpires safely and sustainably.

In developed countries such as the US, EU, and Japan, regulatory frameworks for nanotechnology are relatively more advanced, though still evolving. In the US, the FDA and the Environmental Protection Agency (EPA) oversee the safety of nanomaterials in products, with the FDA regulating nanomaterials used in food, drugs, and cosmetics [151]. However, there is no single, comprehensive federal law governing nanotechnology. The NNI in the US has established guidelines and research priorities, but the regulatory landscape remains fragmented. Similarly, in the EU, the European Chemicals Agency and European Food Safety Authority provide oversight of nanomaterials, particularly in relation to consumer safety and environmental impact [152]. The EU's REACH regulation

(Registration, Evaluation, Authorization, and Restriction of Chemicals) includes provisions for nanomaterials, ensuring their safety evaluation before being placed on the market [153]. In Japan, the Ministry of Economy, Trade, and Industry plays a leading role in nanotech safety, with the government working to align regulations to both encourage innovation and ensure public safety [154].

**Table 7.** Overview of the regulatory frameworks for nanotechnology in different countries.

Country	Regulatory Body/Institution
United States	<ul style="list-style-type: none"> <li>• Food and Drug Administration (FDA)</li> <li>• Environmental Protection Agency (EPA)</li> <li>• National Nanotechnology Initiative (NNI)</li> </ul>
European Union	<ul style="list-style-type: none"> <li>• European Chemicals Agency (ECHA)</li> <li>• European Food Safety Authority (EFSA)</li> </ul>
Japan	<ul style="list-style-type: none"> <li>• National Institute of Advanced Industrial Science and Technology (AIST)</li> </ul>
India	<ul style="list-style-type: none"> <li>• Department of Biotechnology (DBT)</li> <li>• Ministry of Environment, Forest and Climate Change (MoEFCC)</li> </ul>
Brazil	<ul style="list-style-type: none"> <li>• National Health Surveillance Agency (ANVISA)</li> </ul>
South Africa	<ul style="list-style-type: none"> <li>• National Research Foundation (NRF)</li> <li>• Department of Science and Innovation (DSI)</li> </ul>
Australia	<ul style="list-style-type: none"> <li>• National Industrial Chemicals Notification and Assessment Scheme (NICNAS)</li> </ul>
Canada	<ul style="list-style-type: none"> <li>• Health Canada</li> <li>• Canadian Standards Association (CSA)</li> </ul>
China	<ul style="list-style-type: none"> <li>• National Nanotechnology Initiative (China)</li> <li>• Ministry of Science and Technology (MOST)</li> </ul>
Republic of Korea	<ul style="list-style-type: none"> <li>• National Nanotechnology Research and Development Program (NNRDP)</li> <li>• Ministry of Science and ICT</li> </ul>
United Kingdom	<ul style="list-style-type: none"> <li>• Health and Safety Executive (HSE)</li> <li>• Food Standards Agency (FSA)</li> </ul>
Mexico	<ul style="list-style-type: none"> <li>• Mexican Institute of Standardization and Certification (IMNC)</li> <li>• National Council of Science and Technology (CONACYT)</li> </ul>
Russia	<ul style="list-style-type: none"> <li>• Federal Service for Environmental, Technological, and Nuclear Supervision (Rostekhnadzor)</li> </ul>
Singapore	<ul style="list-style-type: none"> <li>• Singapore Standards Council</li> <li>• National Environment Agency (NEA)</li> </ul>
Thailand	<ul style="list-style-type: none"> <li>• National Nanotechnology Center (NANOTEC)</li> <li>• Ministry of Science and Technology</li> </ul>
New Zealand	<ul style="list-style-type: none"> <li>• Environmental Protection Authority (EPA)</li> <li>• Ministry for Business, Innovation and Employment (MBIE)</li> </ul>
Saudi Arabia	<ul style="list-style-type: none"> <li>• Saudi Food and Drug Authority (SFDA)</li> <li>• King Abdulaziz City for Science and Technology (KACST)</li> </ul>

In developing countries, the regulatory landscape for nanotechnology is less mature and more varied. Countries like India, Brazil, and South Africa have begun to recognize the importance of regulating nanomaterials but often lack comprehensive frameworks to manage their risks. In India, the Department of Biotechnology and the Ministry of Environment, Forest and Climate Change are involved in nanotechnology regulation, but there are no specific laws dedicated to nanomaterials. Instead, nanomaterials are assessed under existing chemical safety regulations [155]. Similarly, in Brazil, the National Health

Surveillance Agency (ANVISA) is responsible for regulating nanomaterials in health-related products, but the country faces challenges in creating standardized procedures for safety evaluation [156,157]. In South Africa, the government has focused on building public awareness and developing safety protocols for the use of nanotechnology, particularly in the context of mining and agriculture [158]. As these countries begin to scale up nanotech research and industry, there is an increasing need for clear, cohesive regulatory strategies that address safety and ethical considerations while promoting innovation.

Given the global nature of nanotechnology research and commercialization, there is a growing recognition of the need for international collaboration to create consistent and harmonized regulatory standards. Organizations like the OECD and the International Organization for Standardization are working toward creating international guidelines and safety standards for nanomaterials. Harmonization of regulations across borders is essential to facilitate trade, ensure consistent safety protocols, and prevent regulatory loopholes. Additionally, as nanotechnology becomes more integrated into consumer products and healthcare, ethical considerations such as privacy, accessibility, and equitable distribution will need to be addressed. The future of nanotechnology regulation will require a dynamic approach, adaptable to new scientific developments, while fostering global cooperation to ensure that the benefits of nanotech are maximized while minimizing potential risks.

### 13. Conclusions and Future Outlook

Nanotechnology has developed into a multifaceted domain with extensive applications across various industries, including energy, electronics, healthcare, and consumer goods. The economic influence of nanotechnology is anticipated to persist in its expansion, propelled by continuous innovation, global cooperation, and governmental endorsement. By 2024, nanotechnology significantly contributes to the global economy, with China at the forefront in patent applications and publications, succeeded by the US, Japan, and the Republic of Korea. As the discipline evolves, further investment in research, workforce development, and regulatory structures will be crucial to guarantee its sustained expansion and incorporation into diverse sectors. The future of nanotechnology will rely on continuous public and private investment, together with international cooperation to tackle issues with safety, regulation, and commercialization. As global rivalry in nanotechnology escalates, nations and corporations must adapt to the swiftly changing environment to preserve their competitive advantage.

Governments play a pivotal role in fostering nanotechnology innovation, which has the potential to significantly drive sustainable economic development. Through targeted funding, policy frameworks, and strategic initiatives, governments can support the growth of this transformative technology, ensuring that it benefits various sectors including healthcare, energy, agriculture, and manufacturing. Public sector initiatives not only provide the necessary financial support for early-stage research and development but also help mitigate risks and guide the responsible use of nanomaterials. Their efforts can lay the foundation for an innovation ecosystem that promotes both technological advancements and long-term economic prosperity.

A key aspect of government initiatives is the establishment of public–private partnerships. These collaborations enable governments to leverage private sector expertise, resources, and market reach while ensuring that innovations align with public safety and regulatory standards. In nanotechnology, public–private partnerships can facilitate the translation of research from the lab to commercialization, speeding up the development of nanotech products for industrial and consumer use. For instance, government-led funding programs for small and medium enterprises in nanotech allow them to innovate and scale faster, contributing to job creation and sustainable economic growth.

For nanotechnology to drive sustainable development, governments must invest in education and workforce development to nurture a highly skilled workforce. Nanotechnology demands expertise in multiple fields such as materials science, physics, engineering, and biology. Governments that prioritize STEM (science, technology, engineering, and mathematics) education and offer specialized training programs can create a pipeline of talent that accelerates research and commercialization efforts. Furthermore, fostering educational partnerships with universities, research institutions, and industries can ensure that the workforce is equipped to meet the challenges posed by rapidly evolving nanotech applications.

To ensure that nanotechnology innovation is sustainable, governments must develop robust policy frameworks that balance economic growth with environmental and health safety. Regulatory oversight is crucial for preventing potential risks related to the toxicity of nanomaterials or their environmental impact. Governments should implement policies that encourage innovation while also establishing clear guidelines for the safe use of nanomaterials, ensuring public trust in these technologies. At the same time, supporting environmental sustainability through nanotechnology—such as in energy-efficient materials and green manufacturing processes—can enhance the positive societal impacts of these innovations.

Looking ahead, the future of nanotechnology innovation will increasingly depend on global collaboration and cross-border research initiatives. As nanotechnology has wide-ranging applications, the challenges and opportunities presented by this field are shared by many nations. Governments must continue to promote international cooperation in both research and policy making, establishing common standards and ensuring that nanotechnology is developed in a way that benefits all. The growing emphasis on United Nations SDGs presents new opportunities for nanotechnology to contribute to solving global challenges, such as clean energy, healthcare access, and environmental conservation. By aligning national policies with these global objectives, governments can ensure that nanotechnology remains a driving force for positive, long-term economic and social change.

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## References

1. Malik, S.; Muhammad, K.; Waheed, Y. Nanotechnology: A Revolution in Modern Industry. *Molecules* **2023**, *28*, 661. [[CrossRef](#)] [[PubMed](#)]
2. Yadav, V.K.; Malik, P.; Khan, A.H.; Pandit, P.R.; Hasan, M.A.; Cabral-Pinto, M.M.S.; Islam, S.; Suriyaprabha, R.; Yadav, K.K.; Dinis, P.A.; et al. Recent Advances on Properties and Utility of Nanomaterials Generated from Industrial and Biological Activities. *Crystals* **2021**, *11*, 634. [[CrossRef](#)]
3. Bayda, S.; Adeel, M.; Tuccinardi, T.; Cordani, M.; Rizzolio, F. The History of Nanoscience and Nanotechnology: From Chemical-Physical Applications to Nanomedicine. *Molecules* **2020**, *25*, 112. [[CrossRef](#)] [[PubMed](#)]

4. Joudeh, N.; Linke, D. Nanoparticle Classification, Physicochemical Properties, Characterization, and Applications: A Comprehensive Review for Biologists. *J. Nanobiotechnol.* **2022**, *20*, 262. [CrossRef]
5. Szczyglewska, P.; Feliczak-Guzik, A.; Nowak, I. Nanotechnology—General Aspects: A Chemical Reduction Approach to the Synthesis of Nanoparticles. *Molecules* **2023**, *28*, 4932. [CrossRef]
6. NNI Supplement to the President’s 2024 Budget | National Nanotechnology Initiative. Available online: <https://www.nano.gov/2024BudgetSupplement> (accessed on 6 December 2024).
7. NNI 20th Anniversary | National Nanotechnology Initiative. Available online: <https://www.nano.gov/anniversarysymposium> (accessed on 8 December 2024).
8. China Is the Largest Contributor to Global Patent Applications, Substantially Ahead of Other Countries—Our World in Data. Available online: <https://ourworldindata.org/data-insights/china-is-the-largest-contributor-to-global-patent-applications-substantially-ahead-of-other-countries> (accessed on 8 December 2024).
9. National Science Board—News—Global Competitors Outpace U.S. in Patents. Available online: [https://www.nsf.gov/nsb/news/news\\_summ.jsp?cntn\\_id=309184](https://www.nsf.gov/nsb/news/news_summ.jsp?cntn_id=309184) (accessed on 8 December 2024).
10. Small Science, Big Impact on the U.S. Economy! | National Nanotechnology Initiative. Available online: <https://www.nano.gov/node/5669> (accessed on 8 December 2024).
11. Roco, M.C. National Nanotechnology Initiative at 20 Years: Enabling New Horizons. *J. Nanopart. Res.* **2023**, *25*, 197. [CrossRef]
12. Search Results | Nanotechnology Products Database | NPD. Available online: <https://product.statnano.com/product/all> (accessed on 8 December 2024).
13. Pokrajac, L.; Abbas, A.; Chrzanowski, W.; Dias, G.M.; Eggleton, B.J.; Maguire, S.; Maine, E.; Malloy, T.; Nathwani, J.; Nazar, L.; et al. Nanotechnology for a Sustainable Future: Addressing Global Challenges with the International Network4Sustainable Nanotechnology. *ACS Nano* **2021**, *15*, 18608–18623. [CrossRef]
14. Elzein, B. Nano Revolution: “Tiny Tech, Big Impact: How Nanotechnology Is Driving SDGs Progress”. *Heliyon* **2024**, *10*, e31393. [CrossRef]
15. Sustainable Development. Available online: <https://sdgs.un.org/> (accessed on 7 December 2024).
16. Cheng, H.N.; Doemeny, L.J.; Geraci, C.L.; Schmidt, D.G. Nanotechnology Overview: Opportunities and Challenges. In *Nanotechnology: Delivering on the Promise Volume 1*; ACS Symposium Series; American Chemical Society: Washington, DC, USA, 2016; Volume 1220, pp. 1–12.
17. National Academies of Sciences. *A Quadrennial Review of the National Nanotechnology Initiative*; National Academies Press: Washington, DC, USA, 2020; ISBN 978-0-309-67465-2.
18. Nanotech Diplomacy: Opportunities and Challenges for International Cooperation | UNCTAD. Available online: <https://unctad.org/news/nanotech-diplomacy-opportunities-and-challenges-international-cooperation> (accessed on 8 December 2024).
19. Mariyam, S.; Upadhyay, S.K.; Chakraborty, K.; Verma, K.K.; Duhan, J.S.; Muneer, S.; Meena, M.; Sharma, R.K.; Ghodake, G.; Seth, C.S. Nanotechnology, a Frontier in Agricultural Science, a Novel Approach in Abiotic Stress Management and Convergence with New Age Medicine-A Review. *Sci. Total Environ.* **2024**, *912*, 169097. [CrossRef]
20. Singh, S.; Singh, R.; Singh, K.; Katoch, K.; Zaeen, A.A.; Birhan, D.A.; Singh, A.; Sandhu, H.S.; Singh, H.; Sahrma, L.K. Smart Fertilizer Technologies: An Environmental Impact Assessment for Sustainable Agriculture. *Smart Agric. Technol.* **2024**, *8*, 100504. [CrossRef]
21. Kumar, S.; Nehra, M.; Deep, A.; Kedia, D.; Dilbaghi, N.; Kim, K.H. Quantum-Sized Nanomaterials for Solar Cell Applications. *Renew. Sustain. Energy Rev.* **2017**, *73*, 821–839. [CrossRef]
22. Horizon Europe—European Commission. Available online: [https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe\\_en](https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en) (accessed on 8 December 2024).
23. China’s New Renewable Energy Plan: Key Insights for Businesses. Available online: <https://www.china-briefing.com/news/chinas-new-renewable-energy-plan-key-insights-for-businesses/> (accessed on 8 December 2024).
24. Elhenawy, S.; Khraisheh, M.; AlMamani, F.; Al-Ghouti, M.; Selvaraj, R.; Al-Muhtaseb, A. Emerging Nanomaterials for Drinking Water Purification: A New Era of Water Treatment Technology. *Nanomaterials* **2024**, *14*, 1707. [CrossRef] [PubMed]
25. Nasrollahzadeh, M.; Sajjadi, M.; Iravani, S.; Varma, R.S. Carbon-Based Sustainable Nanomaterials for Water Treatment: State-of-Art and Future Perspectives. *Chemosphere* **2021**, *263*, 128005. [CrossRef] [PubMed]
26. Nanomedicine | Research and Innovation. Available online: <https://projects.research-and-innovation.ec.europa.eu/en/projects/success-stories/all/nanomedicine> (accessed on 8 December 2024).
27. Bhatia, P.; Vasaiakar, S.; Wali, A. A Landscape of Nanomedicine Innovations in India. *Nanotechnol. Rev.* **2018**, *7*, 131–148. [CrossRef]
28. Malik, S.; Muhammad, K.; Waheed, Y. Emerging Applications of Nanotechnology in Healthcare and Medicine. *Molecules* **2023**, *28*, 6624. [CrossRef]
29. Kumar, A.; Tyagi, P.K.; Tyagi, S.; Ghorbanpour, M. Integrating Green Nanotechnology with Sustainable Development Goals: A Pathway to Sustainable Innovation. *Discov. Sustain.* **2024**, *5*, 1–13. [CrossRef]

30. Periakaruppan, R.; Romanovski, V.; Thirumalaisamy, S.K.; Palanimuthu, V.; Sampath, M.P.; Anilkumar, A.; Sivaraj, D.K.; Ahamed, N.A.N.; Murugesan, S.; Chandrasekar, D.; et al. Innovations in Modern Nanotechnology for the Sustainable Production of Agriculture. *ChemEngineering* **2023**, *7*, 61. [[CrossRef](#)]
31. Huang, Y.; Guo, X.; Wu, Y.; Chen, X.; Feng, L.; Xie, N.; Shen, G. Nanotechnology's Frontier in Combatting Infectious and Inflammatory Diseases: Prevention and Treatment. *Signal Transduct. Target. Ther.* **2024**, *9*, 1–50.
32. Şenel Zor, T.; Aslan, O. The Effect of Activity-Based Nanoscience and Nanotechnology Education on Pre-Service Science Teachers' Conceptual Understanding. *J. Nanopart. Res.* **2018**, *20*, 75. [[CrossRef](#)]
33. Bhalla, N.; Jayaprakash, A.; Ingle, N.; Patel, H.; Patri, S.V.; Haranath, D. Fabrication and Infusion of Potent Silver Doped Nano ZnO Aimed to Advance Germicidal Efficacy of Health and Hygiene Products. *J. Sci. Adv. Mater. Devices* **2022**, *7*, 100487. [[CrossRef](#)]
34. Kunduru, K.R.; Nazarkovsky, M.; Farah, S.; Pawar, R.P.; Basu, A.; Domb, A.J. Nanotechnology for Water Purification: Applications of Nanotechnology Methods in Wastewater Treatment. In *Water Purification*; Academic Press: Cambridge, MA, USA, 2017; pp. 33–74. ISBN 9780128043004.
35. Elrashidi, A.; Emar, A.; Yousef, A.; Elzein, B. Light Harvesting Improvement of A-Si:H Solar Cell Through Nano-Grating Structure and Plasmonic Nanoparticles. *J. Nanoelectron. Optoelectron.* **2019**, *14*, 543–550. [[CrossRef](#)]
36. Chausali, N.; Saxena, J.; Prasad, R. Nanotechnology as a Sustainable Approach for Combating the Environmental Effects of Climate Change. *J. Agric. Food Res.* **2023**, *12*, 100541. [[CrossRef](#)]
37. Shafique, M.; Luo, X. Nanotechnology in Transportation Vehicles: An Overview of Its Applications, Environmental, Health and Safety Concerns. *Materials* **2019**, *12*, 2493. [[CrossRef](#)] [[PubMed](#)]
38. Nie, C.-C.; Li, X.-G.; Shi, S.-X.; Wang, Y.-S.; Lyu, X.-J.; Li, G.-Y.; Zhu, X.-N.; Wang, Z. Eco-Friendly Strategy for Advanced Recycling Waste Copper from Spent Lithium-Ion Batteries: Preparation of Micro-Nano Copper Powder. *Sep. Purif. Technol.* **2023**, *322*, 124277. [[CrossRef](#)]
39. Li, P.; Zeng, H.C. Hierarchical Nanocomposite by the Integration of Reduced Graphene Oxide and Amorphous Carbon with Ultrafine MgO Nanocrystallites for Enhanced CO<sub>2</sub> Capture. *Environ. Sci. Technol.* **2017**, *51*, 12998–13007. [[CrossRef](#)]
40. Huang, L.; Song, F.; Ding, H.; Wang, Y.; Zhu, W. Hydrophobic Polyacrylonitrile/Pitch Electrospun Nanofibers for Oil Spill Cleanup: Fabrication, Optimization, and Kinetic Investigations. *J. Water Process Eng.* **2022**, *50*, 103210. [[CrossRef](#)]
41. Kristanti, R.A.; Liong, R.M.Y.; Hadibarata, T. Soil Remediation Applications of Nanotechnology. *Trop. Aquat. Soil Pollut.* **2021**, *1*, 35–45. [[CrossRef](#)]
42. Alabdulatif, A.; Thilakarathne, N.N.; Lawal, Z.K.; Fahim, K.E.; Zakari, R.Y. Internet of Nano-Things (IoNT): A Comprehensive Review from Architecture to Security and Privacy Challenges. *Sensors* **2023**, *23*, 2807. [[CrossRef](#)]
43. Vaverková, M.D.; Polak, J.; Kurcusz, M.; Jena, M.K.; Murali, A.P.; Nair, S.S.; Aktaş, H.; Hadinata, M.E.; Ghezelayagh, P.; Andik, S.D.S.; et al. Enhancing Sustainable Development Through Interdisciplinary Collaboration: Insights from Diverse Fields. *Sustain. Dev.* **2024**. *Early View*. [[CrossRef](#)]
44. Ellwood, P.; Williams, C.; Egan, J. Crossing the Valley of Death: Five Underlying Innovation Processes. *Technovation* **2022**, *109*, 102162. [[CrossRef](#)]
45. Scaling-Up, Standardizing, and Making It Safe: Nanotechnologies in Manufacturing | National Nanotechnology Initiative. Available online: <https://www.nano.gov/node/1570> (accessed on 8 December 2024).
46. The Challenges Behind Scaling Up Nanomaterials. Available online: <https://www.azonano.com/article.aspx?ArticleID=6126> (accessed on 8 December 2024).
47. Rambaran, T.; Schirhagl, R. Nanotechnology from Lab to Industry—A Look at Current Trends. *Nanoscale Adv.* **2022**, *4*, 3664–3675. [[CrossRef](#)] [[PubMed](#)]
48. NIH SEED SBIR and STTR Funding Opportunities. Available online: <https://seed.nih.gov/small-business-funding/find-funding/sbir-sttr-funding-opportunities> (accessed on 22 January 2025).
49. Oficina de Desarrollo y tecnologías de Harvard Harvard Office of Technology Development Research Collaborations. Available online: <https://otd.harvard.edu/industry-investors/research-collaborations/> (accessed on 22 January 2025).
50. Shu, L.; Wang, W.; Ng, C.I.; Zhang, X.; Huang, Y.; Wu, C.; Pan, X.; Huang, Z. A Pilot Study Exploiting the Industrialization Potential of Solid Lipid Nanoparticle-Based Metered-Dose Inhalers. *Pharmaceutics* **2023**, *15*, 866. [[CrossRef](#)] [[PubMed](#)]
51. Rubin, G.D.; Abramson, R.G. Creating Value through Incremental Innovation: Managing Culture, Structure, and Process. *Radiology* **2018**, *288*, 330–340. [[CrossRef](#)] [[PubMed](#)]
52. Weng, Y. Risk Analysis and Management Strategies for Entrepreneurial Investment. *Front. Bus. Econ. Manag.* **2024**, *15*, 160–164. [[CrossRef](#)]
53. D'Avenio, G.; Daniele, C.; Grigioni, M. Critical Issues of the Regulatory Pathway for Nanostructured Medical Devices. *AIP Conf. Proc.* **2021**, *2416*, 020002.
54. Lee, A. A Comprehensive Review and Investigation of Business Models. *Enigm. Econ.* **2024**, *1*, 49–54. [[CrossRef](#)]
55. Gassmann, O.; Bader, M.A.; Thompson, M.J. Fundamentals of Intellectual Property Rights. In *Management for Professionals*; Springer: Cham, Switzerland, 2021; Volume F450, pp. 1–25.

56. Chong, Y.T.; Chen, C.H. Customer Needs as Moving Targets of Product Development: A Review. *Int. J. Adv. Manuf. Technol.* **2010**, *48*, 395–406. [CrossRef]
57. Kaur, S.; Medhi, B. Guidelines for Nanopharmaceutical Products for Regulatory Approval. *Int. J. Pharm. Sci. Nanotechnol.* **2022**, *15*, 5723–5725.
58. Aithal, P.S.; Aithal, A. Business Strategy for Nanotechnology Based Products and Services. *Int. J. Manag. Sci. Bus. Res.* **2016**, *5*, 139–149. [CrossRef]
59. Popo-Olanian, O.; James, O.O.; Udeh, C.A.; Daraojimba, R.E.; Ogedengbe, D.E. A review of U.S. Strategies for Stem Talent Attraction and Retention: Challenges and Opportunities. *Int. J. Manag. Entrep. Res.* **2022**, *4*, 588–606. [CrossRef]
60. Ostaev, G.; Zlobina, O.; Gogolev, I.; Kislickiy, P. Financial Management: Planning, Design and Management. *Russ. J. Manag.* **2023**, *11*, 193–210. [CrossRef]
61. Adair, M.; Kenny, B.; McGuirk, H. Stand Alone or Continue to Support: Exploring the Need for Post Incubation Services for New and Growing Enterprises. *Ir. Bus. J.* **2021**, *13*, 3. [CrossRef]
62. Creating New Knowledge in Nanotechnology and Turning It into Better Quality of Life, Competitiveness and Jobs. Available online: [https://ec.europa.eu/commission/presscorner/detail/en/ip\\_04\\_639](https://ec.europa.eu/commission/presscorner/detail/en/ip_04_639) (accessed on 23 January 2025).
63. El-Meligi, A.A. Future of Nanotechnology. In *The Art of Nanomaterials*; Bentham Science Publishers: Sharjah, United Arab Emirates, 2022; pp. 88–95.
64. Merzbacher, C. *National Nanotechnology Initiative: A Model for Advancing Revolutionary Technologies*; Springer: Cham, Switzerland, 2020; pp. 121–133.
65. Wang, C.; Zhang, J.; Wu, Z. The Application of Nanomaterials in Energy Materials. *Highlights Sci. Eng. Technol.* **2023**, *58*, 188–193. [CrossRef]
66. 2021 Tough Tech Landscape | The Engine. Available online: <https://engine.xyz/reports/2021-tough-tech-landscape> (accessed on 23 January 2025).
67. Nanobiotix Provides Business Update and Reports Full Year 2023 Financial Results—Nanobiotix. Available online: <https://ir.nanobiotix.com/news-releases/news-release-details/nanobiotix-provides-business-update-and-reports-full-year-2023> (accessed on 23 January 2025).
68. Nanosys and Samsung Electronics Announce Strategic Alliance to Accelerate Commercial Applications of Nano-Architected Materials for the Electronics and Solar Markets—Nanosys. Available online: <https://nanosys.com/press-releases/2010/08/10/nanosys-and-samsung-electronics-announce-strategic-alliance-to-accelerate-commercial-applications-of-nano-architected-materials-for-the-electronics-and-solar-markets> (accessed on 23 January 2025).
69. Intel Launches \$1 Billion Fund to Build a Foundry Innovation Ecosystem. Available online: <https://www.intel.com/content/www/us/en/newsroom/news/intel-launches-1-billion-fund-build-foundry-innovation-ecosystem.html> (accessed on 23 January 2025).
70. Flagship Pioneering and Pfizer Partner to Accelerate Development of Innovative Medicines Targeting Unmet Needs. Available online: <https://www.prnewswire.com/news-releases/flagship-pioneering-and-pfizer-partner-to-accelerate-development-of-innovative-medicines-targeting-unmet-needs-301879155.html> (accessed on 23 January 2025).
71. In Brief: Shell, BP and ExxonMobil-Backed Fund Bets on Batteries. Available online: <https://www.newprivatemarkets.com/in-brief-shell-bp-and-exxonmobil-backed-fund-bets-on-batteries/> (accessed on 23 January 2025).
72. Tawiah, B.; Ofori, E.A.; George, S.C. *Nanotechnology in Societal Development*; Springer: Singapore, 2024; pp. 1–64. ISBN 978-981-97-6184-5.
73. Sergio, I.; Iandolo, S.; Ferragina, A.M. Inter-Sectoral and Inter-Regional Knowledge Spillovers: The Role of ICT and Technological Branching on Innovation in High-Tech Sectors. *Technol. Forecast. Soc. Chang.* **2023**, *194*, 122728. [CrossRef]
74. Meissner, D. Public-Private Partnership Models for Science, Technology, and Innovation Cooperation. *J. Knowl. Econ.* **2019**, *10*, 1341–1361. [CrossRef]
75. Nanosys Completes Commercial Agreement with LGIT for Its Quantum Rail™ Lighting Products—Nanosys. Available online: <https://nanosys.com/press-releases/2010/01/21/nanosys-completes-commercial-agreement-with-lgit-for-its-quantum-rail-lighting-products> (accessed on 24 January 2025).
76. Liefner, I.; Si, Y.-F.; Schäfer, K. A Latecomer Firm’s R&D Collaboration with Advanced Country Universities and Research Institutes: The Case of Huawei in Germany. *Technovation* **2019**, *86–87*, 3–14. [CrossRef]
77. Ouyang, B.; Shan, C.; Shen, S.; Dai, X.; Chen, Q.; Su, X.; Cao, Y.; Qin, X.; He, Y.; Wang, S.; et al. AI-Powered Omics-Based Drug Pair Discovery for Pyroptosis Therapy Targeting Triple-Negative Breast Cancer. *Nat. Commun.* **2024**, *15*, 7560. [CrossRef]
78. Horizon Europe, Budget—Publications Office of the EU. Available online: <https://op.europa.eu/en/publication-detail/-/publication/1f107d76-acbe-11eb-9767-01aa75ed71a1> (accessed on 24 January 2025).
79. Airbus Graphene Flagship Project—The Graphene Council. Available online: <https://www.thegraphenecouncil.org/blogpost/1501180/337982/Airbus-Graphene-Flagship-Project?tag=Airbus> (accessed on 24 January 2025).

80. National Mission on Nano Science And Technology—GeeksforGeeks. Available online: <https://www.geeksforgeeks.org/national-mission-on-nano-science-and-technology/> (accessed on 24 January 2025).
81. Zhu, S.; Nguyen, M.T.; Yonezawa, T. Micro- and Nano-Encapsulated Metal and Alloy-Based Phase-Change Materials for Thermal Energy Storage. *Nanoscale Adv.* **2021**, *3*, 4626–4645. [CrossRef]
82. Abdulfasi, M. The Transformative Patent Landscape in Saudi Arabia Since the Saudi Vision 2030 Announcement. *Publications* **2024**, *12*, 47. [CrossRef]
83. Boston Research Center: Advancing Research for Energy Applications. Available online: <https://www.aramcoexpats.com/articles/boston-research-center-advancing-research-for-energy-applications/> (accessed on 24 January 2025).
84. STATNANO: Nano Science, Technology and Industry Information. Available online: <https://statnano.com/> (accessed on 13 December 2024).
85. New START.Nano Cohort Is Developing Solutions in Health, Data Storage, Power, and Sustainable Energy | MIT News | Massachusetts Institute of Technology. Available online: <https://news.mit.edu/2025/new-startnano-cohort-developing-solutions-health-data-storage-power-0123> (accessed on 24 January 2025).
86. IBM and MIT to Pursue Joint Research in Artificial Intelligence, Establish New MIT-IBM Watson AI Lab | MIT News | Massachusetts Institute of Technology. Available online: <https://news.mit.edu/2017/ibm-mit-joint-research-watson-artificial-intelligence-lab-0907> (accessed on 24 January 2025).
87. Making Carbon Our Ally | George, R. Brown School of Engineering | Rice University. Available online: <https://engineering.rice.edu/news/making-carbon-our-ally> (accessed on 24 January 2025).
88. Ten Years of Research, Innovation and Collaboration: The Graphene Flagship and the 2DM Community | Graphene Flagship. Available online: <https://graphene-flagship.eu/materials/news/ten-years-of-research-innovation-and-collaboration-the-graphene-flagship-and-the-2dm-community/> (accessed on 24 January 2025).
89. UCLA-Industry Partnership to Develop New Nanotechnology | UCLA Health. Available online: <https://www.uclahealth.org/news/release/ucla-industry-partnership-to-develop-new-nanotechnology> (accessed on 24 January 2025).
90. Global Nanotechnology Market Poised to Reach 183.7 Billion by 2028. Available online: <https://www.bccresearch.com/pressroom/nan/global-nanotechnology-market-poised-to-reach-1837-billion-by-2028> (accessed on 24 January 2025).
91. NIST System Replicated by Chip Maker | NIST. Available online: <https://www.nist.gov/news-events/news/2016/06/nist-system-replicated-chip-maker> (accessed on 24 January 2025).
92. Nano-Bio Materials Consortium | SEMI. Available online: <https://www.semi.org/en/communities/nbmc> (accessed on 24 January 2025).
93. BASF and Fraunhofer IPMS Celebrate Ten Years of R&D Collaboration on Innovative Solutions in the Field of Semiconductor Manufacturing. Available online: <https://www.basf.com/global/en/media/news-releases/2024/10/p-24-302> (accessed on 24 January 2025).
94. Institute of Industrial Science, The University of Tokyo, Prime Planet Energy & Solutions Inc., Panasonic Corporation, Toyota Tsusho Corporation Commences Industry-University Collaborative Research on Battery Resources and Recycling—Institute of Industr. Available online: <https://www.iis.u-tokyo.ac.jp/en/news/3760/> (accessed on 24 January 2025).
95. Ma, X.; Tian, Y.; Yang, R.; Wang, H.; Allahou, L.W.; Chang, J.; Williams, G.; Knowles, J.C.; Poma, A. Nanotechnology in Healthcare, and Its Safety and Environmental Risks. *J. Nanobiotechnol.* **2024**, *22*, 715. [CrossRef]
96. National Patterns of R&D Resources. 2013. Available online: <https://nap.nationalacademies.org/catalog/18317/national-patterns-of-rd-resources-future-directions-for-content-and> (accessed on 24 January 2025).
97. Home | Nanotechnology Products Database | NPD. Available online: <https://product.statnano.com/> (accessed on 13 December 2024).
98. Wu, D.; Xu, G.; Tan, J.; Wang, X.; Zhang, Y.; Ma, L.; Chen, W.; Wang, K. Nanophotonic Structures Energized Short-Wave Infrared Quantum Dot Photodetectors and Their Advancements in Imaging and Large-Scale Fabrication Techniques. *Nanoscale* **2024**. [CrossRef] [PubMed]
99. Pathak, A.K.; Dhakate, S.R. Carbon Nanomaterial-Carbon Fiber Hybrid Composite for Lightweight Structural Composites in the Aerospace Industry: Synthesis, Processing, and Properties. In *Advanced Composites in Aerospace Engineering Applications*; Springer: Cham, Switzerland, 2022; pp. 445–470. ISBN 9783030881924.
100. Subhedar, K.M.; Singh, B.P. Introduction to Carbon Nanotubes and Graphene and Their Emerging Applications. In *Emerging Applications of Carbon Nanotubes and Graphene*; CRC Press: Boca Raton, FL, USA, 2023; pp. 1–22. ISBN 9781000838633.
101. Asyraf, M.R.M.; Ilyas, R.A.; Sapuan, S.M.; Harussani, M.M.; Hariz, H.M.; Aiman, J.M.; Baitaba, D.M.; Sanjay, M.R.; Ishak, M.R.; Mazlan, N.; et al. Advanced Composite in Aerospace Applications: Opportunities, Challenges, and Future Perspective. In *Advanced Composites in Aerospace Engineering Applications*; Springer: Cham, Switzerland, 2022; pp. 471–498. ISBN 9783030881924.
102. What Are Nanocoatings?—NanoSlic. Available online: <https://nanoslic.com/about-nanocoatings/> (accessed on 24 January 2025).
103. Ultra-Thin Plasma Coatings—P2i. Available online: <https://www.p2i.com/solutions/> (accessed on 24 January 2025).

104. Jia, Y.; Han, J.; Lichtfouse, E. Fluoropolymers and Nanomaterials, the Invisible Hazards of Cell Phone and Computer Touchscreens. *Environ. Chem. Lett.* **2024**, 1–8. [CrossRef]
105. Tenchov, R.; Bird, R.; Curtze, A.E.; Zhou, Q. Lipid Nanoparticles from Liposomes to mRNA Vaccine Delivery, a Landscape of Research Diversity and Advancement. *ACS Nano* **2021**, *15*, 16982–17015. [CrossRef] [PubMed]
106. Noor, R. Developmental Status of the Potential Vaccines for the Mitigation of the COVID-19 Pandemic and a Focus on the Effectiveness of the Pfizer-BioNTech and Moderna mRNA Vaccines. *Curr. Clin. Microbiol. Rep.* **2021**, *8*, 178–185. [CrossRef]
107. Ramachandran, S.; Satapathy, S.R.; Dutta, T. Delivery Strategies for mRNA Vaccines. *Pharmaceut. Med.* **2022**, *36*, 11–20. [CrossRef]
108. Biscaia-Caleiras, M.; Fonseca, N.A.; Lourenço, A.S.; Moreira, J.N.; Simões, S. Rational Formulation and Industrial Manufacturing of Lipid-Based Complex Injectables: Landmarks and Trends. *J. Control. Release* **2024**, *373*, 617–639. [CrossRef]
109. Ashraf, M.; Ahmad, M.S.; Inomata, Y.; Ullah, N.; Tahir, M.N.; Kida, T. Transition Metal Nanoparticles as Nanocatalysts for Suzuki, Heck and Sonogashira Cross-Coupling Reactions. *Coord. Chem. Rev.* **2023**, *476*, 214928. [CrossRef]
110. Ismael, M.; Sharma, A.; Kumar, N. An Extensive Catalytic Potential of Sustainable TiO<sub>2</sub>-Based Materials Fabricated via Flame Spray Pyrolysis: A Comprehensive Review. *Sustain. Mater. Technol.* **2024**, *40*, e00826. [CrossRef]
111. Kumar, S.; Bharti, B.; Zha, X.; Ouyang, F.; Ren, P. Recent Development in Industrial Scale Fabrication of Nanoparticles and Their Applications. In *Liquid and Crystal Nanomaterials for Water Pollutants Remediation*; CRC Press: Boca Raton, FL, USA, 2022; pp. 88–118. ISBN 9781003091486.
112. Eftekhari, K.; Parakhonskiy, B.V.; Grigoriev, D.; Skirtach, A.G. Advances in Nanoarchitectonics: A Review of “Static” and “Dynamic” Particle Assembly Methods. *Materials* **2024**, *17*, 1051. [CrossRef]
113. Ahmed, S.F.; Mofijur, M.; Rafa, N.; Chowdhury, A.T.; Chowdhury, S.; Nahrin, M.; Islam, A.B.M.S.; Ong, H.C. Green Approaches in Synthesising Nanomaterials for Environmental Nanobioremediation: Technological Advancements, Applications, Benefits and Challenges. *Environ. Res.* **2022**, *204*, 111967. [CrossRef]
114. Smart from the Start: Fully Automated Fabs Deliver Competitive Advantage. Available online: <https://www.appliedmaterials.com/us/en/nanochip-fab-solutions/nanochip-fab-solutions-express-march-2018/smart-from-the-start-fully-automated-fabs-deliver-competitive-advantage.html> (accessed on 24 January 2025).
115. Altammar, K.A. A Review on Nanoparticles: Characteristics, Synthesis, Applications, and Challenges. *Front. Microbiol.* **2023**, *14*, 1155622. [CrossRef] [PubMed]
116. Nazim, M.; Ahmad, R. Introduction to Advanced Electronic Materials for Clean Energy Applications. In *Advances in Electronic Materials for Clean Energy Conversion and Storage Applications*; Woodhead Publishing: Cambridge, UK, 2023; pp. 3–26. ISBN 9780323912068.
117. Harun-Ur-Rashid, M.; Jahan, I.; Foyez, T.; Imran, A. Bin Bio-Inspired Nanomaterials for Micro/Nanodevices: A New Era in Biomedical Applications. *Micromachines* **2023**, *14*, 1786. [CrossRef] [PubMed]
118. Mahmud, M.Z. Al A Concise Review of Nanoparticles Utilized Energy Storage and Conservation. *J. Nanomater.* **2023**, *2023*, 5432099. [CrossRef]
119. Ninduwezuor-Ehiobu, N.; Tula, O.A.; Daraojimba, C.; Ofonagoro, K.A.; Ogunjobi, O.A.; Gidiagba, J.O.; Egbokhaebho, B.A.; Banson, A.A. Exploring Innovative Material Integration in Modern Manufacturing for Advancing U.S. Competitiveness in Sustainable Global Economy. *Eng. Sci. Technol. J.* **2023**, *4*, 140–168. [CrossRef]
120. Singh, N.B.; Kumar, B.; Usman, U.L.; Susan, M.A.B.H. Nano Revolution: Exploring the Frontiers of Nanomaterials in Science, Technology, and Society. *Nano-Struct. Nano-Objects* **2024**, *39*, 101299. [CrossRef]
121. Srivastav, A.K.; Das, P.; Srivastava, A.K. Future Trends, Innovations, and Global Collaboration. In *Biotech and IoT*; Apress: Berkeley, CA, USA, 2024; pp. 309–398. ISBN 979-8-8688-0527-1.
122. Sharma, A.; Manocha, D.; Arora, A.; Kumar, A.; Srivastava, C.M.; Rawat, V.; Kim, H.; Verma, M.; Rao, G.K. Applications of Green Nanomaterials in Electronic and Electrical Industries. In *Green Nanomaterials for Industrial Applications*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 397–421. ISBN 9780128236222.
123. Park, H.; Otte, A.; Park, K. Evolution of Drug Delivery Systems: From 1950 to 2020 and Beyond. *J. Control. Release* **2022**, *342*, 53–65. [CrossRef]
124. Virmani, K.; Deepak, C.; Sharma, S.; Chadha, U.; Selvaraj, S.K. Nanomaterials for Automotive Outer Panel Components: A Review. *Eur. Phys. J. Plus* **2021**, *136*, 1–29. [CrossRef]
125. Subhan, M.; Choudhury, K.; Neogi, N. Advances with Molecular Nanomaterials in Industrial Manufacturing Applications. *Nanomanufacturing* **2021**, *1*, 75–97. [CrossRef]
126. Addula, S.R.; Tyagi, A.K. Future of Computer Vision and Industrial Robotics in Smart Manufacturing. In *Artificial Intelligence-Enabled Digital Twin for Smart Manufacturing*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2025; pp. 505–539. ISBN 9781394303601.
127. *The Impacts of Nanotechnology on Companies*; OECD: Paris, France, 2010.
128. Shamoan, A.; Haleem, A.; Bahl, S.; Javaid, M.; Bala Garg, S. Role of Energy Technologies in Response to Climate Change. *Mater. Today Proc.* **2022**, *62*, 63–69. [CrossRef]

129. Zhang, H.; Li, S.; Ma, X. Transforming Healthcare with Nanomedicine: A SWOT Analysis of Drug Delivery Innovation. *Drug Des. Devel. Ther.* **2024**, *18*, 3499–3521. [CrossRef]
130. Kumah, E.A.; Fopa, R.D.; Harati, S.; Boadu, P.; Zohoori, F.V.; Pak, T. Human and Environmental Impacts of Nanoparticles: A Scoping Review of the Current Literature. *BMC Public Health* **2023**, *23*, 1059. [CrossRef] [PubMed]
131. Woolley, J.L.; MacGregor, N. Science, Technology, and Innovation Policy Timing and Nanotechnology Entrepreneurship and Innovation. *PLoS ONE* **2022**, *17*, e0264856. [CrossRef] [PubMed]
132. Nanotechnology in Japan: Market Report. Available online: <https://www.azonano.com/article.aspx?ArticleID=3559> (accessed on 24 January 2025).
133. Nanotechnology in South Korea: Market Report. Available online: <https://www.azonano.com/article.aspx?ArticleID=3576> (accessed on 24 January 2025).
134. Hsieh, S.; Lin, P.Y.; Lin, I.H.; Beck, D.E.; Lin, C.H. Assessing the Contribution of Semiconductors to the Sustainable Development Goals (SDGs) from 2017 to 2022. *Heliyon* **2023**, *9*, 2405–8440. [CrossRef] [PubMed]
135. Singh, P.; Gupta, P.; Verma, V.; Yadav, N.; Pandey, N.K. *Nanotechnology: Social Acceptance, Cultural Impact and Privacy*; Springer: Singapore, 2024; pp. 65–93. ISBN 978-981-97-6184-5.
136. Taking the Automotive Experience to the Next Level with Future Connected Vehicles—NTT. Available online: <https://www.global.ntt/insights-hub/taking-the-automotive-experience-to-the-next-level-with-future-connected-vehicles/> (accessed on 24 January 2025).
137. South Korea to Invest over \$620 Million in Nanotech R&D | ZDNET. Available online: <https://www.zdnet.com/article/south-korea-to-invest-over-620-million-in-nanotech-r-d/> (accessed on 24 January 2025).
138. Pandey, G. Challenges and Future Prospects of Agri-Nanotechnology for Sustainable Agriculture in India. *Environ. Technol. Innov.* **2018**, *11*, 299–307. [CrossRef]
139. Okonkwo, E.C.; Abdullatif, Y.M.; AL-Ansari, T. A Nanomaterial Integrated Technology Approach to Enhance the Energy-Water-Food Nexus. *Renew. Sustain. Energy Rev.* **2021**, *145*, 111118. [CrossRef]
140. Garg, S.; Rumjit, N.P.; Roy, S. Smart Agriculture and Nanotechnology: Technology, Challenges, and New Perspective. *Adv. Agrochem* **2024**, *3*, 115–125. [CrossRef]
141. Kahn, M.J. The Status of Science, Technology and Innovation in Africa. *Sci. Technol. Soc.* **2022**, *27*, 327–350. [CrossRef]
142. Corsi, I.; Venditti, I.; Trotta, F.; Punta, C. Environmental Safety of Nanotechnologies: The Eco-Design of Manufactured Nanomaterials for Environmental Remediation. *Sci. Total Environ.* **2023**, *864*, 161181. [CrossRef]
143. Talebian, S.; Rodrigues, T.; Das Neves, J.; Sarmiento, B.; Langer, R.; Conde, J. Facts and Figures on Materials Science and Nanotechnology Progress and Investment. *ACS Nano* **2021**, *15*, 15940–15952. [CrossRef]
144. Kajal, M.; Trikha, R.; Singh, K. A Comprehensive Study of the Governance of India’s Scientific, Technological, and Innovative Endeavors. In *Science, Technology and Innovation Ecosystem: An Indian and Global Perspective*; Springer: Singapore, 2024; pp. 37–55. ISBN 9789819728152.
145. Shivani, N.; Thakur, P.; Thakur, A. Ethical, Legal, and Socio-Economic Impacts of Nanotechnology. In *Green Nanobiotechnology*; CRC Press: Boca Raton, FL, USA, 2024; pp. 291–310. ISBN 9781040259467.
146. Allan, J.; Belz, S.; Hoeveler, A.; Hugas, M.; Okuda, H.; Patri, A.; Rauscher, H.; Silva, P.; Slikker, W.; Sokull-Kluettgen, B.; et al. Regulatory Landscape of Nanotechnology and Nanoplastics from a Global Perspective. *Regul. Toxicol. Pharmacol.* **2021**, *122*, 104885. [CrossRef]
147. Wasti, S.; Lee, I.H.; Kim, S.; Lee, J.H.; Kim, H. Ethical and Legal Challenges in Nanomedical Innovations: A Scoping Review. *Front. Genet.* **2023**, *14*, 1163392. [CrossRef] [PubMed]
148. Subhan, M.A.; Subhan, T. Safety and Global Regulations for Application of Nanomaterials. In *Nanomaterials Recycling*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 83–107. ISBN 9780323909822.
149. Ali, F.; Neha, K.; Parveen, S. Current Regulatory Landscape of Nanomaterials and Nanomedicines: A Global Perspective. *J. Drug Deliv. Sci. Technol.* **2023**, *80*, 104118. [CrossRef]
150. Hristozov, D.; Badetti, E.; Bigini, P.; Brunelli, A.; Dekkers, S.; Diomede, L.; Doak, S.H.; Fransman, W.; Gajewicz-Skretna, A.; Giubilato, E.; et al. Next Generation Risk Assessment Approaches for Advanced Nanomaterials: Current Status and Future Perspectives. *NanoImpact* **2024**, *35*, 100523. [CrossRef] [PubMed]
151. Singh, R.; Kumar, S. Regulatory and Safety Concerns Regarding the Use of Active Nanomaterials in Food Industry. In *Nanotechnology Advancement in Agro-Food Industry*; Springer: Singapore, 2023; pp. 269–306. ISBN 978-981-99-5045-4.
152. Gottardo, S.; Mech, A.; Drbohlavová, J.; Małyska, A.; Bøwadt, S.; Riego Sintes, J.; Rauscher, H. Towards Safe and Sustainable Innovation in Nanotechnology: State-of-Play for Smart Nanomaterials. *NanoImpact* **2021**, *21*, 100297. [CrossRef] [PubMed]
153. Asselin, L.; Baze, A.; Ory, B.; Wiss, L.; Schäfer, A.; Horbal, L.; Higgins, L.; Richert, L. Comparative Evaluation of Rat and Human in Vitro Assays for Evaluation of Thyroid Toxicity. *ALTEX* **2024**. Online ahead of print. [CrossRef]
154. Amutha, C.; Gopan, A.; Pushbalatatha, I.; Ragavi, M.; Reneese, J.A. *Nanotechnology and Governance: Regulatory Framework for Responsible Innovation*; Springer: Singapore, 2024; pp. 481–503. ISBN 978-981-97-6184-5.

155. Kumari, R.; Suman, K.; Karmakar, S.; Mishra, V.; Lakra, S.G.; Saurav, G.K.; Mahto, B.K. Regulation and Safety Measures for Nanotechnology-Based Agri-Products. *Front. Genome Ed.* **2023**, *5*, 1200987. [[CrossRef](#)]
156. Vlaicu, P.A.; Untea, A.E.; Varzaru, I.; Saracila, M.; Oancea, A.G. Designing Nutrition for Health—Incorporating Dietary By-Products into Poultry Feeds to Create Functional Foods with Insights into Health Benefits, Risks, Bioactive Compounds, Food Component Functionality and Safety Regulations. *Foods* **2023**, *12*, 4001. [[CrossRef](#)]
157. Ferreira, M.; Matos, A.; Couras, A.; Marto, J.; Ribeiro, H. Overview of Cosmetic Regulatory Frameworks around the World. *Cosmetics* **2022**, *9*, 72. [[CrossRef](#)]
158. Reddy, K.; Singh, S. Regulation of Nanotechnology and Nano-Enabled Products: The Implications of the Consumer Protection Act 68 of 2008 in South Africa. *Afr. J. Int./Multidiscip. Stud.* **2022**, *4*, 325–337. [[CrossRef](#)]

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