Integrating Nanotechnology and Biotechnology into Sustainable Solutions in Healthcare

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Abstract

Nanobiotechnology provides disruptive approaches to diagnostics, medication delivery, surgery, and treatments, transforming healthcare. Innovative tools including nanomedicine, biosensors, and lab-on-nanoparticles offer early illness diagnosis and specific therapies. Nanotechnology additionally improves chemotherapy, surgical accuracy, and regenerative therapies, with advancements such as nanorobotics. Sustainable healthcare solutions use nanotechnology for the purification of water and bioremediation, which promotes ecological sustainability. Nanobiotechnology promotes high-performance, cost-effective goods, however, there are still issues with public acceptability and scalability. Safety regulations and multidisciplinary collaboration are crucial to address toxicological problems and ensure well-being. Considering the challenges, nanobiotechnology has enormous promise to overcome disparities in medical care, promote fitness equity, and propel worldwide health breakthroughs. Nanobiotechnology can optimize societal advantages by combining advances in science with public health policies, paving the way for an increasingly sustainable and accessible healthcare system.

Keywords: Nanobiotechnology, Healthcare, Nanomedicine, Sustainable Solution, Drug Delivery

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Introduction

Nanoscience is a hot issue in the realm of science, the majority of the continuing debates, definitions, and spotlight are centered on nanotechnology. Consequently, it is a wide phrase that embodies the pinnacle of man's insatiable need for knowledge with practical applications (Suhag et al., 2023). The word nanotechnology refers to any kind of technique that operates on the nanoscale and has real-world applications, such as using individual atoms and molecules to create functional structures. There are numerous present and predicted developments in nanoscale research and nanotechnology concerning applications in medicine, agriculture, energy electronics, and so on (Nasrollahzadeh et al., 2019).

Biotechnology, as the name implies, is a blend of biology and technology. Biotechnology, which is based on biological methods and genetic engineering, builds on these accomplishments by utilizing live creatures or their derivatives to develop novel solutions (Naz, 2015). Biotechnology is the combined use of biochemistry, engineering, and microbiology disciplines to accomplish technical or industrial use of the abilities of microbes and produced cells from tissues. The scope of its use covers everything from agriculture (Cropping Systems, Animal Husbandry, Soil Conservation as well as Soil Science, Seed Technology, Plant Physiology, Crop Management, and so on.) to industry (Pharmaceutical, Food Chemical, Textiles, Byproducts, and so on.), Cell Biology, Medicine, Environmental Conservation, and Nutrition, which makes it one of the most rapid expanding fields (Bhushan, 2017).

The combination of biotechnology and nanotechnology provides an exciting opportunity for scientific discovery, providing transformational answers to a wide range of medical concerns. (Patel et al., 2021). Nanobiotechnology has enormous potential in medicine to transform diagnostics, drug delivery, and treatments. Nano-sized materials and gadgets can travel the human body's complex pathways with remarkable accuracy, improving methodologies for imaging, allowing targeted medication administration, and aiding early illness diagnosis (Hassan & Fathi, 2024). In addition, advances in nanomedicine provide individualized therapies suited to specific genetic profiles, resulting in a new age of personalized medicine.

This chapter investigates the synergistic combination of nanotechnology and biotechnology to create novel and long-lasting solutions to healthcare concerns. It stresses how these multidisciplinary areas may help with essential concerns including illness diagnosis, therapy, medication delivery, and customized medicine. It focuses on the fundamentals of nanotechnology and biotechnology, outlining their distinct contributions to healthcare.

Fundamentals of Nanotechnology and Biotechnology

1. Principles of Nanotechnology

Nanotechnology is the field of science and engineering that involves the nanoscale creation, development, and applications of systems, devices, and structures (Whitesides, 2005). The following are the main components of nanotechnology. Nanoparticles are the particles that have dimensions in between one and one hundred nanometres. They have distinctive physio-chemical properties that are not present in bulk material due to their size (Tang & Kotov, 2005). Localized Plasmon resonance can be considered as an example which allows the gold nanoparticles to display varying hues depending upon their size (Ghosh & Pal, 2007). Nanoparticles are utilized for drug administration, imaging, and diagnostic purposes due to their ability to cross the biological membrane and target specific tissues or cells (Barua & Mitragotri, 2014). Nanomaterials are those materials that have at least one nanoscale dimension and they can be moulded in many forms like films, nanoparticles, nanofibers, and nanowires. As per (Liu et al., 2012), these materials exhibit unusual catalytic, electromagnetic, and mechanical, properties. Carbon nanomaterials, like carbon nanotubes as well as graphene, exhibit unique mechanical, thermal, and electrical, characteristics (Patel et al., 2019). Metal oxide nanomaterials, such as quantum dots and zinc oxide nanomaterial, are used for energy storage, sensing, as well as catalysis (Figure 1) (Concina & Vomiero, 2015).

Nanostructures, such as nanoplates and nanorods, are another significant aspect of nanotechnology. The fabrication of nanodevices for the tasks of energy creation, electronics, and photonics primarily relies upon nanostructure (Yu et al., 2012). Scientists may create new goods with greater durability by manufacturing materials at the level of the nanoscale, and their potential uses include health, electronics, agriculture, and safeguarding the environment (Ragesh et al., 2014).

2. Principles of Biotechnology

Biotechnology is the use of biological materials such as cells and molecules to create technologies and products which help humanity. In the words of (Gvrilescu & Chisti 2005), this discipline is related to molecular biology, genetics, and biology. It includes biological molecules, which are vital in different fields such as bioprocessing and genetic engineering (Bhardwaj et al., 2019). For instance, with the use of Recombinant DNA technology, it is feasible to synthesize insulin by inoculating the insulin gene from humans in a bacterial cell, which produces a large amount of it (Bhoria et al., 2022). This discipline employs cell culture techniques to produce helpful goods such as vaccines and monoclonal antibodies (Javanmard, 2023). Along with this stem cells hold significant beneficiary results in tissue engineering and regenerative medicines (Gomez-Cid et al., 2021). Biotechnology takes control of biological systems to produce useful products (McCarty & Ledesma-Amaro, 2019). For instance, metabolic engineering deals with altering the metabolic pathways of microorganisms to enhance the synthesis of desired products like industrial enzymes, biofuels, and antibiotics (Intasian et al., 2021). Synthetic biology deals with the creation of novel biological elements and systems that have applications in environmental sustainability, agriculture, and medicine. Biotechnology addresses challenges in business, agriculture, and the health sector by utilizing biological processes and living things such as proteomics, metabolomics, and genomes, which accelerates the field's development.

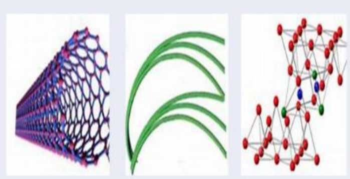
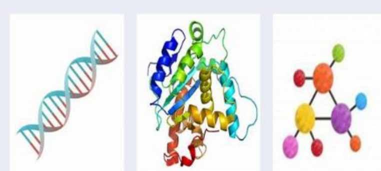
	Nanotechnology	Biotechnology
Scale of Materials	~1 to 100 nm (with a few examples in the 100 to 300 nm range)	Modification of: biomolecules (0.3 to 15 nm) Engineering of: viruses (100s of nm), bacteria (1 to 3 µm), animal and human cells (10 to 25 µm), plant cells (10 to 100 µm)
Materials		
Applications	Medication and drugs, nanofabrics, energy, cosmetics, nanobiotechnology, optical engineering, defense and security	Medical diagnosis, fermentation technology, pharmaceuticals, agriculture, improvement in food technology, environment and energy management, recombinant DNA technology

Fig. 1: Difference between biotechnology and nanotechnology (Mehta, 2013).

3. Intersection of Nanotechnology and Biotechnology: Nanobiotechnology

A new multidisciplinary field called nanobiotechnology has evolved by combining nanotechnology and biotechnology. This field of study combines biological elements with nanoscale materials, systems, and methods to bring novel approaches to agricultural, environmental, and healthcare issues. Nanobiotechnology is primarily concerned with the manufacture and application of nanoscale chemicals to regulate, modify, and analyse biological processes (Singer et al., 2018). This method allows researchers to create hybrid systems with improved functionality and features (Castillo et al., 2017). Nanobiotechnology applications include nanoscale devices for drug delivery (Dendrimers, liposomes, and polymeric nanoparticles), as well as biosensors for the engineering of tissues as shown in Figure 2. These strategies enable controlled release, minimal side effects, and optimal medication absorption. Doxil (liposomal doxorubicin), a type of nanocarrier employed in cancer therapy, targets tumor cells while protecting healthy tissues (Kaasgaard & Andresen, 2010). Gold nanoparticles and quantum dots serve as biosensors for detecting environmental contaminants, diseases, and biomolecules. Diseases can be detected early using nanomaterials. In lateral flow assays (like the COVID-19 rapid tests), gold nanoparticles are utilized to visualize test results. (Huang et al., 2020).

Polymers, ceramics, and composite materials are utilized to synthesize nanostructured scaffolds that allow cell growth, proliferation, and differentiation by engaging with extracellular matrix. This field is also necessary to form 3D-printed tissues and organs (Rana et al., 2017).

Nanoscale and nanorobots are examples of nanoscale materials that are used to address diseases at different levels of cellular organization. Like gold nanoparticles are used in photothermal therapy to kill cancerous cells (Vankayala et al., 2014). By modulating the nanocarriers to target specific cells or tissues, harmful effects can be lessened, and therapeutic efficacy can be increased. According to (Morais et al., 2014), nanomaterials offer more effective electro-mechanical and optical qualities which help in the synthesis of revolutionary biomaterials, devices, and techniques.

However, nanobiotechnology has revolutionized medical research but this field has some safety, ethical, and environmental issues too. Therefore, is essential to carefully examine the toxicity level of these nanomaterials along with their effects on mankind and the environment. For this purpose, regulatory frameworks are being developed (Ahmadi & Ahmadi, 2013).

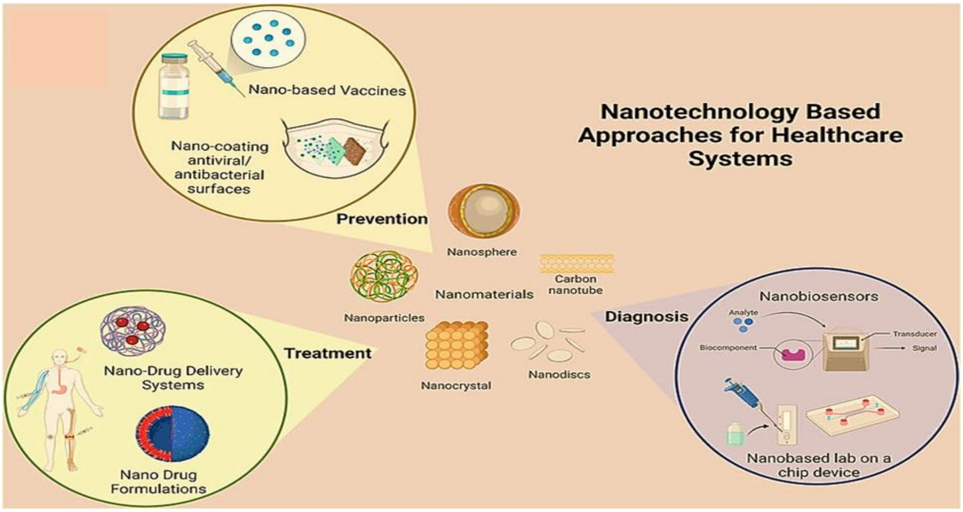


Fig. 2: Diagrammatic representation of nanotechnology-based approaches for healthcare sustainable solution systems (Pokrajac et al., 2021). The figure was created using the Bio Render online tool.

Applications of Nanobiotechnology in Healthcare

Nanobiotechnology has a vast impact on different healthcare sectors. Nowadays, scientists are trying to employ nanoparticles in diagnostics, drug delivery or development, and therapeutics (Table 1).

1. Nanotechnology and Surgery

Researchers are developing nanorobotics (NRBTs) in surgery to improve surgical performance. NRBTs are nanoscale devices that can perform surgery with more accuracy. Surgical nanorobotics is the creation and use of small robots or nanorobots capable of performing surgical operations with great precision and efficiency (Yoon & Kim, 2020). NRBTs may carry out cellular surgeries on a neuron and single dendrite without compromising neurons in a complex network. The well-controlled nano-scissor functionality of NRBTs was confirmed in an animal model (Mazumder et al., 2020). Similarly, nano-bioelectric medicine (NBOE) has been incorporated into surgery. NBOE uses electrical impulses to boost the body's healing systems. NBOE may be used in cancer, cardiovascular diseases, and other problems in the body (Zhang et al., 2022). Implantable medical nanogenerators (IMNGs) were recently brought to the market. IMNGs are nanosensors that use mechanical power from body motions to produce electrical energy. Implanted IMNGs may power a wide range of medical devices, including medication delivery systems, pacemakers, and neurostimulators (Malik et al., 2023).

2. Nanotechnology and Cancer

Nanoparticles (NPs) can carry hundreds of specific anti-cancer compounds to tumor sites. When investigating the links between the usage of NPs and cancer, it is necessary to investigate the tumor diagnosis and treatment strategies linked with nanotechnology (Souri et al., 2022). The focus is on improving chemotherapy medicines' pharmacokinetics and pharmacodynamic properties, as well as their tumor-targeting efficacy. Similarly, NRBTs can be coupled with many gene therapies against cancers (Chouhan & Rangi, 2023). Several innovative nanomedicines have been authorized by globally known health agencies, such as the Food and Drug Administration and the European Medicine Agency (EMA) (Kumar et al., 2021). Figure 3 further summarizes several applications of nanotechnology and biotechnology in healthcare.

Sustainable Solutions in Healthcare Using Nanotechnology and Biotechnology

1. Environmental Sustainability

Bioremediation is the process of utilizing living organisms like fungi, bacteria, and plants to reduce the toxicity of soil. It is a green as well as cost-effective methodology for the treatment of polluted environments. This methodology can enhance its efficiency by integrating with nanoparticles. It has been found that nanoparticles have the efficacy to enhance the remediation process (Usman et al. 2020). Nano-remediation is a sustainable method that helps reduce contaminants within the soil using different mechanisms present in the nanotechnology discipline. For example, various types of nanoparticles such as iron oxide and nano zero-valent iron (nZVI) have been highly employed in bioremediation due to their high action towards the strength of very strong pollutants even including chromium Cr (VI) because of their higher activity (Luo et al., 2021). The use of nanocomposites like Fe3O4/biochar neutralizes harmful contaminants by boosting this process with the dehalogenation and dichlorination of organic pollutants (Usman et al., 2020). The bioremediation process also played a great role in water purification. The utilization of nanoparticles removes pathogens and organic pollutants. For instance, magnetic nanoparticles can remove dye effectively, and nano-absorbents, such as activated carbon and silica gel, provide very cost-effective solutions for water purification (Ali et al., 2020).

Table 1: Applications of Nanobiotechnology in the Healthcare sector

Application	Examples	Explanation	Reference
Diagnostics	Biosensors	Highly sensitive biosensors that can identify even trace amounts of biomolecules in physiological fluids like blood and urine have been made possible by nanotechnology, which can help with early illness identification and treatment.	(Malik et al., 2023).
	Nanopore sequencing	An innovative technique that detects DNA or RNA molecule sequences using nanopores, enabling quick and precise diagnosis of genetic illnesses and cancer.	(Y. Wang et al., 2021).
	Nanomedicine	It can be utilized in both in vitro (via nanodevices at the subcellular level, with samples prepared from human tissue, cell culture, and body fluids) and in vivo diagnostics. In in vivo diagnostics, the nanomedicine approach is being used to develop devices capable of working, responding, and modifying within the human body with the sole purpose of early diagnosis of any irregularities in the human body that could lead to toxicity or tumor development events.	(Malik et al., 2023).
	Lab-on-nanoparticles	Tiny devices that can perform multiple functions (drug delivery and diagnostics). These tiny devices are made up of nanoparticles that can detect changes in the body.	(Welch et al., 2021).
Pharmaceuticals	Nano-based drug delivery systems	Nanoparticles can deliver drugs to target sites; they can also enhance in vivo drug stability, solubility of drugs, and absorption/distribution of drugs in the body.	(Oroojalian et al., 2020; Sahu et al., 2021).
	DNA-based drug delivery systems	DNA guns and DNA vaccinations are two examples of DNA-based medication delivery systems that have been developed in recent years. These DNA-based systems enable molecules and nanostructures to self-assemble, improving therapeutic targeting and lowering the toxicity of drugs.	(Liu et al., 2023).
Therapeutics.	Gene therapy	Polyplex micelles are advanced self-assembled nanoscale structures of two cationic polymers containing small interfering RNA (knockdown genes) or plasmid DNA (carry therapeutic genes). Pancreatic adenocarcinoma is among the tumors for which these polyplex micelle-based therapeutic approaches have been studied.	(Salameh et al., 2020; Uchida & Kataoka, 2019).
	Bone regeneration	Nanoparticles can be utilized to make scaffolds that resemble bone structures, which can help direct the formation of new bones and promote bone regeneration. Similar research is being done to create prosthetic joints and nanoscale coverings for knees and hips that imitate collagen and work to stabilize the osteoblasts' process of forming new bone.	(Z. Wang et al., 2021; Wen et al., 2023).
	Regenerative medicine	Nano assemblies' potent tissue regeneration capabilities have significantly improved tissue repair. These technologies are focused on mechanical processes that start tissue regeneration, such as cellular adhesion, migration, and differentiation.	(Malik et al., 2023).

This bioremediation process is also utilized for the treatment of wastewater in which solid waste causes pathogenic organisms to flourish in it due to a rich quantity of carbohydrates and proteins. Efficient microorganisms such as lactic acid bacteria can make wastewater break down fast by triggering mechanisms of fermentation and composting, and this technique becomes extremely powerful in treating wastewater (Shahcheragh et al., 2022). In addition to this, Streptomyces sp. Z38 has been identified as an effective agent for the degradation of heavy metals and biodegradation of organic pollutants through the production of silver nanoparticles that help in the bioremediation process (Costa et al., 2020). Besides, water purification is also boosted by the improvement of filter efficiency such as graphene-based carbon nanotubes and carbon channels that help enhance water permeability besides improving the rate of removal of pollutants (Lohrasebi and Koslowski 2019). Copper nanoparticles play a very crucial role in the purification of wastewater if combined with other materials like Polyethylene Terephthalate filters and Polyacrylonitrile nanofibers. They are antimicrobial in nature and offer significant synergistic effects (Bashir et al., 2021). In nanotechnology, these advancements represent a very important step toward more sustainable, efficient, and cost-effective remediation processes.

2. Economic Sustainability

Various sectors of the economy such as energy, medicine, manufacturing, nanotechnology, and biotechnology have the potential to drive significant improvements by enhancing the performance of products along with reducing costs. As a consequence, there is an increasing requirement for quantitative data to evaluate the economic impact of nanotechnology to direct policymakers, decisions, and investment strategies. The integration of nanostructures and the fundamental understanding of applying nano methodologies to technological innovations can direct the establishment of more reasonable products with greater performance (Zucker and Darby, 2005). However, the economic implications of this field remain underexplored, as most economic insights into nanotechnology are based on experiences with earlier technologies. While new applications of existing technologies often have higher initial costs, they are eventually offset by enhanced performance and cost reductions in the long term. The implementation of nanotechnology is expected to follow a similar pattern, where substantial investments in new production facilities, equipment, and raw materials will lead to higher initial costs, which will decrease as economies of scale are achieved. Furthermore, evaluating nanotechnology's economic impact goes beyond traditional research metrics, such as the number of published papers and patents, to include factors like job creation, manufacturing cost reduction, and the development of new products and services. These factors are important in understanding how nanotechnology can play a great role in the growth of the economy and industry (Morse, 2012).

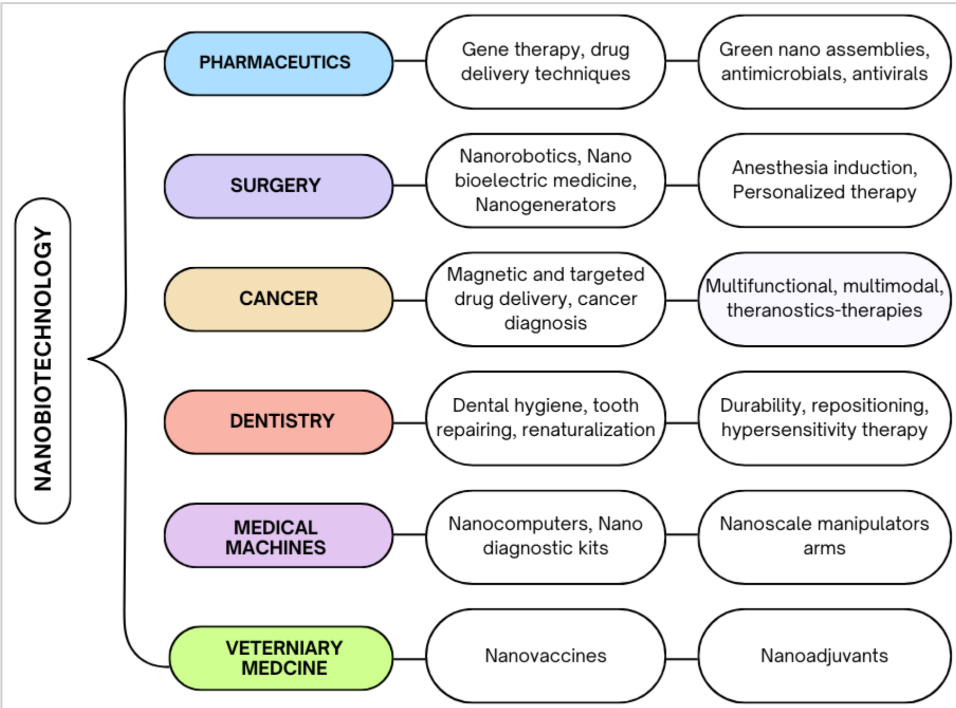


Fig. 3: Flowchart displaying a summary of several applications of nanobiotechnology

In the advancement of nanotechnology, public investment is crucial as it supports fundamental research and addresses societal challenges like environmental and healthcare concerns. It accelerates the commercialization of novel techniques. However, there are many challenges in evaluating the economic impact of nanotechnology. This includes the versatile nature of technology, the challenge of isolating its contributions from other different technologies and its contributions from those of other technologies, and the complexity of collecting correct data because of the established information of business (Babatunde et al., 2019). Moreover, the longer cycle between investments and returns hinder the analysis of the economic value of nanotechnology. To overcome these problems, a proper combination of quantitative and qualitative measures like life cycle analysis, cost-benefit analysis, and markers of research along with developmental investment are necessary for the analysis of the economic impact of nanotechnology. Above that, public acceptance is of great importance in the realization of nanotechnology applications wherein there is a possibility that their commercialization could be stifled by the lack of public trust and interest not only for high-value low-risk products but also beyond. Therefore, proper strategy assessment of nanotechnology has to be undertaken to ensure that it will share significant economic and societal gain throughout its lifetime (Zucker and Darby, 2005).

3. Social Sustainability

Safety in nanotechnology is a very serious issue. There is widespread uncertainty around the possible risks and benefits of nanomaterials, particularly in environmental and medical settings. This uncertainty extends across various sectors, complicating the evaluation of risks associated with new technologies. Unlike more traditional fields, where risk calculations can be more precisely made such as in toxicology, where dose effects are measurable, nanotechnology involves risks that are harder to quantify. Many of these issues, including concerns about the safety of nanomaterials, may only be fully understood through large-scale population studies, such as longitudinal cohort studies or big data analyses, which can help clarify long-term effects (Oluwoye, 2015). As nanotechnology advances in sectors like agriculture (Pramanik et al., 2020), water purification (Sahu et al., 2021), healthcare (Patel et al., 2015), and environmental bioremediation, its potential to improve lives is clear (Babatunde et al., 2019). Even though these innovations also come into existence with great responsibilities for private sectors, governments, and the public to guarantee their secure and moral consumption.

The societal controversy surrounding the development of new technologies, such as GMOs, has historically impacted on the commercialization of these products. Fears of unplanned consequences and public debates on following the introduction of GM crops, have directed to refusal or slow implementation of such technologies in various regions of the world (Dale,2004; Hall, 2007). Likewise, the safety concerns of nanotechnology products including nutritional supplements, cosmetics, and drugs are expected to influence their approval. For successful commercialization, the understanding of societal responses to nanotechnology is very important. As with previous technologies, factors including demographic variables (age, education, gender, income), level of awareness, and concerns about safety, health, environmental impact along with sustainability play major responsibility in determining public discernment and acceptance (Gupta et al., 2015; Rahim et al., 2015; Ganesh Pillai and Bezbaruah, 2017). To facilitate the responsible introduction of nano-biotechnologies, stakeholders must address these concerns by providing transparent information about potential risks and benefits ensuring that public safety remains a priority (Figure 4).

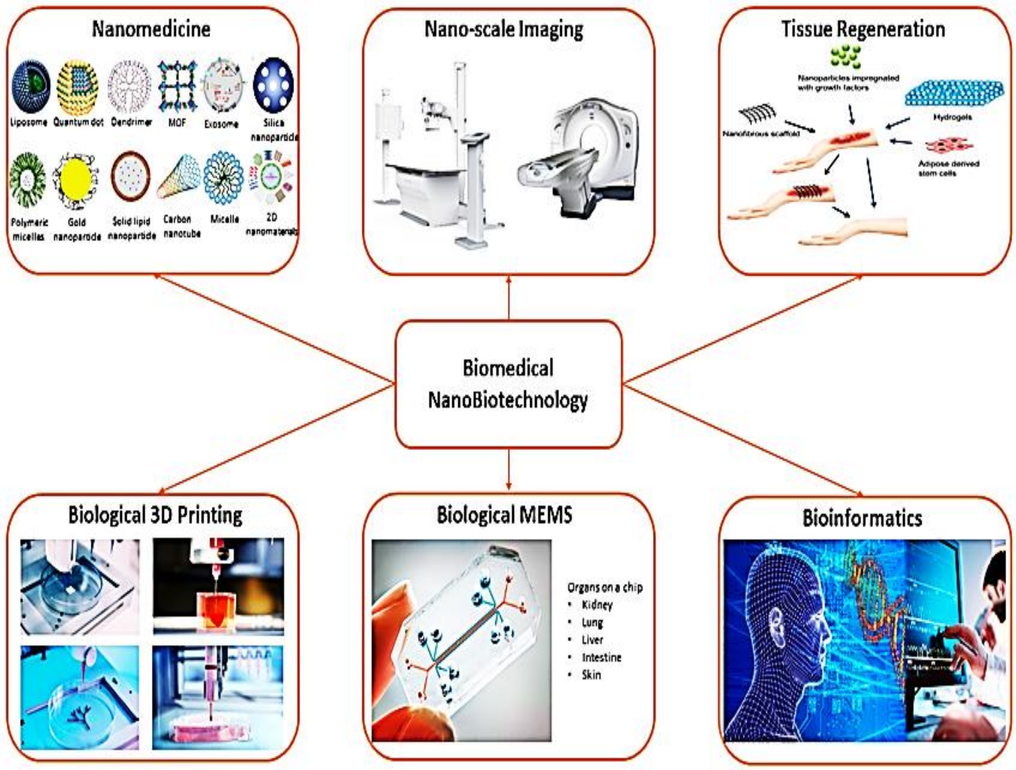


Fig. 4: Sustainable solutions of nanobiotechnology in the healthcare system (Al Sharabati et al., 2022).

Challenges and Future Directions

In recent decades, nanotechnology has received a lot of attention due to its groundbreaking and omnipresent nature. Despite the massive government-aided investment in nanotechnology-based goods, the concurrent industrialization of these systems is not gaining the same momentum. The technology, nevertheless, addresses the unfulfilled requirements of the pharmaceutical sector, such as modifying the formulation of medication to enhance their bioavailability, solubility, or toxicity profiles, to be evidenced by the broad range of outstanding research publications that appear across different scientific newspapers and journals (Kaur et al., 2014). The primary obstacles in promoting of these nanotechnology innovations may be classified as:

1. Insufficient system of regulation
2. Lack of appreciation and acceptability from the public, physicians, and industry
3. Developmental challenges include scalability, repeatability, characterization, quality assurance, and appropriate translation.
4. Toxicological concerns along with safety profiles
5. Lack of interdisciplinary platforms
6. Inadequate intellectual property security

Despite encouraging breakthroughs in experimental animal models, the clinical implementation of nanomedicines is still a lengthy, biased, and frequently unsuccessful process. Specified methods are absent, and the identification of materials and biological processes, as well as statistical evaluations that are frequently used, are typically insufficient. Furthermore, the wide and considerable variability of models used, refusal to share data, and inaccuracies in research design have impeded the advancement of nanomedicines into the final clinical investigation phases. In contrast, contradictory results discovered between published and industry-obtained information along with the difficulty in locating acceptable commercial collaborators owing to the problematic voids in translation have led to the abandonment of future investigations. The overall success rate in cancer clinical studies reduces from 94% in phase I to 48% in the second stage and 14% in the third phase. The practical use of nanomedicine is heavily reliant on the thorough and painstaking evaluation of related characteristics, as tiny modifications to chemistry or manufacturing procedures can cause significant modifications in tolerability and biodistribution (Đorđević et al., 2022).

The United States regulatory assessment procedure for nanotechnology and biotechnology goods works in tandem. The two systems contain data controls, security endpoints, as well as actors regulated by comparable or identical groups, laws, and rules. In both nanotechnology and biotechnology, the industry is frequently the primary developer and broadcaster of safety research for regulatory bodies as well as the general public. This might result in skewed information, whether intentional or not, indicating an infringement of integrity. The pre-market research is frequently not necessary, notably for genetically altered foods (per FDA policy) and nanomaterials with similar molecular formulae to existing chemicals. If no obligatory pre-market regulatory clearance procedures exist, negative health impacts from nanoparticles are unlikely to be evaluated. This absence of need could give rise to a violation of equality, as vulnerable communities are, by definition, disproportionately impacted by harmful health impacts (Kuzma & Besley, 2008).

Multidisciplinary groups creating nanomedicines by linking material science, novel platform evaluation, and models of disease more effectively akin to desired medical conditions, whereas influencing the present regulatory structures according to science-based norms, will undoubtedly produce the data needed to grant marketing approval for the disruptive innovations demanded to address the world's remaining gaps for treatments and health care (Đorđević et al., 2022). The possibilities for using nanomedicine to enhance health are endless. Incorporating public health skills is critical for maximizing benefits in both population and individual health. This effect on nanomedicine research will aid in identifying the most pressing areas for technical innovation, determining how to optimally allocate resources, and shaping policies to safeguard both the environment and humans. Adopting an integrated approach to nanotechnology education and research will effectively enhance the status of the knowledge, leading to a higher return upon investment benefiting the general population. The study and creation of innovative nanomedicine uses, linked with wellness concepts, will revolutionize the wellness of people worldwide (Pautler & Brenner, 2010).

Conclusion

The combination of nanotechnology and biotechnology transforms healthcare by introducing inventive, novel, and sustainable solutions. Nanobiotechnology blends precision and biological variety to provide personalized therapies, enhanced treatment, and early detection. Biodegradable nanoparticles reduce trash and toxicity, improving sustainability. Expandable solutions improve accessibility, hence promoting wellness equity. Scalable solutions offer a link to global medical professionals and other stakeholders. However, ethical problems, legislative barriers, and future safety implications must be addressed. Collaboration among policymakers, researchers, and stakeholders is critical for overcoming these obstacles and realizing the full promise of nanobiotechnology.

References

Ahmadi, M., & Ahmadi, L. (2013). Ethical considerations of nanobiotechnology. *Journal of Biomaterials and Tissue Engineering, 3(3)*, 335-352. https://doi.org/10.1166/jbt.2013.1090

Ali, M. E., Hoque, M. E., Safdar Hossain, S. K., & Biswas, M. C. (2020). Nanoadsorbents for wastewater treatment: next generation biotechnological solution. *International Journal of Environmental Science and Technology, 17(9)*, 4095-4132.

Al Sharabati, M., Sabouni, R., & Husseini, G. A. (2022). Biomedical applications of metal– organic frameworks for disease diagnosis and drug delivery: a review. *Nanomaterials, 12*(2), 277. https://doi.org/10.3390/nano12020277

Babatunde, D. E., Denwigwe, I. H., Babatunde, O. M., Gbadamosi, S. L., Babalola, I. P., & Agboola, O. (2019). Environmental and societal impact of nanotechnology. *IEEE Access, 8*, 4640-4667. https://doi.org/10.1109/ACCESS.2019.2961513

Barua, S., & Mitragotri, S. (2014). Challenges associated with penetration of nanoparticles across cell and tissue barriers: a review of current status and future prospects. *Nano today, 9(2)*, 223-243. https://doi.org/10.1016/j.nantod.2014.04.008

Bashir, F., Irfan, M., Ahmad, T., Iqbal, J., Butt, M. T., Sadef, Y., Umbreen, M., Shaikh, I.A., & Moniruzzaman, M. (2021). Efficient utilization of low cost agro materials for incorporation of copper nanoparticles to scrutinize their antibacterial properties in drinking water. *Environmental Technology & Innovation, 21*, 101228. https://doi.org/10.1016/j.eti.2020.101228

Bhardwaj, N., Kumar, B., & Verma, P. (2019). A detailed overview of xylanases: an emerging biomolecule for current and future prospective. *Bioresources and Bioprocessing, 6(1)*, 1-36.

Bhoria, S., Yadav, J., Yadav, H., Chaudhary, D., Jaiwal, R., & Jaiwal, P. K. (2022). Current advances and future prospects in production of recombinant insulin and other proteins to treat diabetes mellitus. *Biotechnology Letters, 44(5)*, 643-669.

Bhushan, B. (2017). Introduction to nanotechnology. *Springer Handbook of Nanotechnology*, 1-19. https://link.springer.com/chapter/10.1007/978-3-662-54357-3_1.

Castillo, R. R., Baeza, A., & Vallet-Regí, M. (2017). Recent applications of the combination of mesoporous silica nanoparticles with nucleic acids: development of bioresponsive devices, carriers and sensors. *Biomaterials Science, 5(3)*, 353-377.

Chouhan, A. S., & Rangi, N. (2023). A Research on Future Scenario in the Field of Role of Nanorobotics a Device for Diagnosis and Treatment. *Global Academic Journal of Medical Sciences, 5*, 85-95. https://doi.org/10.36348/gajms.2023.v05i02.004

Concina, I., & Vomiero, A. (2015). Metal oxide semiconductors for dye-and quantum-dot-sensitized solar cells. *Small, 11*(15), 1744-1774. https://doi.org/10.1002/smll.201402334

Costa, J. S. D., Hoskisson, P. A., Paterlini, P., Romero, C. M., & Alvarez, A. (2020). Whole genome sequence of the multi-resistant plant growth-promoting bacteria Streptomyces sp. Z38 with potential application in agroindustry and bio-nanotechnology. *Genomics, 112*(6), 4684-4689. https://doi.org/10.1016/j.ygeno.2020.08.022/

Dale, P. J. (2004). Public-good plant breeding: What should be done next? *Journal of Commercial Biotechnology, 10*, 199-208.

Đorđević, S., Gonzalez, M. M., Conejos-Sánchez, I., Carreira, B., Pozzi, S., Acúrcio, R. C., & Vicent, M. J. (2022). Current hurdles to the translation of nanomedicines from bench to the clinic. *Drug Delivery and Translational Research*, 1-26. https://link.springer.com/article/10.1007/S13346-021-01024-2

Ganesh Pillai, R., & Bezbaruah, A. N. (2017). Perceptions and attitude effects on nanotechnology acceptance: an exploratory framework. *Journal of Nanoparticle Research, 19*(2), 41.

Gavrilescu, M., & Chisti, Y. (2005). Biotechnology—a sustainable alternative for chemical industry. *Biotechnology Advances, 23*(7-8), 471-499. https://doi.org/10.1016/j.biotechadv.2005.03.004

Ghosh, S. K., & Pal, T. (2007). Interparticle coupling effect on the surface plasmon resonance of gold nanoparticles: from theory to applications. *Chemical Reviews, 107*(11), 4797-4862.https://pubs.acs.org/doi/full/10.1021/cr0680282.

Gomez-Cid, L., Grigorian-Shamagian, L., Sanz-Ruiz, R., de la Nava, A. S., Fernández, A. I., Fernandez-Santos, M. E., & Fernandez-Aviles, F. (2021). The essential need for a validated potency assay for cell-based therapies in cardiac regenerative and reparative medicine. A practical approach to test development. *Stem Cell Reviews and Reports, 17*(6), 2235-2244.

Gupta, N., Fischer, A. R., & Frewer, L. J. (2015). Ethics, risk and benefits associated with different applications of nanotechnology: a comparison of expert and consumer perceptions of drivers of societal acceptance. *NanoEthics, 9*, 93-108.

Hassan, L., & Fathi, A. (2024). The Convergence of Nanotechnology and Biotechnology: Small-Scale Solutions for Big Challenges in Medicine, Energy, and Environment. *Journal of Academic Sciences, 6*(1), 1-8.

Huang, C., Wen, T., Shi, F. J., Zeng, X. Y., & Jiao, Y. J. (2020). Rapid detection of IgM antibodies against the SARS-CoV-2 virus via colloidal gold nanoparticle-based lateral-flow assay. *ACS Omega, 5*(21), 12550-12556. https://pubs.acs.org/doi/full/10.1021/acsomega.0c01554.

Intasian, P., Prakinee, K., Phintha, A., Trisrivirat, D., Weeranoppanant, N., Wongnate, T., & Chaiyen, P. (2021). Enzymes, in vivo biocatalysis, and metabolic engineering for enabling a circular economy and sustainability. *Chemical Reviews, 121*(17), 10367-10451. https://pubs.acs.org/doi/full/10.1021/acs.chemrev.1c00121.

Javanmard, S. (2023). An overview of the various appropriate types of cell lines for the production of monoclonal antibodies. *Experimental and Applied Medical Science, 4*(1), 476-501. https://doi.org/10.46871/eams.1254823.

Kaasgaard, T., & Andresen, T. L. (2010). Liposomal cancer therapy: exploiting tumor characteristics. *Expert Opinion on Drug Delivery, 7*(2), 225-243. https://doi.org/10.1517/17425240903427940.

Kaur, I. P., Kakkar, V., Deol, P. K., Yadav, M., Singh, M., & Sharma, I. (2014). Issues and concerns in nanotech product development and its commercialization. *Journal of Controlled Release, 193*, 51-62. https://doi.org/10.1016/j.jconrel.2014.06.005.

Kumar, R., Jha, K., & Barman, D. (2021). Nanotechnology in oral cancer prevention and therapeutics: A literature review. *Indian Journal of Medical and Pediatric Oncology, 42*(02), 146-152. DOI: https://doi.org/10.1055/s-0041-1732856

Kuzma, J., & Besley, J. C. (2008). Ethics of risk analysis and regulatory review: From bio-to nanotechnology. *Nanoethics, 2*, 149-162. https://link.springer.com/article/10.1007/s11569-008-0035-x

Liu, J. W., Liang, H. W., & Yu, S. H. (2012). Macroscopic-scale assembled nanowire thin films and their functionalities. *Chemical Reviews, 112*(8), 4770-4799. https://pubs.acs.org/doi/full/10.1021/cr200347w.

Liu, J., Xie, G., Lv, S., Xiong, Q., & Xu, H. (2023). Recent applications of rolling circle amplification in biosensors and DNA nanotechnology. *TrAC Trends in Analytical Chemistry, 160*, 116953. https://doi.org/10.1016/j.trac.2023.116953.

Lohrasebi, A., & Koslowski, T. (2019). Modeling water purification by an aquaporin-inspired graphene-based nano-channel. *Journal of Molecular Modeling, 25*, 1-9. https://link.springer.com/article/10.1007/s00894-019-4160-y.

Luo, Z., Zhu, J., Yu, L., & Yin, K. (2021). Heavy metal remediation by nano zero-valent iron in the presence of microplastics in groundwater: Inhibition and induced promotion on aging effects. *Environmental Pollution, 287*, 117628. https://doi.org/10.1016/j.envpol.2021.117628.

Malik, S., Muhammad, K., & Waheed, Y. (2023). Emerging applications of nanotechnology in healthcare and medicine. *Molecules, 28*(18), 6624. https://doi.org/10.3390/molecules28186624.

Mazumder, S., Biswas, G. R., & Majee, S. B. (2020). Applications of nanorobots in medical techniques. *International Journal of Pharmaceutical Sciences and Research, 11*, 3150. http://dx.doi.org/10.13040/IJPSR.0975-8232.11(7).3150-59.

McCarty, N. S., & Ledesma-Amaro, R. (2019). Synthetic biology tools to engineer microbial communities for biotechnology. *Trends in Biotechnology, 37*(2), 181-197.

Mehta, M. D. (2013). From biotechnology to nanotechnology: what can we learn from earlier technologies?. *In Nanotechnology* (pp. 121-129). Routledge.

Morais, M. G. D., Martins, V. G., Steffens, D., Pranke, P., & da Costa, J. A. V. (2014). Biological applications of nanobiotechnology. *Journal of Nanoscience and nanotechnology, 14*(1), 1007-1017. https://doi.org/10.1166/jnn.2014.8748.

Morse, J. (2012). Assessing the economic impact of nanotechnology: The role of nanomanufacturing. *NNN Newsletter, 5*(3), 1–5. Available: http://eprints.internano.org/1745/.

Nasrollahzadeh, M., Sajadi, S. M., Sajjadi, M., & Issaabadi, Z. (2019). An introduction to nanotechnology. *In Interface science and technology,* (Vol. *28*, pp. 1-27). Elsevier. https://doi.org/10.1016/B978-0-12-813586-0.00001-8.

Naz, Z. (2015). Introduction to biotechnology. DOI: https://doi.org/10.13140/RG.2.1.3517.8968

Oluwoye, J. (2015). 'Age as a predictor of social acceptance of nanotechnology and nano-based food: A conceptual framework. *American International Journal of Contemporary Rese, 5*(6), 14-21.

Oroojalian, F., Charbgoo, F., Hashemi, M., Amani, A., Yazdian-Robati, R., Mokhtarzadeh, A., & Hamblin, M. R. (2020). Recent advances in nanotechnology-based drug delivery systems for the kidney. *Journal of Controlled Release, 321*, 442-462. https://doi.org/10.1016/j.jconrel.2020.02.027.

Patel, J. K., Patel, A., & Bhatia, D. (2021). Introduction to nanomaterials and nanotechnology. *In Emerging technologies for nanoparticle manufacturing*, (pp. 3-23). Cham: Springer International Publishing. https://link.springer.com/chapter/10.1007/978-3-030-50703-9_1.

Patel, K. D., Singh, R. K., & Kim, H. W. (2019). Carbon-based nanomaterials as an emerging platform for theranostics. *Materials Horizons, 6*(3), 434-469.

Patel, S., Nanda, R., & Sahoo, S. (2015). Nanotechnology in healthcare: applications and challenges. *Medicinal Chemistry, 5(12)*, 2161-0444. https://doi.org/10.4172/2161-0444.1000312.

Pautler, M., & Brenner, S. (2010). Nanomedicine: promises and challenges for the future of public health. *International Journal of Nanomedicine*, 803-809. https://www.tandfonline.com/doi/full/10.2147/IJN.S13816#d1e94.

Pokrajac, L., Abbas, A., Chrzanowski, W., Dias, G. M., Eggleton, B. J., Maguire, S., & Mitra, S. (2021). Nanotechnology for a sustainable future: Addressing global challenges with the international network sustainable nanotechnology. *ACS Nano, 15*(12), 18608–18623. https://pubs.acs.org/doi/full/10.1021/acsnano.1c10919.

Pramanik, P., Krishnan, P., Maity, A., Mridha, N., Mukherjee, A., & Rai, V. (2020). Application of nanotechnology in agriculture. *Environmental Nanotechnology Volume 4*, 317-348. https://link.springer.com/chapter/10.1007/978-3-030-26668-4_9.

Ragesh, P., Ganesh, V. A., Nair, S. V., & Nair, A. S. (2014). A review on self-cleaning and multifunctional materials. *Journal of Materials Chemistry A, 2*(36), 14773-14797.

Rahim, R. A., Kassim, E. S., Azizli, H. M., Sari, N. A. M., & Abdullah, S. (2015). Nanotechnology acceptance: A case study of university students in Malaysia. *International Journal of Latest Research in Science and Technology, 4*(2), 11-15. https://www.researchgate.net/publication/275830144.

Rana, D., Kumar, T. S., & Ramalingam, M. (2017). Impact of nanotechnology on 3D bioprinting. *Journal of Bionanoscience, 11*(1), 1-6. https://pubs.acs.org/doi/full/10.1021/acsomega.0c01554.

Sahu, J. N., Karri, R. R., Zabed, H. M., Shams, S., & Qi, X. (2021). Current perspectives and future prospects of nano-biotechnology in wastewater treatment. *Separation & Purification Reviews, 50*(2), 139-158. https://doi.org/10.1080/15422119.2019.1630430.

Sahu, T., Ratre, Y. K., Chauhan, S., Bhaskar, L., Nair, M. P., & Verma, H. K. (2021). Nanotechnology based drug delivery system: Current strategies and emerging therapeutic potential for medical science. *Journal of Drug Delivery Science and Technology, 63*, 102487. https://doi.org/10.1016/j.jddst.2021.102487.

Salameh, J. W., Zhou, L., Ward, S. M., Santa Chalarca, C. F., Emrick, T., & Figueiredo, M. L. (2020). Polymer-mediated gene therapy: Recent advances and merging of delivery techniques. Wiley Interdisciplinary Reviews: *Nanomedicine and Nanobiotechnology, 12*(2), e1598. https://doi.org/10.1002/wnan.1598.

Shahcheraghi, N., Golchin, H., Sadri, Z., Tabari, Y., Borhanifar, F., & Makani, S. (2022). Nano-biotechnology, an applicable approach for sustainable future. *3 Biotech, 12*(3), 65. https://link.springer.com/article/10.1007/s13205-021-03108-9.

Singer, A., Markoutsa, E., Limayem, A., Mohapatra, S., & Mohapatra, S. S. (2018). Nanobiotechnology medical applications: overcoming challenges through innovation. The *EuroBiotech Journal, 2*(3), 146-160. https://doi.org/10.2478/ebtj-2018-0019.

Souri, M., Soltani, M., Kashkooli, F. M., Shahvandi, M. K., Chiani, M., Shariati, F. S., & Munn, L. L. (2022). Towards principled design of cancer nanomedicine to accelerate clinical translation. *Materials Today Bio, 13*, 100208. https://doi.org/10.1016/j.mtbio.2022.100208.

Suhag, D., Thakur, P., & Thakur, A. (2023). Introduction to nanotechnology. *Integrated Nanomaterials and their Applications*, 1-17. https://link.springer.com/chapter/10.1007/978-981-99-6105-4_1

Tang, Z., & Kotov, N. A. (2005). One-dimensional assemblies of nanoparticles: preparation, properties, and promise. *Advanced Materials, 17*(8), 951-962.https://doi.org/10.1002/adma.200401593.

Uchida, S., & Kataoka, K. (2019). Design concepts of polyplex micelles for in vivo therapeutic delivery of plasmid DNA and messenger RNA. *Journal of Biomedical Materials Research Part A, 107*(5), 978-990. https://doi.org/10.1002/jbm.a.36614.

Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S. A., ur Rehman, H., Ashraf, I., & Sanaullah, M. (2020). Nanotechnology in agriculture: Current status, challenges and future opportunities. *Science of the Total Environment, 721*, 137778. https://doi.org/10.1016/j.scitotenv.2020.137778.

Vankayala, R., Lin, C. C., Kalluru, P., Chiang, C. S., & Hwang, K. C. (2014). Gold nanoshells-mediated bimodal photodynamic and photothermal cancer treatment using ultra-low doses of near infra-red light. *Biomaterials, 35*(21), 5527-5538. https://doi.org/10.1016/j.biomaterials.2014.03.065.

Wang, Y., Zhao, Y., Bollas, A., Wang, Y., & Au, K. F. (2021). Nanopore sequencing technology, bioinformatics and applications. *Nature Biotechnology, 39*(11), 1348-1365.

Wang, Z., Agrawal, P., & Zhang, Y. S. (2021). Nanotechnologies and nanomaterials in 3D (Bio) printing toward bone regeneration. *Advanced NanoBiomed Research, 1*(11), 2100035. https://doi.org/10.1002/anbr.202100035.

Welch, E. C., Powell, J. M., Clevinger, T. B., Fairman, A. E., & Shukla, A. (2021). Advances in biosensors and diagnostic technologies using nanostructures and nanomaterials. *Advanced Functional Materials, 31*(44), 2104126. https://doi.org/10.1002/adfm.202104126.

Wen, J., Cai, D., Gao, W., He, R., Li, Y., Zhou, Y., & Xiao, Y. (2023). Osteoimmunomodulatory nanoparticles for bone regeneration. *Nanomaterials, 13*(4), 692. https://doi.org/10.3390/nano13040692.

Whitesides, G. M. (2005). Nanoscience, nanotechnology, and chemistry. *Small, 1*(2), 172-179. https://doi.org/10.1002/smll.200400130

Yoon, H. J., & Kim, S. W. (2020). Nanogenerators to power implantable medical systems. *Joule, 4*(7), 1398-1407.

Yu, R., Lin, Q., Leung, S. F., & Fan, Z. (2012). Nanomaterials and nanostructures for efficient light absorption and photovoltaics. *Nano Energy, 1*(1), 57-72. https://doi.org/10.1016/j.nanoen.2011.10.002.

Zhang, Y., Zhang, Y., Han, Y., & Gong, X. (2022). Micro/nanorobots for medical diagnosis and disease treatment. *Micromachines, 13*(5), 648. https://doi.org/10.3390/mi13050648.

Zucker, L. G., & Darby, M. R. (2005). Socio-economic impact of nanoscale science: Initial results and nano bank. *National Bureau of Economic Research, Cambridge, MA, USA, NBER Working Paper 11181*. Available: https://www.nber.org/papers/w11181.pdf.