THE ROLE OF NANO BIOTECHNOLOGIES IN MATERIAL SCIENCE

S.V. TAGIYEV
Azerbaijan State Oil and Industry University, AZ-1010, Baku, Azerbaijan
safar.taqiyev@mail.ru

The integration of nanotechnology and biotechnology has transformed material science and resulted in formation advanced materials with the precision of nanoscale engineering and the adaptability of biological systems. These technologies opened the door to the development of materials that require less weight, have more strength, are smarter, and are more eco-friendly. Nanotech operates at the atomic and molecular level and therefore can produce materials with enhanced physical and chemical properties; on the contrary, bio-tech makes use of living organisms and the biological molecules to create materials that reflect the functions and structures of the nature. The combination of different methods has resulted in significant advancements in various fields such as biomedical engineering, energy conversion and storage, environmental protection, and agricultural systems. Among the most impactful developments during the years 2020 to 2025 are the use of artificial intelligence (AI) in materials design, biomanufacturing, 3D bioprinting, and sustainable nanocomposites, which have completely changed the route of research in materials worldwide. Nonetheless, existing concerns about the safety, ethical use, and scaling-up of production are still there. This paper presents an investigation into the nano- and biotechnologies that are interfacing with material science, the ways of hybrid materials creation, their utilisations, and the networking towards safety and sustainability manner of implementation.

Keywords: Nanostructured materials, Biotechnology, Nanobiosensors, Artificial Intelligence (AI).
DOI: https://doi.org/10.70784/ajp.1.2026138

INTRODUCTION

Over the last few decades, material science has undergone a complete metamorphosis from the investigation of bulk properties to the control of matter at the atomic and molecular level. Two main areas, nanotechnology and biotechnology, which are different but complementary, played key roles in this metamorphosis as they opened up ways to design materials with total control even over their structure and function. Nanotechnology concerns, on the one hand, dimensions smaller than hundred nanometers, where quantum and surface effects are in full force and give rise to materials with different sorts of electrical, mechanical, optical, and catalytic properties. On the other hand, biotechnology is about making use of biological processes, enzymes, and genetic mechanisms to manufacture materials that are renewable, adaptive, and self-healing.

The combination of the two areas resulted in a new generation of materials that are now called nano-biomaterials or bio-nanocomposites. These materials inherit the best qualities of both worlds, namely, the precision and strength of nanoscale systems and the sustainability and diversity of biological structures [1]. For instance, nanostructured coatings can boost mechanical and thermal properties of biopolymers, while biological molecules can direct the arrangement of nanoparticles with astonishing precision.

In recent years breakthroughs in computational modeling, machine learning, and AI-assisted laboratories have speeded up material discovery. AI algorithms can forecast the behavior of new compounds before they are chemically synthesized, thus, making it possible to find out the best combinations regarding the required applications. When automation and robotics are added, it results in a scenario where the development cycle is cut short and efficiency is enhanced.

This document aims to investigate the place where nanotechnology and biotechnology meet in the context of material science, recapitulate the latest accomplishments, evaluate their future uses, and spot the issues and the paths to go towards the sustainable and moral application.

This growing interest is also linked to the need for materials that are able to meet multiple demands. Advanced technologies require good mechanical performances, limited chemical activity, biological tolerance and reduced environmental impact, that standard materials are unable to combine together, while nanosystems offer innovative ways to engineer multifunctional bio-hybrid constructs.

At the same time, the definition of sustainable fabrication processes based on natural polymers, biogenic compounds, cell manufacturing or reduced energy input is an additional challenge that scientists are currently facing in order to move from an exploratory experimentation to a real production of innovative bio-hybrid materials.

1. RESEARCH METHODS (Combination of Nano- and Biotechnologies in Material Science)

Nanotechnology has potential to alter the atoms and molecules at such a small scale that it would bring about significant changes in the properties of materials. Nanoparticles, nanowires, and nanosheets are the materials which demonstrate different quantum behaviors and properties as compared to their bulk counterparts. The carbonaceous nanomaterials like graphene and carbon nanotubes are not only the strongest but at the same time the lightest and age-old conductors, which makes them the most suited for energy and high-performance composite applications.

131, H.Javid ave, AZ-1073, Baku
Institute of Physics
E-mail: jophphysics@gmail.com

Metal oxide nanoparticles such as titanium dioxide, zinc oxide, and iron oxide are among the most utilized ones due to their optically and chemically controllable properties and variety of applications (sensors, catalysts, and biomedical imaging) where they are used. Comparative data showing the advantages in properties of nanostructured materials compared to bulk materials are given in Table 2.1. below

Table 1.1

Advantages of nanostructured materials over bulk materials

Property	Bulk Material	Nanostructured Material	Improvement / Effect
Grain size	>1 µm	<100 nm	Increased grain boundary density enhances hardness and strength
Tensile strength	200–400 MPa	500–1500 MPa	2–5× higher mechanical resistance due to nanoscale refinement
Electrical conductivity	Constant for a given alloy	Tunable (increases or decreases depending on quantum effects)	Electronic band structure can be engineered at the nanoscale
Thermal conductivity	Nearly constant	Size-dependent	Can be enhanced or reduced depending on phonon scattering
Corrosion resistance	Moderate	High	Dense nanocoatings minimize oxidation and ion diffusion
Chemical reactivity	Low	High	Large surface-to-volume ratio increases catalytic activity

This table demonstrates how nanoscale control of grain boundaries and interfaces leads to drastic improvements in strength, conductivity, and surface reactivity. What makes them much more efficient option for almost any purposes.

The strengthening behavior of nanostructured materials mathematically can expressed by using the size-dependent yield strength equation shown in following formula:

$$\sigma_{Yield} = \sigma_{bulk} \left(\frac{D_{bulk}}{D}\right)^{m} \qquad (1.1)$$

Where**:**

- σYield = yield strength of the nanoscale material.
- σbulk = yield strength of the corresponding bulk material.
- Dbulk = characteristic length of the bulk material (e.g., grain size)
- D = characteristic length in the nanomaterial (e.g., grain size or diameter)
- m = scaling exponent (depends on material and deformation mechanism)

This equation captures the ″smaller = stronger" effect,which is commonly observed in nanomaterials. When the grain size otherwise structural dimension (D) decreases, the ratio (D_bulk / D) increases, which results in higher yield strength. This phenomenon explains why nanocrystalline metals, ceramic nanocomposites, and nano-reinforced polymers show significantly improved mechanical properties in comparison with bulk materials and as result are more efficient. The relationship highlights how atomic-level control of structure directly affects macroscopic strength, and bu that forms a key principle in nanomaterial design.

Biotechnology, on the contrary, offers the natural templates and self-assembly techniques copied from living organisms. Among the very notable natural polymers are, for instance, DNA, collagen, chitosan, cellulose, and silk fibroin; and they are now mainly the route to material fabrication because of their biocompatibility and biodegradability. Besides, through metabolic engineering, microbes can be modified to produce certain polymers or nanoparticles of metals under very mild and environmentally friendly conditions; and as an example, bacteria and fungi have been 'trained' in producing silver and gold nanoparticles for applications in the coatings of bacteria resistant and sensors.

The greatest inventions occur at the intersection of the two sciences. They have a common ground at which nano-bio interfaces facilitate the conversation between artificial materials and living cells. Organ specific drug delivery that is accomplished through highly selective use of functionalized nanoparticles could .

Between the years 2020 and 2025, there has been a growing trend among researchers to look for and develop ways of making sustainable more production methods. Today, green plant extracts and waste biomass have been adopted as non-toxic methods for the production of nanoparticles [3]. The resulting products [i.e. nanoparticles] are less harmful to human health because of the chemicals used in the process. The eco and circular economy is thus one of the main beneficiaries, as these methods can be used more profitably than any other method. Moreover, the introduction of nano-fillers into bio-inks has accompanied the evolution of additive manufacturing, especially in 3D bioprinting, to elevate the optical and biological compatibility of the latter.

These developments have also opened up new possibilities in the tissue engineering and regenerative medicine spheres. Nanostructured surfaces can be tuned to control cell adhesion, proliferation, and differentiation while biodegradable biological polymers can be also used for generating suitable microenvironments for tissue growth. The combination of these tools enables the design and fabrication of materials with well-defined properties that can be used in order to grow a diverse range of tissues, including bone, skin, cartilage, and others.

The Composite materials offer the potential to develop smart and responsive materials that can be used in a number of applications. Nano-bio materials can be functionalized to respond to changes in temperature, pH, light, and other factors, offering unique control over their properties. Such versatility can be used in the creation of responsive devices, biosensors, implantable medical devices, and smart drug delivery systems, among other applications.

Materials informatics is set to play a transformative role in the design of these new materials, by providing insights into the relationships between the material design and properties. This field can accelerate the discovery of new materials by reducing the time and effort needed to test potential combinations of nanoscale materials and biological additives, as well as elucidating the role of various factors and interactions. Using such approaches, it will become possible to create materials with desired properties by design, which will be critical in the development of responsive, smart materials.

2. RESULTS (Applications and Emerging Directions)

2.1 Medicine and Healthcare

The most obvious areas where nano- and biotechnologies have made their presence felt are in health care. Among the other things that nanoparticles have been able to do, one of them is to carry drugs, vaccines, and genetic materials very effectively. An example is lipid nanoparticles which contributed a lot to the current mRNA vaccine usage against infectious diseases all over the world. Not only vaccination, but also polymeric and metallic nanoparticles are being actively used for cancer therapy where they can accurately understand the tumor location and then deliver the drugs based on internal signals such as pH or temperature [7].

Nanostructured biomaterials are also driving forward regenerative medicine. The bioengineered tissues printed with the nano-reinforced bio-inks demonstrate better mechanical stability and cell adhesion, which are among the best requirements for organ repair and transplantation. The latest reports talk about 3D printing of skin, cartilage, and bone using nanocellulose, hydroxyapatite and graphene-based materials. These materials can be tailored to fulfill the specific anatomical and biological requirements of each individual patient.

Biosensing is another fast growing area. Nanobiosensors that make use of quantum dots, carbon nanofibers, or gold nanoparticles can identify the biomarkers for diseases with such astonishing sensitivity that they can even pick up those for diabetes, cancer, and Alzheimer′s [2]. When these sensors are combined with AI algorithms, they can quickly and accurately process and interpret the complicated biological data of the patient in real-time, thus, making personalized medicine and early disease prevention possible.

In many nano-biosensing and microfluidic diagnostic platforms, analyte movement and detection depend on coupled convection–diffusion transport, described by the general equation shown in Fig 3.1. below

$$\frac{\partial C}{\partial t} + \boldsymbol{u} \cdot \nabla C = D\nabla^2 C + R \qquad (2.1)$$

Where:

- C = concentration of the species (e.g., analyte in biosensor)
- u = fluid velocity field
- D = diffusion coefficient
- R = reaction term (if species is consumed/produced)
- ∇ and ∇^2 = gradient and Laplace operators respectively
- ∂ – partial derivative symbol, represents change of a concentration over time

This equation is essential for description of how analytes are transported and detected in nano-biosensors and lab on a chip systems. It representsthe effects of fluid flow, molecular diffusion, and surface reactions, showing how these factors determine detection's speed and sensitivity. By controlling parameters such as diffusion coefficient (D) and fluid velocity (u) through nanostructured designs, engineers

can increase biosensor performance, enhance stability of the signal , and improve analytical efficiency overall.

2.2 Energy and Environmental Sustainability

The combination of nanotechnology and biotechnology is substantially influencing the energy and environmental domains. Nanostructured materials in energy storage not only present higher energy densities but also allow for quicker charge-discharge cycles. Some bio-based materials like carbon nanotubes and nanocellulose have been gaining acceptance as eco-friendly battery and supercapacitor electrodes.

The integration of AI in the process of discovering materials pushed the new energy materials' identification even faster [5]. DeepMind's GNoME (Graph Networks for Materials Exploration) initiative along with others have produced millions of probable compounds thought to be stable and having high conductivity [6]. A few among them have already started to be utilized for solid-state batteries, fuel cells, and hydrogen storage.

Biotechnology contributes its part towards sustainability by supplying raw materials which are renewable. Enzyme-based catalysts and microbial systems can aid energy conversion reactions at lower temperatures and possibly producing less toxic waste. For example, bio-nano hybrid catalysts are being produced for the water-splitting and CO_2 reduction processes allowing transformation of these processes into green methods for providing clean energy.Environmental cleanup has reaped a lot from bio-nanocomposites made of natural polymers and magnetic nanoparticles. These materials not only capture but also degrade the toxins in a very efficient manner. They can easily be separated from the water, and thus the operation costs are minimized. The biodegradable nanocomposites made from cellulose, starch, and chitosan are being utilized for making sustainable packaging materials that naturally decompose, hence lessening the burden caused by plastic waste [4].

The application of nano-biological materials is no longer limited to the separation of contaminants and the creation of sustainable packaging. The unique properties of nanomaterials can be combined with the selectivity of biological receptors and molecules for sensors that can detect heavy metals, pesticides, organic pollutants, and microorganisms at low concentrations. Such tools, combined with wireless technologies and artificial intelligence, can enable real-time monitoring of the environment and early warning of deviations in the parameters of water, soil, and air.

Another promising direction of the joint use of nano- and biotechnologies is connected with carbon management. Nanostructured materials have a high surface area and can be tuned to have specific properties, such as affinity to CO 2 molecules. Living organisms and their derivatives, such as enzymes and microorganisms, can catalyze the conversion of this gas into valuable products. Joint use of CO 2 separation and conversion membranes and bioconversion units can lead to the creation of effective systems for carbon utilization.

At the very same time integrated utilization of nano- and biotechnologies opens up new opportunities for creating multifunctional devices for use in alternative energy or a sustainable economy. Artificial intelligence can be used to accelerate the discovery of new materials and their production technologies. The capabilities of machine learning can be used to analyze the relationship between the properties of nanomaterials, their component, structure, and conditions of preparation and processing. Thus, it will be possible to quickly find promising candidates among tens or hundreds of thousands of possible options. Various algorithms can be used to determine the optimal conditions for producing such materials to reduce energy costs, raw materials, solvents, and waste.

However, the use of nano-biological materials requires ecological assessment and risk analysis. The use of such nanomaterials can lead to negative consequences for the environment due to their low probability of biodegradation or the release of toxic substances during their use or preparation technology. The joint action of several factors, such as the specific surface area of the particles, their surface chemistry, and the concentration of nanoparticles, will have a greater impact on their toxicological and ecological properties. Moreover, for each specific application, a risk assessment strategy should be developed that takes into account interactions with various components of the environment.

Finally, before introducing any nano-biological material into practical use, it is necessary to study its properties and behavior both at the stage of preparation of pilot batches and during large-scale industrial manufacturing. Although promising results were obtained in laboratory studies at the level of individual cells or model systems, scaling these results to industrial conditions may be complicated by many factors. Uniformity and reproducibility of characteristics are guaranteed only by standardization of production technology and its all stages. A long-term experiment on the properties of materials under working conditions will allow researchers to talk about their prospects for use with more confidence.

2.3 DISCUSSION (Challenges, Safety, and Ethical Considerations)

Nano- and biotechnologies, on the one hand, are promising but on the other hand, they pose safety, regulation, and ethical responsibility challenges. Due to their tiny size, nanoparticles can enter living cells and build up in various body parts which makes their toxicity and the overall health impact of their presence a concern. Even though the majority of nanomaterials are not a threat to the environment, one has to know the end products of their disintegration very well in order to afford the environment safety.

From the point of view of a manufacturer, it is still not easy to upscale laboratory methods to industrial levels. The process of getting the nanomaterials with the same properties and the no-contamination during each stage

of the process would demand a hefty investment in machines and also in the workers who will be ensuring the quality of the final product.

Regulatory frameworks are changing but still have not been each other's match globally. There is still a gap in the existence of common methods to measure the toxicity, stability, and whereabouts of the nano-bio materials in the environment. The use of engineered biological systems or AI in materials design raises ethical concerns which need to be addressed through the provision of transparency, accountability, and public engagement.

Another challenge is to develop reliable long-term assessments of nano-bio materials in their entire lifecycle. Their production, use, recycling, and disposal should be subject to comprehensive analyzes to reveal potential risks to humans and the environment. Moreover, to enhance safety levels and promote general acceptance, closer cooperation between scientists, industries, and authorities is needed.

The described concerns should not disrupt the development of novel materials and technologies. However, nanotechnology and biotechnology should be carefully evaluated in order to ensure that their benefits outweigh potential risks and possibility of negative consequences. The implementation of appropriate safety tests, the development of adequate materials, and the application of sustainable production methods can help achieve this goal.

CONCLUSION

The combination of nanotechnology and biotechnology represents one of the most dynamic and promising directions in contemporary materials science. Their integration makes it possible to develop smart, adaptive, multifunctional, and sustainable materials capable of operating effectively in both physical and biological environments.They can also be designed to last longer and to work well in both living systems and man made settings. Work at the small scale can help fix issues seen with older materials. It also creates new chances for progress in medicine, power systems, cleanup efforts, and industrial tools.

In healthcare, nano bio materials are being studied for drug delivery that is timed and focused. They are also used in tissue repair and tissue growth support. Other uses include biosensing and diagnostic tools. Some groups are also working on regenerative medicine ideas. Because these materials can respond at the level of cells and molecules, they can help make treatments more exact. They also support devices that can fit biological needs better. Biocompatible nanomaterials combined with natural components can help form useful scaffolds. They can support implants, wearable sensors, and diagnostic platforms that react to changes. With these advances, healthcare could become more accurate, more efficient, and more tailored to each person.

Beyond medicine, the convergence of nanotechnology and biotechnology cansignificantly contribute to development of enhanced energy and environmental options. Nanostructured materials may raise the output of energy storage systems. They can also improve energy conversion devices. while bio-based and biodegradable nanocomposites offer opportunities for reducing dependence on conventional materials with greater environmental impact.

[1] *H. Shin.* Deep convolutional neural network-based signal quality assessment for photoplethysmogram. Computers in Biology and Medicine, 145, 105430. 2022.

[2] *A. Esteva*, et al. Deep learning-enabled medical computer vision. NPJ Digital Medicine, 4(1), 5. 2021.

[3] *J.G. Webster*, et al. Medical instrumentation: Application and design. John Wiley & Sons, 5th ed., 928 p. 2020.

[4] *G. Ciofani.* Insights in Nanobiotechnology 2022/2023, Frontiers in Bioengineering and Biotechnology, 2023, 11, 1265842.

[5] *S. Yadav* et al., Nanobiosensors in neurodegenerative disease diagnosis, Frontiers in Nanotechnology, 2025, 7, 1389421.

[6] *J. Nandhini* et al., Eco-friendly bio-nanocomposites: pioneering sustainable approaches, Nanoscale Research Letters, 2024, 19(1), 12–34.

[7] *V.S.K. Bharathi* et al., Evolution of Bionanocomposites: Innovations and Applications, Foods 2024, 13(8), 1254.

[8] *B. Madika* et al., Artificial Intelligence for Materials Discovery, Nature Reviews Materials, 2024, 9(3), 185–201.

[9] *A. Merchant, S. Batzner*, et al. [DeepMind]. (2023). "Scaling deep learning for materials discovery (GNoME)." *Nature*, 624, 80–85.

[10] *S. Sreejith.* Recent advances in nano biosensors: An overview, Journal of Measurement, 2024, 18(2), 1104–1122.

[11] *N. Rawat*, et al. Nanobiomaterials: exploring mechanistic roles in combating microbial infections and cancer. Discover Nano, 18(1), 158. 2023. https://doi.org/10.1186/s11671-023-03946-x

[12] *A. Khosravi*, et al. Sustainable synthesis: natural processes shaping the nanocircular economy. Environmental Science: Nano, 11, 688–707. 2024. https://doi.org/10.1039/D3EN00973D

[13] *X. Huang*, et al. Trends, risks and opportunities in environmental nanotechnology. Nature Reviews Earth & Environment, 5, 572–587. 2024. https://doi.org/10.1038/s43017-024-00567-5

[14] *A.I. Osman*, et al. Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review. Environmental Chemistry Letters, 22, 841–887. 2024. https://doi.org/10.1007/s10311-023-01682-3

[15] *P. Mohite*, et al. Sustainable and consumer-centric nanotechnology-based materials: An update on the multifaceted applications, risks and tremendous opportunities. Nano-Structures & Nano-Objects, 38, 101148. 2024. https://doi.org/10.1016/j.nanoso.2024.101148

[16] *R. Pattnaik*, et al. Prospects and challenges of nanomaterials in sustainable food preservation and packaging: A review. Discover Nano, 19, 178. 2024. https://doi.org/10.1186/s11671-024-04142-1

[17] *B. Elzein*. Nano Revolution: "Tiny tech, big impact: How nanotechnology is driving SDGs progress". Heliyon, 10(10), e31393. 2024. https://doi.org/10.1016/j.heliyon.2024.e31393

[18] *A.K.* Cheetham, et al. Artificial Intelligence Driving Materials Discovery? Perspective on the Article: Scaling Deep Learning for Materials Discovery. Chemistry of Materials, 36(8), 3490-3495, 2024. https://doi.org/10.1021/acs.chemmater.4c00643

Received: 18.02.2026