



REVIEW ARTICLE

Exploring the future of nano-physiochemistry: A review of current trends and prospects

Marwah J Hezam¹, Mohammed Zorah², Mustafa Ridha Shiha³, Hasan Ali Alsailawi^{4,5} & Mustafa Mudhafar^{1,6*}

¹Department of Medical Physics, University of Kerbala, Karbala 56001, Iraq

²Department of Computer Techniques Engineering, Imam Alkadhim University College, Baghdad 10001, Iraq

³College of Pharmacy, Ahl Al Bayt University, Karbala 56001, Iraq

⁴Department of Basic Sciences, University of Kerbala, Karbala 56001, Iraq

⁵Department of Anesthesia Techniques, AlSafwa University College, Karbala 56001, Iraq

⁶Department of Anesthesia Techniques and Intensive Care, Al-Taff University College, Karbala 56001, Iraq

*Correspondence email - almosawy2014@gmail.com

Received: 21 April 2025; Accepted: 16 July 2025; Available online: Version 1.0: 10 September 2025

Cite this article: Marwah JH, Mohammed Z, Mustafa RS, Hasan AA, Mustafa M. Exploring the future of nano-physiochemistry: A review of current trends and prospects. Plant Science Today (Early Access). <https://doi.org/10.14719/pst.9006>

Abstract

In the last decade, nanotechnology has garnered significant interest from both academia and business, serving a crucial function in the advancement of medical, biological and economical fields. The chemical and physical (nano-physiochemistry) functionalization of textiles by nanotechnology has initiated a new stage in sophisticated materials characterized by enhanced characteristics and functionalities. Nano-physiochemistry is an area of knowledge focused on obtaining and characterizing materials at the nanometric scale. This subdiscipline has made valuable contributions to research, industry, technology and environment, including applications in electronics, nanodevices and systems, composite materials, biotechnology, medicine and the textile industry. The aim of this study is to critically review the current advancements in nano-physiochemistry, exploring its future directions, emerging trends and potential applications. The present study also includes an overview of the chemical and physical methods for the preparation of nanomaterials, along with a discussion of various characterization techniques employed to analyze these materials. In conclusion, this review highlights the advancements in nano-physiochemistry, focusing on its future directions and potential applications. It emphasizes the role of chemical and physical methods in the preparation of nanomaterials and the importance of various characterization techniques in understanding their properties. Ongoing research is essential to optimize these methods and explore new prospects for the broader application of nano-physiochemistry.

Keywords: chemical and physical methods; nanoparticle clusters; nano-physiochemistry; nanotechnology; prospects

Introduction

In recent decades, chemistry has opened new avenues for multidisciplinary research by merging knowledge from its five classic areas represented by organic, inorganic, theoretical, computational, analytical and physical chemistry (1). One such example is nano-physiochemistry, a field that allows the synthesis of complex materials or systems using methods based on molecular self-assembly (2). The prefix nano is derived from the Latin *nanus*, which means dwarf in Spanish and refers to one billionth of a meter (1×10^{-9} m). To get a clearer idea of how tiny the nanometric scale is, some examples can be cited, such as the diameter of a human hair of approximately 75000 nm, that of a red blood cell of 3000 nm and the distance between two gold atoms in a ring or coin of this chemical element is 0.3 nm. Consequently, studying the nanoworld means placing oneself within the framework of action of atoms and molecules (3). A similar scenario for chemistry constitutes a common explanatory framework in the study of properties, composition and transformation of matter.

Nano-physiochemistry encompasses those activities that use traditional approaches, tools and chemistry models to obtain materials on a nanometric scale. The nanostructured products thus obtained have diverse applications ranging from catalysis and obtaining drugs with greater specificity to produce of photovoltaic cells, optical devices, semiconductors and reinforced or biodegradable polymers (4–6).

In the field of environment, the communication of aspects related to nano-physiochemistry is revealed as a pertinent issue for three reasons: the first is that being a recent area of research, its approach in classrooms and laboratories allows the teaching and learning process of chemistry up to date; The second is related to the possibility of undertaking a teaching-learning process of the subject based on contextualization, by showing the effectiveness of the applications that arise from nano-physiochemistry in the effective resolution of problems that impact social, economic and environmental life and the third reason is linked to promoting among students the construction of an informed opinion on the benefits, limitations and risks

associated with nano-physiochemistry in particular and with nanotechnology in general, an essential requirement to promote participation in the public debate on the subject (7).

Some specialists point out that promoting informed dialogue between all sectors involved in developing nanoscience and externally with society is the most praiseworthy and effective way to ensure that the various products generated by this field benefit the majority and maintain harmony with the environment (8). What is sought is the construction of a genuine understanding of the relevance and implications of nanoscience by society, strengthening its governance criteria (9). Formal and informal education play a crucial role in achieving this objective since educational institutions and the media are the main ways to bring the knowledge and advances generated by nano research to society. Forming critical and participatory citizenship in science and technology is one of the key objectives of both democratic societies and contemporary educational paradigms (10,11). The following paragraphs will address some theoretical background of nano chemistry, its basic concepts, methodology, sensitive applications and its relevance and presence in the school environment.

History of nano-physiochemistry

The first reference to nano-physiochemistry is a lecture by the renowned physicist Richard Feynmann in 1959 at the California Institute of Technology (Caltech), entitled 'There's Plenty of Room at the Bottom'. In this academic lecture, Feynmann proposed manipulating matter atom by atom to create materials with unusual or little-known properties (12). At the same time, he set the standard for obtaining materials using the two most important approaches in nanotechnology: the bottom-up methodology (ascending synthesis), traditionally implemented by chemists, which consists of building from small to large and the top-down methodology (descending synthesis), based on miniaturization, which is conventionally used by physics (13). It should be noted that although these two approaches were developed independently, they do not currently compete but rather complement each other. An example of this is their joint use in training courses and research in materials science and engineering.

It took 30 years for Feynmann's ideas on the possibility of influencing the behavior of matter at the nanometric scale to crystallize. This happened in 1989, when scientists from the IBM company, using the advances of the time in Scanning Tunneling Microscopy (STM), managed to obtain an arrangement of 35 individual xenon atoms on a nickel substrate in the shape of the three letters of the company's logo. This event became a milestone for modern science, as for the first time, a certain number of atoms could be placed precisely on a flat surface (14).

In 1985, the discovery that helped lay the foundations for nano-physiochemistry was reported by a research team at Rice University, consisting of chemists Harold W Croto, Robert F Curl and Richard E Smalley, who reported the discovery of a spherical molecule of 60 carbon atoms with a geometry very similar to a soccer ball and only 0.7 nm in diameter. This previously unknown molecule was obtained within the framework of an experiment of vaporizing graphite with a laser at a temperature above 10000 °C to simulate carbon aggregates in the interstellar medium. The resulting spherical molecule was named C₆₀ fullerene and is considered the first reported nanostructured

allotrope of the element carbon. For this work, the team led by Harold W Croto was awarded the Nobel Prize in Chemistry in 1996. Currently, fullerenes of various sizes have been synthesized, the smallest being the 20-carbon atom C₂₀, but the most abundant and representative continues to be C₆₀ (15). Research into fullerenes was extended in later years, producing molecules called Carbon Nanotubes (CNTs), nanostructures characterized by their high resistance.

The bottom-up approach to nanostructures and nanomaterials was lucidly popularized by Richard E Smalley at the beginning of the 21st century, thanks to his participation in a controversial and famous debate on how to conceptualize nanotechnology that he held with MIT engineer Erick Drexler. This much-discussed debate took place between 2001 and 2003 in two North American science magazines, Scientific American and Chemical & Engineering News and has been studied extensively by social science specialists to illustrate the role played by the media and para-scientific aspects in defining an agenda around emerging techno-scientific fields (16,17). In the debate, R Smalley shrewdly communicated the factors that chemistry takes into account in obtaining nanomaterials, such as the study of reaction conditions, the use of catalysts, the consideration of geometry, size, reactivity and selectivity of the reacting species, as well as a significant variable resulting from the processes of molecular self-assembly, imperfections (18), in contrast to a vision based on obtaining something that Drexler called molecular assemblers, a kind of nanoscopic machines that would allow the absolute positional control of atoms and molecules in obtaining nanomaterials. Over the years, this vision of Drexler was revealed to be erroneous. The imperfections defended by Smalley play such a relevant role in synthesizing some nanometric materials that they acquire specific and distinctive functions thanks to them. An example of this is issues doped with organic molecules obtained by the sol-gel method; their physical properties and high thermal stability are mainly due to the imperfect geometry of the glassy matrix (19). Fig.1 shows the general mechanism of the synthesis of nanomaterials.

Another vital antecedent of nano-physiochemistry is the so-called supramolecular chemistry. In 1987, chemists Donald J Cram, Charles J Pedersen and Jean-Marie Lehn received the Nobel Prize in Chemistry for designing molecules that mimic the behavior of some natural substances involved in biological processes. These researchers demonstrated that highly selective molecules can be obtained in laboratories that react with other atoms, just like enzymes do in cellular processes (20). To do so, they implemented advanced organic chemistry techniques accompanied by complex theoretical calculations. The results Donald Cram's team reported increased the interest and mastery of selectivity in obtaining chemical complexes. Today, selectivity is a crucial factor in molecular self-assembly, the process on which nano-physiochemistry is based. Finally, a research that can also be considered as a historical precedent of nano-physiochemistry was the discovery of conductive polymers by chemists Alan Hegger, Alan MacDiarmid and Hideki Shirakawa for which they received the Nobel Prize in Chemistry in 2000 (21,22).

Generalities of nano-physiochemistry

Nano-physiochemistry strengthens the research horizon of chemistry by dealing with the synthesis and characterization of materials developed through techniques or procedures based

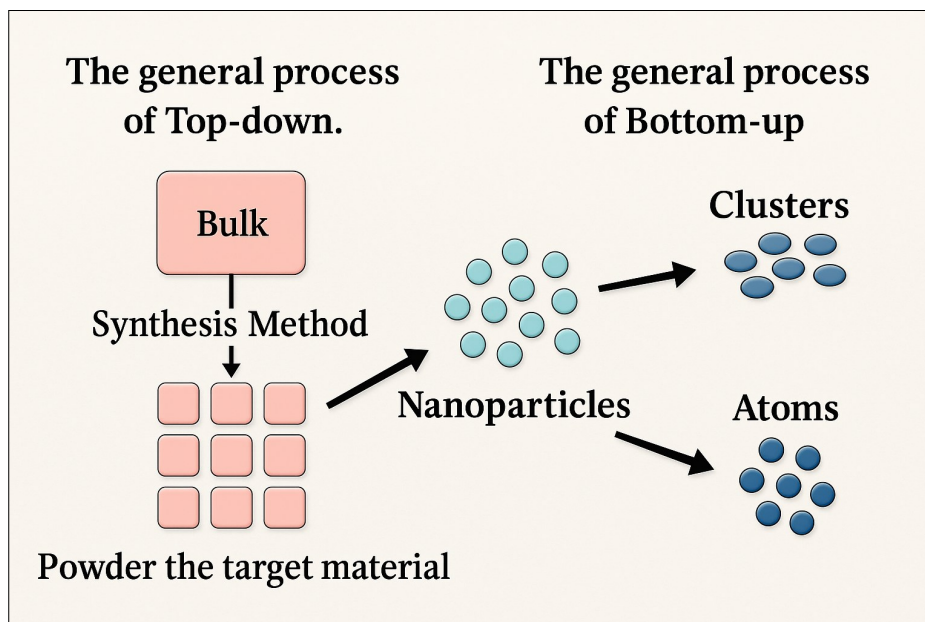


Fig. 1. The general mechanism of synthesis process of nanoparticles.

on molecular self-assembly (23). This phenomenon is based on using weak or intermolecular forces such as Van der Waals forces, hydrogen bonds and electrostatic interactions between the reacting chemical entities. One issue that favors spontaneity and a certain degree of thermodynamic control is that, in self-assembly, atoms and molecules seek to acquire a state of minimum energy by diffusing on surfaces or forming structures that favor them energetically and enhance molecular growth (24,25).

What makes nano-physiochemistry and nanoscience, in general, unique and exciting is that at the nanometric scale, the properties of matter change drastically due to quantum effects. This unusual behavior can contradict what we perceive with our senses. For example, when metals such as gold, silver and copper are divided into tiny fragments that border the nanometric scale, their metallic shine gradually disappears, giving rise to unconventional hues. It is known that 100 nm gold spheres acquire an orange hue, 50 nm spheres are green and 25 nm spheres are red. This is because the free conduction electrons present on the surfaces of nanoscopic-sized metal spheres can oscillate because of light and absorb energy (26). From the above, it can be noted that another distinctive characteristic of nano-physiochemistry is that it is often aided by and applies the theoretical bases of quantum mechanics in the synthesis and characterization of materials. As mentioned in previous paragraphs, the approach that has accompanied the development of nano-physiochemistry is the so-called bottom-up, which consists of using groups of atoms and molecules as precursors or building blocks of higher-order structures (27).

Bottom-up techniques can be classified into two large categories according to the physical environment in which the nanomaterials are obtained, these are gas phase and liquid phase techniques (28). Examples of bottom-up techniques in the gas phase are vapor deposition and laser ablation. In the liquid phase methods, microemulsions, sol-gel synthesis and those based on photochemistry stand out (29). Another essential aspect to consider in nano-physiochemistry is that various modern microscopy techniques assist it in characterizing the physicochemical properties of nanomaterials, the most common being STM and Scanning Electron Microscopy (SEM).

Gas phase techniques

Chemical Vapor Deposition (CVD) is one of the most representative gas phase techniques. It is based on the dispersion of a chemical precursor in a gaseous state on a substrate where a nano or micromaterial's growth is intended to occur (30). Generally, CVD-based synthesis processes are carried out in high vacuum chambers, are highly selective and are used to obtain some solid nanostructures such as silicon oxide (SiO_2) and CNTs. On the other hand, the laser ablation technique consists of subjecting a target to intense radiation with the help of a laser to split its constituents so that these substances subsequently react again, forming different chemical entities called nanoclusters (31). Laser ablation synthesis is a less selective process than CVD, but it is a cleaner technique because it generates less waste and is usually used for the manufacture of some high-temperature superconductors (32–34), as shown in Fig. 2 & 3.

Gas phase technique is employed to create nanomaterials through the manipulation of the gas phase forever. To create nanomaterials, these methods depend on converting solid or liquid precursor material into vapors, which are later subject to a chemical reaction or physical condensation. The process usually begins with evaporation, in which the precursor materials in which chemical processes (also known as CVD), heat (also known as thermal evaporation) or laser energy (also known as laser ablation) are replaced (35). For example, in CVD, a solid layer of nanometers is accumulated when volatile molecules react or break on a warm substrate. The nuclearity occurs when the atom or molecules in the gas phase become incomplete and start for groups. Under the effect of variables including temperature, pressure, carrier and residence time, these clusters work as seeds for the formation of nanoparticles, which are then maintained by further condensation or chemical surface interaction (36). Ultimately, the produced nanoparticles are collected by deposition on substrates, filtration systems, or condensation on cooled surfaces.

Due to their ability to accurately regulate particle production, gas phase methods are ideal for a wide range of groundbreaking applications. Due to their semiconducting and optical properties, materials including silicon, zinc oxide and

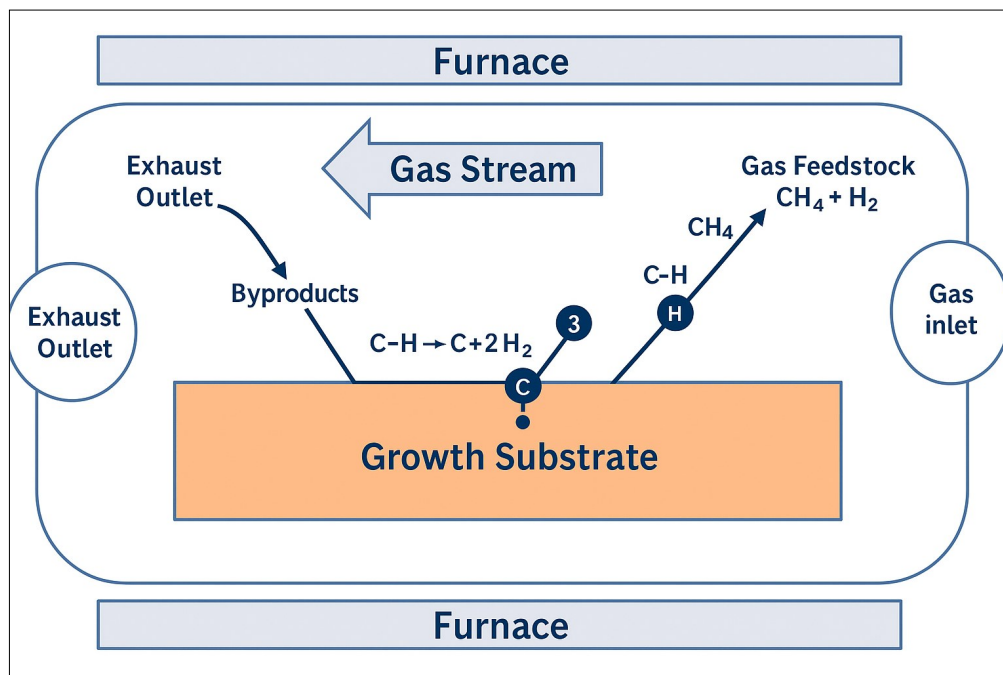


Fig. 2. Schematic diagram of thermal CVD growth of graphene (34).

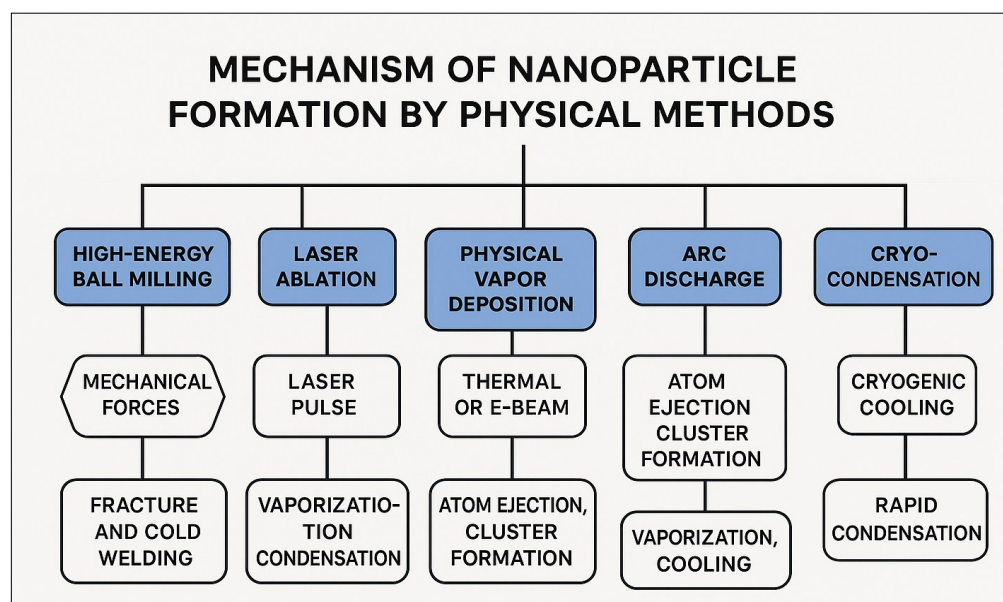


Fig. 3. Mechanisms of nanoparticles using physical methods.

titanium dioxide are used via gas phase techniques in thin film transistors, light-emitting diodes and gas sensors in electronics (37). Nanoparticles of precious metal made from gas phase synthesis, such as platinum, palladium and gold, have high surface areas and special electrical properties that improve reaction rates in chemical production, fuel cells and car catalytic converters. Gas phase deposit of thin films such as Copper-Indium Gallium Selenide (CIGS) or cadmium telluride, which is used in high-efficiency photovoltaic cells, is advantageous for solar energy technologies (38). Gas-phase factory nanoparticles, including gold (for photothermal treatment and medication administration) or iron oxide (for MR contrast agents), provide regulated sizes, morphologies and surface functions for secure biological applications in biomedicine. Furthermore, protective coatings such as titannitride and aluminum oxide are produced, which are coated with CVD to offer wear resistance and thermal protection in the tool, car and aerospace sectors, often using gas phase processes (39).

All in mind, gas phase methods' adaptability and scalability, as well as their ability to provide accurately tailored-made and superior nanomaterials, make them important for use in both industrial and research nanotechnical applications as shown in Fig. 4.

Liquid-phase techniques

Liquid-phase techniques are the most widely used in nanophysiochemistry is, as they involve the action of a solvent and procedures related to the kinetics of crystallization of the desired products, two historical and distinctive methodological aspects of the experimental work undertaken by chemists. Other elements to consider in bottom-up liquid-phase techniques are reducing agents and stabilizers. The former provides electrons in a reaction medium, favoring molecular self-assembly processes. The latter are often very useful in controlling the morphology of nanomaterials (40).

In fluid phase methods for making nanomaterials, especially metallic nanoparticles, reductions are crucial chemical

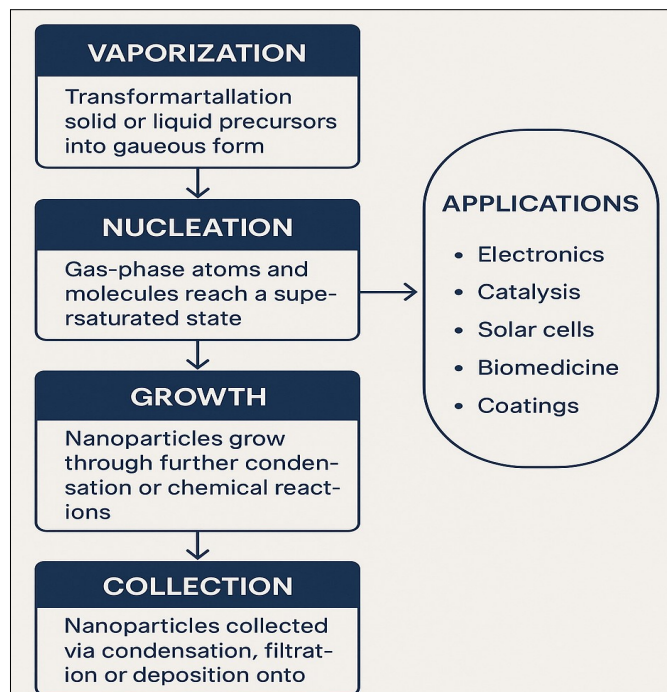


Fig. 4. Mechanism of gas phase techniques.

constituents. Their most important job is to donate electrons to reduce metal ions (such as Au^{3+} , Ag^+ and Cu^{2+}) to their elementary metallic form (such as Au^0 , Ag^0 and Cu^0) (40). The Nucleation process, where individual atoms begin to group to form particles the size of nanometres, are started by this reduction. In addition to affecting the speed of nucleation and growth, the type and strength of the reducing agent has a major impact on the size, shape, monodispersity and crystallinity of the final nanoparticles (41). Strong reductions such as hydrazine and sodium borohydride (NaBH_4) quickly break down metal ions, creating a lot of cores quickly and usually form evenly tiny nanoparticles (42). On the other hand, slower, more regulated nucleation and development are made possible by moderate reductions such as ascorbic acid, glucose and citrate. This can lead to the formation of larger or anisotropic particles such as nanorods, nanoplates or nanotubes (43). When customizing nanoparticles for special applications such as medication, catalysis or sensing, this degree of control is crucial (Fig. 5).

Bottom-up liquid-phase techniques are more numerous than those implemented in the gas phase for reasons of length. Since this work doesn't need to cover all the techniques in detail, only reference will be made to sol-gel synthesis, microemulsions and photochemical pathways in the following paragraphs. The sol-gel technique is a widely used chemical process for obtaining nanomaterials whose main structure is metal oxides. Generally, it starts with a chemical solution (sol) precursor to an integrated network of particles or polymers (41,42). This method's most used chemical precursors are metal chlorides and alkoxide compounds. These compound condensation and polymerization reactions in solutions produce a three-dimensional network in colloidal form (gel). The resulting gel is gradually dehydrated or sometimes calcined to obtain the desired products (43). With this technique, highly pure and homogeneous nanomaterials can be synthesized. Examples of nanomaterials produced by sol-gel are silicon, titanium and vanadium oxide combinations that, when functionalized with rare earth ions, can manufacture lasers and sensors (44,45). Fig. 6 shows the possible process of producing the nanoparticles using bottom-up methods.

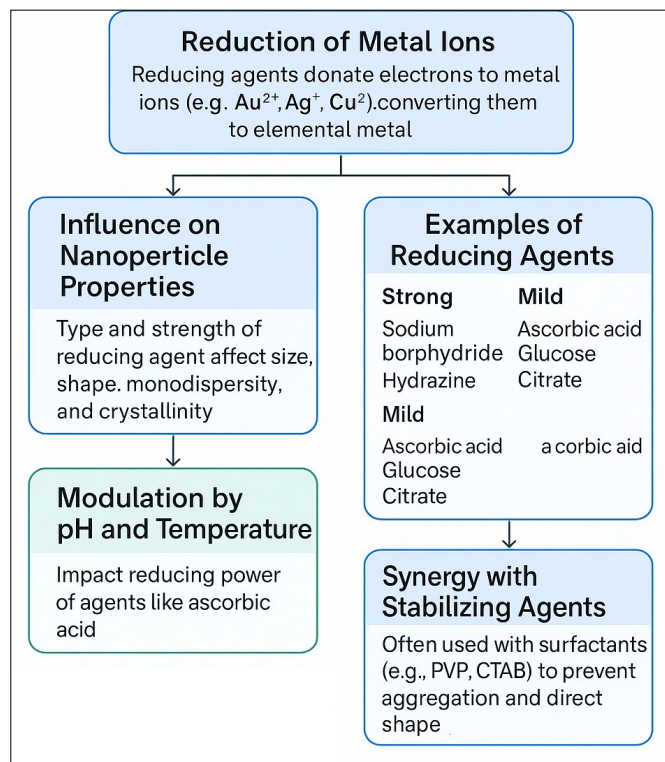


Fig.5. Role of reducing agents in the liquid phase techniques.

Conversely, microemulsions are thermodynamically stable dispersions formed by immiscible liquids of different polarity (for example, water/oil). Microemulsions are conventionally stabilized by adding a surfactant that allows the formation of micelles with a size range of 2 to 15 nm (46,47). In this technique, micelles are responsible for diffusing chemical precursors and promoting molecular growth. Some essential characteristics of microemulsions are their isotropy and transparency and unlike macroscopic emulsions, they do not require an energy input for their formation (48). In addition, with this technique, it is possible to control the synthesized products' dimensions, morphology and composition.

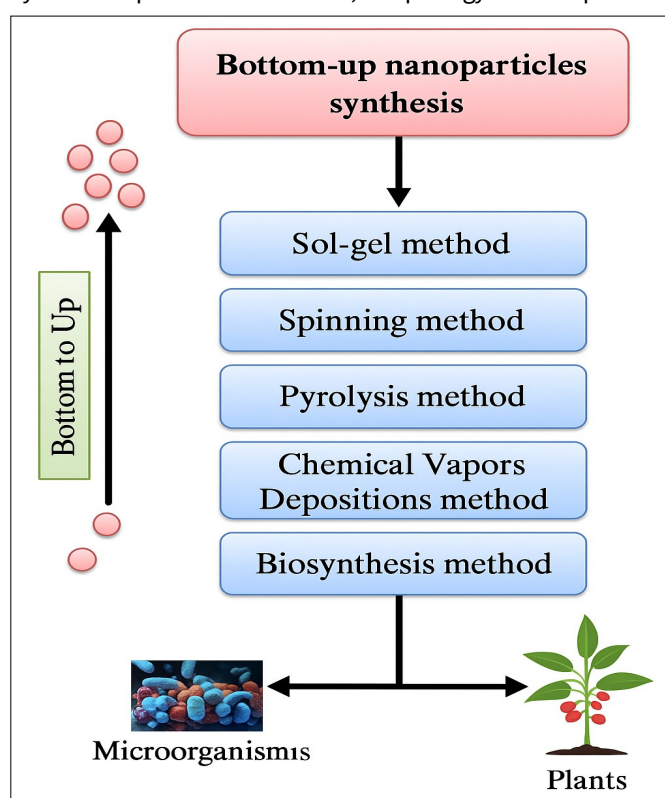


Fig. 6. The bottom-up process of nanoparticles.

Examples of nanostructures that can be obtained with microemulsions are binary particles of metallic elements (Pt/Pd, Pt/Ru, Pt/I) and nanoparticles of metallic oxides and sulfides (49). This technique is also used in developing nanomaterials with repercussions in the pharmaceutical and cosmetics industry (Fig. 7).

On the other hand, the production of nanostructures based on photochemistry is based on the irradiation of a reaction medium with light beams of different wavelengths. This is done to generate highly reactive reducing species such as electrons, radicals, or oxidized species that favor the formation of nanostructures (50).

In photochemical techniques, energies below 60 eV are usually used, characterized by fast and clean processes that generate solid molecular aggregates (51,52). Photochemical methods are used to obtain materials with noble metals, which can be used as photocatalysts and in developing optical devices (53).

The technique of photocatalytic production of nanomaterials starts off evolved with a semiconductor photocatalyst, typically graphitic carbon nitride ($g\text{-C}_3\text{N}_4$), zinc oxide (ZnO) or titanium dioxide (TiO_2), which absorbs photons from a light source (visible or ultraviolet mild, depending at the bandgap). Positively charged holes remain inside the valence band because of the electrons being excited from the valence band to the conduction band with the aid of this absorption. In redox procedures, the produced electron-hole pairs (e^-/h^+) are critical. Metal ions (such Ag^+ , Au^{3+} , or Cu^{2+}) may be decreased through the photoexcited electrons (e^-) to their neutral atomic shape (Ag^0 , Au^0 , etc.), which ultimately nucleate to shape nanoparticles. Concurrently, the holes (h^+) can oxidise natural sacrificial retailers (together with ethanol or plant extracts) or water molecules, generating hydroxyl radicals ($\cdot\text{OH}$) or other oxidised byproducts

that resource in preventing the fee vendors from recombining. Effective nanoparticle production depends on this rate separation and the surface reactions that follow. The resultant metallic atoms are nucleated and grow and the response parameters, which include light depth, precursor attention, solvent and stabiliser presence, can affect the very last nanoparticle characteristics, consisting of size, form and dispersion. All matters taken into consideration, this mechanism is a totally promising method in nanotechnology as it enables the regulated and environmentally pleasant production of nanomaterials underneath ambient instances (54–56) (Fig. 8).

Microscopy

An essential element in nano-physiochemistry is microscopy, an instrumental route conventionally used to characterize synthesized nanomaterial's structural and physicochemical properties. The microscopic techniques that chemistry and nanotechnology rely on generally consist of subjecting a material or target to a specific type of radiation using a probe and decoding the underlying signals through complex detection systems, which can be based on the interactions that occur between the electrons present in the sample and those of the probe or on the measurement of specific physical properties such as voltage, current intensity and magnetic field intensity (57,58). With the help of microscopy, relevant images and data on the properties of specific nanostructures can be obtained indirectly (Fig. 9).

The most common microscopic techniques in nano-physiochemistry, which have been present in its historical development are STM, Transmission Electron Microscopy (TEM) and SEM. In recent years and to a lesser extent, some research has also incorporated Atomic Force Microscopy (AFM) due to the technological importance that the study of surfaces has gained in nanomaterials (59,60).

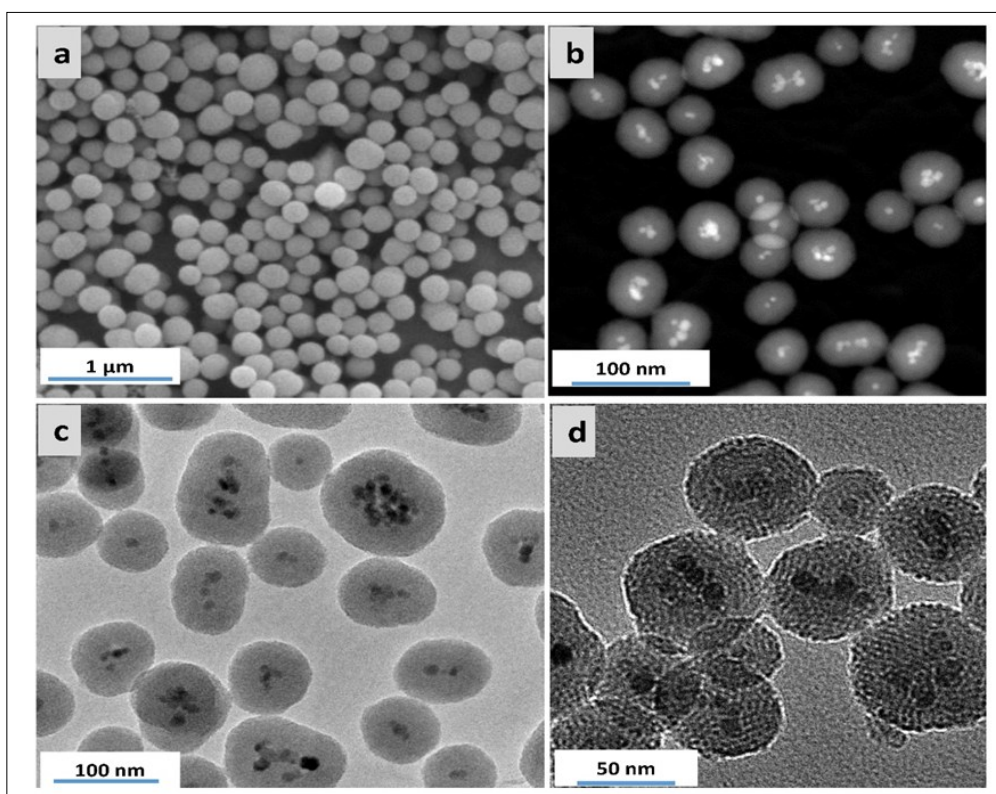


Fig. 7. Electron Microscopy Images of M-Ethylene PMO Nanoparticles (PMO NPs) (46).

(a) SEM image showing surface morphology and particle distribution; (b) STEM image highlighting particle contrast and uniformity; (c) TEM image at 100 nm scale, revealing internal mesostructure; (d) TEM image at 50 nm scale, resolving finer textural features of the framework

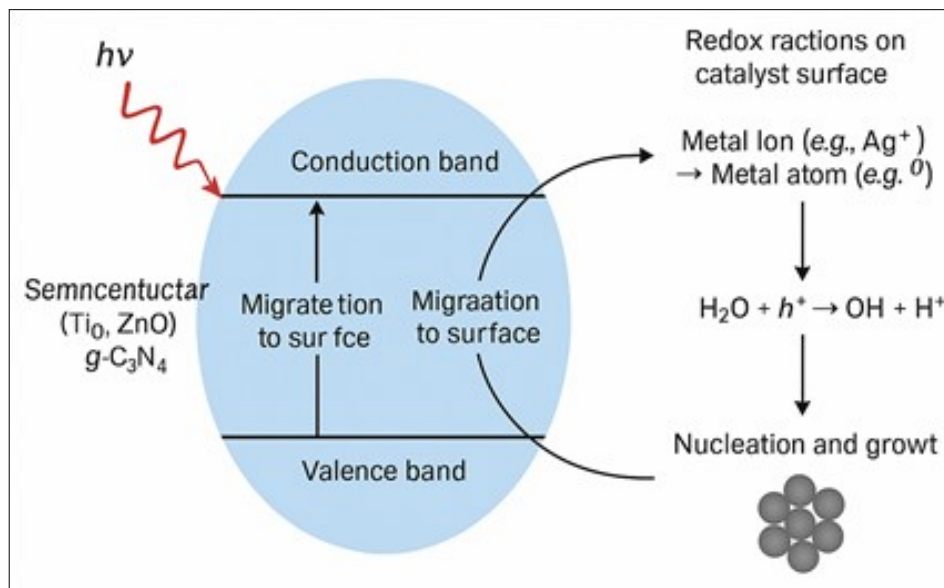


Fig. 8. Proposed mechanism of photocatalyst in the preparation of nanomaterials.

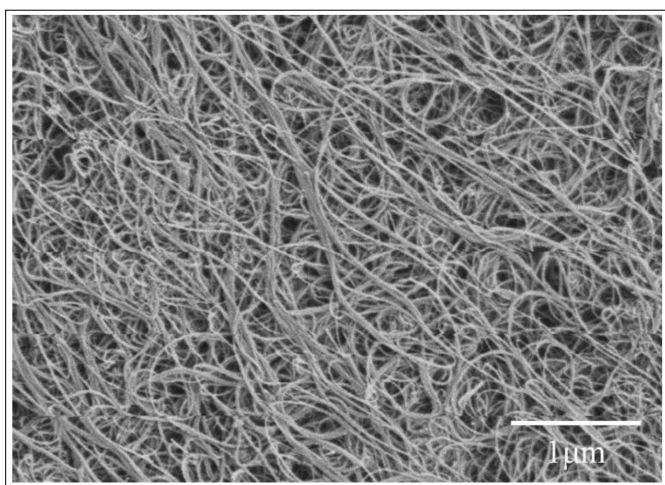


Fig. 9. SEM morphology of as-received Multi-Walled Carbon Nanotubes (MWCNTs) (51).

Optimisation processes in nanomaterial synthesis

Optimization in nanomaterial synthesis is pivotal for tailoring nanoparticle characteristics such as size, morphology, crystallinity and surface functionality, which directly influence their performance in applications like catalysis, drug delivery and electronics. Key synthesis parameters, including precursor concentration, reaction temperature, pH, reaction time, stirring speed and the presence of surfactants or capping agents, significantly impact nucleation and growth processes. For instance, variations in pH and temperature have been shown to affect the size and polydispersity index of biogenically synthesized tungsten trioxide nanoparticles. Similarly, the concentration of reducing agents and silver salts, along with pH and incubation time, are critical in the biosynthesis of silver nanoparticles (61,62).

Getting nanoparticles just right involves a smart approach: researchers systematically optimize the process using statistical tools like Response Surface Methodology (RSM) to figure out how different factors interact and find the best conditions, much like perfecting a complex recipe. Increasingly, they're also using machine learning, where computers learn from past experiments to predict outcomes, significantly speeding up the search for ideal parameters and cutting down on trial and error. Crucially, the basic method of making the

nanoparticles—whether it's physical, chemical, biological, or even eco-friendly "green synthesis" using things like plant extracts—plays a huge role in determining their final properties, allowing for control over things like size and shape. To top it off, automated lab systems are now used to quickly test many ways of making nanoparticles and fine-tune the process on the fly, making the whole discovery and optimization much faster (63,64), as shown in Fig. 10.

In summary, the optimization of nanomaterial synthesis is a multifaceted process that combines the careful control of synthesis parameters with advanced statistical and computational tools. This integrated approach ensures the reproducible production of nanomaterials with tailored properties, meeting the specific requirements of various technological applications.

Applications and socio-environmental implications of nano-physiochemistry

In recent decades, nano-physiochemistry and nanotechnology have significantly expanded and diversified their fields of application. The materials that chemistry generates at the nanometric scale have applications in the fields of catalysis, polymers, medicines, the manufacture of coatings, optical and photonic devices, the production of fragrances and food additives and biotechnology and environmental remediation (65). The following paragraphs describe some applications of nano-physiochemistry in the fields of catalysis, polymer synthesis and materials science. It has been decided to refer only to these three application niches because they constitute representative areas of chemical knowledge and because of the characteristics of this work.

A catalyst is a substance that increases the speed of a chemical reaction by modifying its kinetics and generating an alternate reaction mechanism with a lower activation energy (66). At the nanoscale, the field of heterogeneous catalysis stands out that systems where catalysts are dispersed in highly porous materials. The decrease in particle size in catalysts allows their surface to be more exposed so that a high number of atoms in it become active sites, increasing the efficiency of a reaction. Examples of nano catalysts are molecular aggregates of metal oxides and sulfides produced by sol-gel techniques. It has been

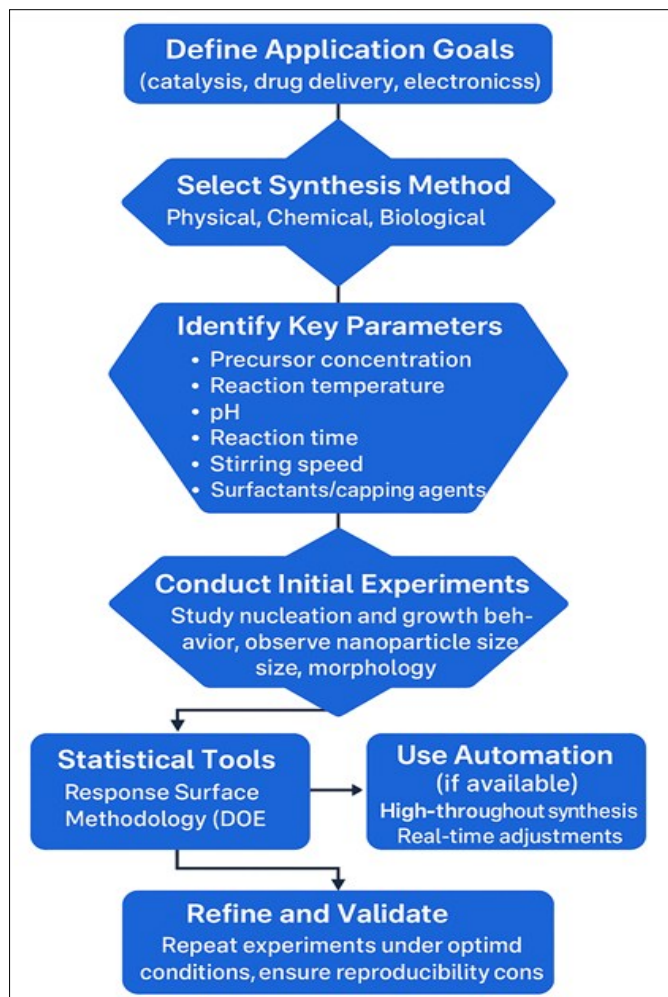


Fig.10. Optimisation processes in nanomaterial synthesis.

reported that titanium oxide (TiO_2) particles favor some environmental bioremediation processes, such as the adsorption of carbon dioxide (CO_2) and sulfuric acid (H_2SO_4), two polluting gases present in the atmosphere. TiO_2 as a catalyst is also referenced in some recent methods related to water purification (67). In the literature, it is mentioned that some nano catalysts made from molybdenum sulfides with traces of nickel (Ni) and cobalt (Co) supported on alumina (Al_2O_3) optimize the removal of Organic Sulfur Compounds (OSC) in different fractions of oil (68). Another group of nanostructured catalysts worth highlighting are those made from palladium (Pd) and supported on insulating or semiconductor materials that, when doped with rare earths, are efficient in reducing CO and hydrocarbons (69,70). Currently, more than 90 % of chemical processes in the world are assisted by catalysis and nano catalysts occupy an essential place.

In the field of polymers, nano-physiochemistry is contributing to improving the properties of these materials by incorporating specific nanostructures. For example, when silica nanoparticles are added to thermoplastic polymers such as polyurethane, their mechanical, thermal and adhesion properties are improved (71). The literature mentions that, by enriching materials such as acrylic with copper nanoparticles, their antibacterial behavior is increased, a relevant fact in the biomedical field because thermopolymerizable acrylic (PMMA) is widely used in the production of various types of prostheses (72). Another material provided by nano-physiochemistry that has a broad impact on the polymer industry is nanofibers, that is, fibers with diameters of up to 100 nm that can be of natural or synthetic

origin. These fibers are usually produced by the electrospinning method, which improves the quality of existing materials due to their reduced surface area. Currently, nanofibers produce protective and sports clothing in materials that allow the controlled release of medicines, support cell growth and produce polymeric membranes (73,74).

Another representative line of research in nano-physiochemistry is related to the production of materials whose structural basis is the nanostructured allotropes of the element carbon, such as fullerenes, CNTs and graphene. In the following lines, reference will be made to some applications based on the first two since chemical research on graphene is relatively recent and is in the consolidation process. The most cited applications of fullerenes are three: 1) they are often used to manufacture lubricants in the automotive industry, 2) they constitute an essential component of organic photovoltaic cells and 3) they can be used as nanostructures that inhibit some viruses.

In lubricants, C_{60} molecules act as nano bearings, interposing themselves with the metal parts of engines, reducing friction and increasing their power (75). In solar panels, fullerenes are incorporated to reduce silicon concentration and optimize the operation of these devices. In this type of photovoltaic cells, an organic polymer is responsible for absorbing sunlight and causing the excitation of electrons; fullerenes, due to their semiconductor properties, act as acceptors, favoring the flow of these particles in these devices (62). In biomedicine, fullerenes can help administer the active ingredients of particular medications due to their high capacity to bind to proteins and complex molecules. Specifically, it has been reported that derivatives of the C_{60} fullerene have the property of inhibiting the development of some viruses, such as HIV and decreasing their spread (76).

Regarding CNTs, their use in the reinforcement of polymeric materials and various processes based on chemical functionalization stands out. For example, when CNTs are added to traditional polymers, they improve their mechanical and thermal properties, resistance and durability and even, in some cases, they confer the property of conductivity (77). On the other hand, when CNTs are functionalized, that is, when various functional groups are incorporated into their structure or they are doped with metals, hybrid nanomaterials are obtained that are useful in the manufacture of biosensors, batteries and materials for the aerospace industry (78,79). The field of carbon-based nanomaterials is very versatile and has generated many scientific publications in the last decade.

Since nano-physiochemistry is an emerging area of research, it is associated with a substantial burden of uncertainty, mainly related to the toxicity and environmental impact of the materials it generates for the industry and research sectors. This is why philosophers, sociologists, economists, educators and disseminators contribute to nano research's ethical, economic, socio-environmental and educational analysis, reinforcing its interdisciplinary dimension (80). Some actions that these experts are proposing to reduce the risks of nanoscience and nanotechnology are the implementation of testing protocols for nanoparticles of synthetic origin, the establishment of standards to regulate their environmental and health repercussions, the study of their relevance and implications in formal and informal scientific education, as well as a series of recommendations regarding nanotechnology governance (81,82).

Therefore, it can be asserted that nano-physiochemistry, in particular and nanotechnology, in general, have a Janus-like face, as they can contribute significantly to human well-being by promoting technological and sustainable development. However, suppose their advances are not regulated based on ethics, environmental protection and common welfare. In that case, their developments can be distorted and generate diseases, exacerbate environmental problems and social and economic conflicts resulting from the overexploitation of resources and their subsequent commercialization.

By imparting modern-day approaches to infection prevention, prognosis and therapy on the molecular and cellular degrees, nanoscience is revolutionizing the fitness enterprise. Targeted drug delivery, where nanoparticles like liposomes, polymeric micelles, dendrimers and stable lipid nanoparticles are designed to supply healing marketers at once to diseased cells like most cancers cells whilst causing the least quantity of damage to healthful tissues, is one of the largest uses. This lessens negative outcomes and improves remedy effectiveness. Furthermore, medicines can be launched from nanocarriers in a regulated or stimuli-responsive manner, relying on the pH, temperature, or enzymes particular to diseased places. Nanomaterials are employed in diagnostics to create imaging assessment dealers and extraordinarily touchy biosensors. The accuracy of imaging modalities is progressed by iron oxide nanostructures, gold nanoparticles and quantum dots. This lessens damaging effects and improves therapy effectiveness. Furthermore, medications can be launched from nanocarriers in a regulated or stimuli-responsive way, relying at the pH, temperature or enzymes unique to diseased places. Nanomaterials are hired in diagnostics to create imaging contrast marketers and extremely touchy biosensors. Iron oxide nanostructures, gold nanoparticles and quantum dots improve the accuracy of imaging strategies like MRI, CT and PET, allowing earlier and extra specific illness identification (83).

Strong antibacterial uses are every other gain of nanoscience. To decrease the danger of infection, metallic nanoparticles with wide-spectrum antibacterial characteristics, together with silver (AgNPs), zinc oxide (ZnO) and titanium dioxide (TiO₂), are blanketed into coatings for surgical gear, medical implants, wound dressings and even hospital surfaces. Nanofibrous scaffolds and nanocomposite hydrogels offer a biomimetic environment in tissue engineering and regenerative medicine that encourages cell adhesion, proliferation and differentiation, making it simpler to heal broken tissues, which include skin, bone and cartilage. Both passive and energetic focused on nanocarriers, as well as Photothermal Therapy (PTT) and Photodynamic Therapy (PDT), wherein nanoparticles convert light energy into heat or reactive oxygen species to break down tumor cells, are ways that nanoscience aids in the treatment of cancer (84-86).

Furthermore, by making it viable to transport CRISPR additives and nucleic acids (DNA, siRNA and mRNA) across biological membranes, nanotechnology improves genetic therapeutics by getting beyond traditional obstacles in gene modification and the silencing of genes linked to infection. Nano sensors incorporated into textiles or bendy devices are utilized in wearable fitness tracking to become aware of biomarkers or physiological alerts in bodily fluids in real-time, supporting

customized treatment and the control of persistent diseases. The promise of nanoscience in enhancing vaccine stability, targeted delivery to immune cells and effective immune activation has also been proven by way of nano vaccines, consisting of the lipid nanoparticles employed in mRNA-based COVID-19 vaccines. All matters considered, nanoscience has completely changed the landscape of healthcare by offering accurate, minimally invasive and extremely successful treatments in a whole lot of clinical specialties (87) (Fig. 11).

Nanoparticles and medical field

Nanoparticles efficiently absorb substantial quantities of medications and traverse the bloodstream rapidly owing to their diminutive surface-area-to-volume ratio. Their increased surface area enhances their mechanical, magnetic, optical and catalytic capabilities, hence augmenting their medicinal use (88-90). The chemical composition categorizes nanoparticles into organic, inorganic and carbon-based classifications. Proteins, carbohydrates, lipids and other organic substances are fabricated into nanoparticles having a diameter of less than 100 nm (91,92).

Inorganic nanoparticles have non-toxicity, hydrophilicity, biocompatibility and enhanced stability compared to organic molecules. Inorganic nanoparticles consist of metal oxides, salts and elemental metals. Fullerenes, CNTs, graphene and its variants are nanomaterials composed of carbon (93-95). These materials have garnered interest in biomedical applications due to their unusual structural dimensions and exceptional mechanical, electrical, thermal, optical and chemical properties. Numerous nanoparticles preserve the chemical characteristics of their bulk counterparts, rendering them advantageous for various applications. Nanoparticles elevate in temperature to eradicate cancer cells upon exposure to light (96-98). Researchers believe that nanoparticles can be directly injected and may induce carcinogenesis. Smart tablets have ingestible sensors that can be wirelessly monitored to adjust medicine dosages according to physiological data. Nanomedicine, akin to any emerging technology, has obstacles, especially in clinical applications upon widespread adoption. The environmental impact of nanotechnology accumulates in biological tissues and organs and can be economically viable (99,100).

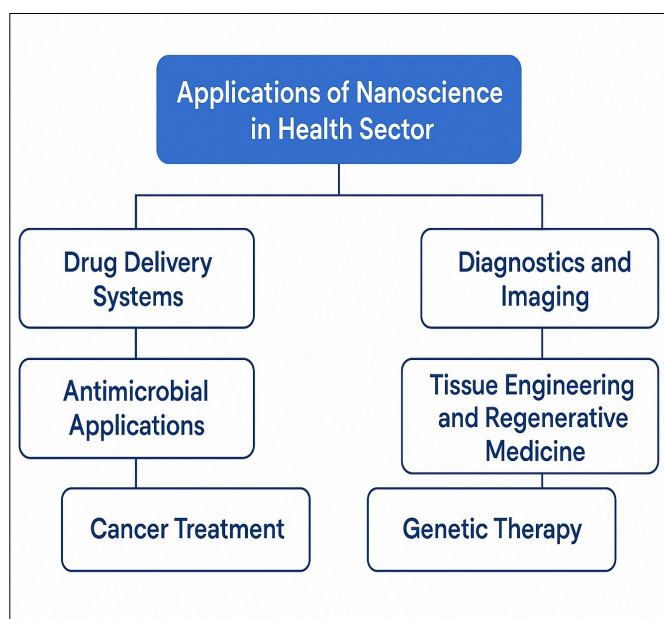


Fig.11. Applications of nanoscience in health sector.

The interaction between the traditional fields of chemistry and nanotechnology has resulted in the development of green nanotechnology. This field serves as an interdisciplinary term for a variety of technologies that are related to nanotechnology, such as nanoparticles, nanotoxicology, nanoscience, nano chemistry and other intricate aspects of material sciences. Fig. 5 illustrates the various classifications of nanotechnology-derived materials based on their prospective medicinal applications.

Documented in the existing literature are metal nanoparticles, dendrimers, liposomes, biodegradable polymers, carbon-based nanomaterials, hydrogel nanocomposites, among numerous others, all supporting the concept of nanotechnology and its prospective applications in medicine (101–103).

Nanofibers have use in surgical fabrics and implants, wound dressings, tissue technologies and synthetic organ components. Researchers are creating intelligent bandages that dissolve into the skin upon the healing of a wound. These intelligent bandages may contain nanofibers capable of detecting indicators of infection, coagulation, or embedded antibiotics (104–106). The advancement of nanomedicine offers the potential for increased life expectancy, benefiting both humanity and the environment, although it will need the use of natural resources. Nanomachines may be employed to construct dwellings and infrastructure on extraterrestrial bodies in preparation for human colonization of space, representing another prospective application of nanotechnology (107–109). Furthermore, scientists are exploring methods to modify human physiology to enable survival in the diverse atmospheres present in other worlds. Nanomedicine refers to the utilization of nanotechnology in healthcare, namely for the diagnosis and treatment of diverse diseases via molecular nanotechnology, nano electronic biosensors and nanoparticles. It facilitates nano-scale assessments of the patient's physiology, pharmaceuticals and medical apparatus, resulting in enhanced precision in medicine over time (110,111). This technology is being utilized in diagnostics and medical devices within the healthcare sector. Innovative diagnostics and therapies are emerging with increased efficacy due to the swift progress in nanotechnology. Cancer research and intelligent medicine are presently utilizing nanomedicine in their treatment. (112–114).

Numerous areas have seen significant transformation due to the application of this technology in the production of novel nanoparticles in recent years. Nanotechnology possesses numerous prospective medical applications, including the development of minuscule biomechanical devices such as nanorobots and nanomachines. The elevated production costs of nanotechnology-based products hinder their mass manufacture (115–117). These products offer cost-effective production alternatives, facilitating the extensive implementation of this technology. Insulin self-monitoring or self-regulation may be unnecessary if nanoparticles effectively elevate glucose levels and stimulate insulin release. The nanoparticles introduced into human circulation can proactively identify illnesses by actively targeting specific enzymes indicative of tumor growth (118–120) (Fig. 12).

Nanotechnology possesses the capacity to significantly enhance healthcare through improved diagnosis, treatment and disease prevention. The potential health uses of nanotechnology are garnering the interest of entrepreneurs, who may initiate a new phase of growth for the industry (121–123). Current diagnostic and therapeutic procedures depend on clinical expertise and the

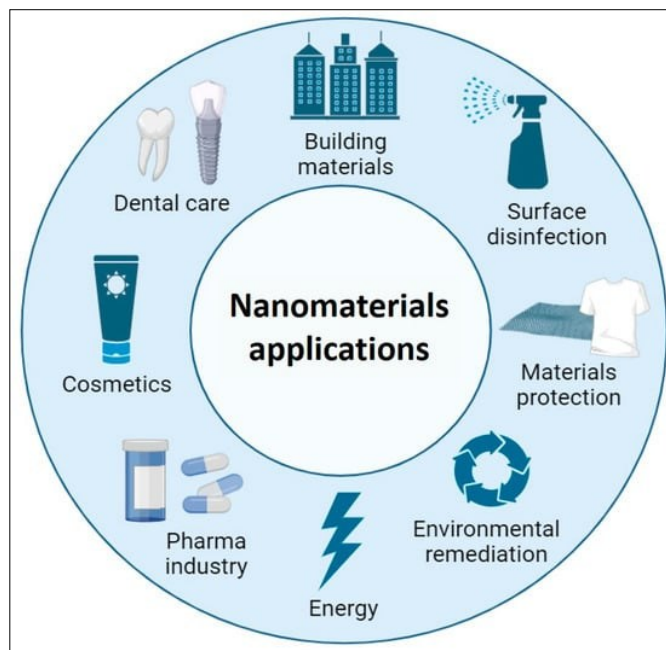


Fig. 12. Several nanomaterial applications (69).

evaluation of external biometric data; however, researchers aspire to focus more on data obtained at the disease site through nanotechnology soon. This technology facilitates the internal delineation of proactive, preventative and tailored medications by allowing our bodies to utilize artificial mechanisms (124–126). One of the top ten examples provided is the utilization of nanomaterials. Enhanced testing accuracy improved medical diagnostics and numerous additional opportunities are emerging due to the manipulation of devices and systems at the nanoscale (127,128).

Nanomaterials in healthcare serve several purposes, including diagnostics, therapies, controls and disease prevention. Nanoparticles are the catalyst for the development of safer and more effective medications, targeted tissue therapies and personalized nanomedicines (129–131). During the 2019 coronavirus pandemic, this technique was employed to sanitize surfaces and personal protective equipment. Nanoparticles have the capability to administer drugs accurately to targeted locations, hence augmenting their efficacy while minimizing adverse effects on surrounding tissues. Another prospective application of nanoparticles is to bypass the blood-brain barrier and administer drugs to the brain, which poses a problem in treating disorders lacking straightforward remedies (132–137) (Fig. 13).

Conclusion

Nano-physiochemistry is positioned to play a significant part in the development of both technology and industry in the years to come. Scientists and engineers could come up with novel answers to some of the most important problems that the world is currently facing if they continue to investigate and use the one-of-a-kind features the nanoscale materials possess. The main goal of green-nanotechnology is to provide humanity with a healthy and pollution-free lifestyle and it has brought around many revolutionary inventions to serve this purpose. This review aims at gathering a collection of data demonstrating the developments and applications of green-nanotechnology (nano-physiochemistry) at the industrial level. These advancements encourage us to make great strides towards attaining a healthy

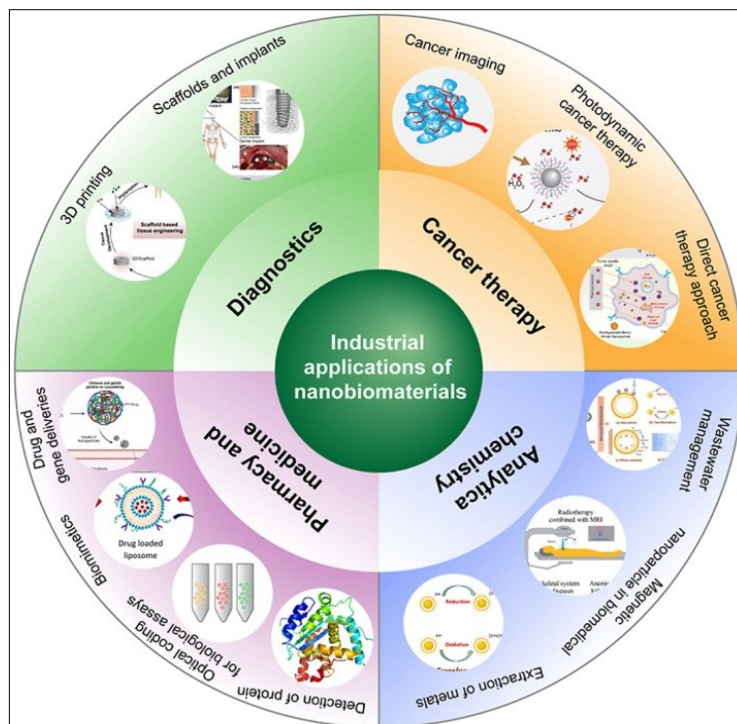


Fig. 13. Schematic diagram explaining the interdisciplinary industrial applications of nano biomaterials (86).

lifestyle and wellness. Regarding the transformative applications of nano-physiochemistry, medicine (via targeted drug delivery), materials science (through the development of stronger and lighter materials) and environmental remediation (through the cleanup of pollution) are all areas that are strongly impacted by nano-physiochemistry. The toxicity and long-term impacts of nanoparticles are still being investigated, which highlights the necessity for comprehensive safety studies. Health and safety concerns are also being taken into consideration.

There are still a lot of nano chemical processes that are being carried out in the laboratory, which presents challenges when it comes to scaling them up for commercial application. Prerequisites for regulation: the regulatory frameworks that are already in place are frequently insufficient to accommodate the rapid breakthroughs in nanotechnology. As a result, revised rules for safety and ethical standards are required. Recent improvements in nanomedicine, energy solutions and sensor technology are promising, showing that nano-physiochemistry could lead to important breakthroughs in a variety of fields. These achievements are among the innovative advancements that have been made. Nano-physiochemistry has the potential to address key global concerns in the future, if research and development are carried out in a responsible manner. However, to achieve sustainable progress, it will be necessary to first carefully assess the dangers involved and the rules that will be imposed.

Acknowledgements

The authors would like to thank the Department of Basic Sciences, College of Dentistry, University of Kerbala, Karbala, Iraq and the Department of Computer Techniques Engineering, Imam Alkadhim University College, Baghdad, Iraq, for making this work team complete the current study starting from the research plan till the finished writing and editing.

Authors' contributions

MJH designed the study and performed the data collection, while MZ and MRS prepared the manuscript and helped with data analysis. HA and MM interpreted the data, wrote the paper and supervised the current study. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

1. Atkins P, De Paula J. Elements of physical chemistry. Oxford University Press; 2013.
2. Tiwari P, Kane SN, Verma R, Tatarchuk T, Mazaleyrat F. Nanochemistry, biotechnology, nanomaterials and their applications. In: Springer proceedings in physics. Springer International Publishing. 2019;214:431–42. <https://doi.org/10.1007/978-3-319-92567-7>
3. Borisenko VE, Ossicini S. What is what in the nanoworld: A handbook on nanoscience and nanotechnology. John Wiley & Sons; 2013. <https://doi.org/10.1002/9783527623334>
4. Fesenko O, Yatsenko L. Nanochemistry, biotechnology, nanomaterials and their applications. Springer International Publishing; 2018. <https://doi.org/10.1007/978-3-319-92567-7>
5. Sudin NAS, Daud N, Mustapa IR, Zorah M. Thermomechanical properties and thermal behavior of poly (lactic acid) composites reinforced with TiO₂ nanofiller. Solid State Phenomena. 2021;317:341–50. <https://doi.org/10.4028/www.scientific.net/SSP.317.341>
6. Samawi KA, Abdulrazzaq SJ, Zorah M, Al-Bahrani M, Mahmoud HAMA, Taki AG, et al. MoS₂/graphdiyne nanotube/MXene 3D-interconnected ternary aerogel: A high-performance electrocatalyst for hydrogen evolution reaction. J Solid State Chem. 2024;334:124690. <https://doi.org/10.1016/j.jssc.2024.124690>
7. Gökçay B, Berna A. Nanotechnology, nanomedicine; ethical

- aspects. *Rev Rom Bioet.* 2015;13(3).
8. Allhoff F, Lin P, Moor JH, Weckert J. *Nanoethics: the ethical and social implications of nanotechnology.* Hoboken: John Wiley & Sons; 2007. p. 416
 9. Daniel CE, Legault GA, Bernier L. Nanotechnology regulation, the French national debate and social dialogue: Nanoworld, great normative expectations? *Lex Electronica.* 2015;20:92.
 10. Stephan S, Mader K. *Bridges between science, society and policy: technology assessment methods and impacts.* Berlin: Springer Science & Business Media; 2013. <https://doi.org/10.1007/978-3-662-06171-8>
 11. Rashid MK, Ali BM, Zorah M, Al-Musawi TJ. Experimental investigation of the effects of grooves in Fe₂O₃/water nanofluid pool boiling. *Fluids.* 2024;9(5):110. <https://doi.org/10.3390/fluids9050110>
 12. Feynman R. There's plenty of room at the bottom. In: Feynman and computation. CRC Press; 2018. p. 63–76 <https://doi.org/10.1201/9780429500459-7>
 13. Bensaude-Vincent B. Two cultures of nanotechnology? In: *Nanotechnology challenges: implications for philosophy, ethics and society.* World Scientific; 2006. p. 7–28 https://doi.org/10.1142/9789812773975_0002
 14. Bayda S, Adeel M, Tuccinardi T, Cordani M, Rizzolio F. The history of nanoscience and nanotechnology: from chemical-physical applications to nanomedicine. *Molecules.* 2019;25(1):112. <https://doi.org/10.3390/molecules25010112>
 15. Li Z, Liu Z, Sun H, Gao C. Superstructured assembly of nanocarbons: fullerenes, nanotubes and graphene. *Chem Rev.* 2015;115(15):7046–117. <https://doi.org/10.1021/cr500411z>
 16. Kaplan S, Radin J. Bounding an emerging technology: Parascientific media and the Drexler-Smalley debate about nanotechnology. *Soc Stud Sci.* 2011;41(4):457–85. <https://doi.org/10.1177/03063127111402722>
 17. Sudin NAS, Mustapa IR, Daud N, Zorah M. Thermomechanical, crystallization and melting behavior of plasticized poly (lactic acid) nanocomposites. *Solid State Phenomena.* 2021;317:351–60. <https://doi.org/10.4028/www.scientific.net/SSP.317.351>
 18. Bueno O. The Drexler-Smalley debate on nanotechnology: incommensurability at work? In: *Nanotechnology challenges: Implications for philosophy, ethics and society.* World Scientific; 2006. p. 29–48 https://doi.org/10.1142/9789812773975_0003
 19. Mangolini L. Synthesis, properties and applications of silicon nanocrystals. *J Vac Sci Technol B.* 2013;31(2). <https://doi.org/10.1116/1.4794789>
 20. Walkey CD. *The biological identity of nanoparticles.* PhD [thesis]. Canada: University of Toronto; 2014. <https://doi.org/10.1038/s41565-021-00860-0>
 21. Klabunde KJ, Sergeev GB. *Nanochemistry.* 2nd ed. Newnes; 2013.
 22. Mudhafara M, Alsailawic HA, Zainold I, Zorah M, Abdulraheem MN, Hasang MM, et al. Extraction, identification of chemical constituents and in vitro evaluation against cells and bacterial pathogens of the leaves of *Polyalthia rumphii*. *J Med Pharm Chem Res.* 2024;6:927–43. <https://doi.org/10.48309/JMPCR.2024.428146.1046>
 23. Cademartiri L, Ozin GA. *Concepts of nanochemistry.* Hoboken: John Wiley & Sons; 2009. p. 282
 24. Chen G, Seo J, Yang C, Prasad PN. Nanochemistry and nanomaterials for photovoltaics. *Chem Soc Rev.* 2013;42(21):8304–38. <https://doi.org/10.1039/C3CS60152F>
 25. Mudhafar M, Zainol I, Abd MY, Alsailawi HA, Ghazaly NM, Hussein RM, et al. The effect of fish collagen on the silver nanoparticles sizes and shapes using modified microwave-assisted green synthesis method and their antibacterial activities. *Heliyon.* 2024;10(12). <https://doi.org/10.1016/j.heliyon.2024.e32837>
 26. Sreenivasulu D, Dasari C. Fundamental ideas of nanomaterials and nanotechnology. In: *Proceedings of National Seminar;* 2017 Mar; Siliguri, India. Siliguri: Roshan Publications; 2017. p. 90–3. https://doi.org/10.1007/978-981-99-6649-3_1
 27. Shanmugam S. *Nanotechnology.* Chennai: MJP Publisher; 2019. p. 12
 28. Yang G. Synthesis, properties and applications of carbyne nanocrystals. *Mater Sci Eng R Rep.* 2022;151:100692. <https://doi.org/10.1016/j.mser.2021.100692>
 29. García-López EI, Liotta LF, Marci G. Preparation of photocatalysts by chemical methodologies. In: *Materials science in photocatalysis.* Elsevier; 2021. p. 13–36 <https://doi.org/10.1016/B978-0-12-821859-4.00006-4>
 30. Pedersen H, Elliott SD. Studying chemical vapor deposition processes with theoretical chemistry. *Theor Chem Acc.* 2014;133:1–10. <https://doi.org/10.1007/s00214-014-1476-7>
 31. Cruz-Alonso M, Fernández B, Álvarez L, González-Iglesias H, Traub H, Jakubowski N, et al. Quantitative imaging of specific proteins in the human retina by laser ablation ICPMS using bioconjugated metal nanoclusters as labels. *Anal Chem.* 2018;90(20):12145–51. <https://doi.org/10.1021/acs.analchem.8b02724>
 32. Bäuerle D. *Laser processing and chemistry.* Springer Science & Business Media; 2013. <https://doi.org/10.1007/978-3-642-82381-7>
 33. Zorah M, Mustapa IR, Daud N, Nahida JH, Sudin NAS. Effects of tributyl citrate plasticizer on thermomechanical attributes of poly lactic acid. *J Adv Res Fluid Mech Therm Sci.* 2019;62(2):274–84.
 34. Saeed M, Alshammari Y, Majeed SA, Al-Nasrallah E. Chemical vapour deposition of graphene -synthesis, characterisation and applications: A review. *Molecules.* 2020;25(17):3856. <https://doi.org/10.3390/molecules25173856>
 35. Sher F, Ziani I, Hameed M, Ali S, Sulejmanović J. Advanced nanomaterials design and synthesis for accelerating sustainable biofuels production—A review. *Curr Opin Green Sustain Chem.* 2024;100925. <https://doi.org/10.1016/j.cogsc.2024.100925>
 36. Ghosh V, Lonhare A. Response surface methodology: A statistical tool to optimize process parameters (quantitative data) to maximize the microbial biomass and their bioactive metabolites. *Ind Manuf Des Quant Qual Anal.* 2024;139–71. <https://doi.org/10.1002/9781394212668.ch5>
 37. Istiqomah A, Saputra OA, Firdaus M, Kusumaningsih T. Response surface methodology as an excellent tool for optimizing sustainable food packaging: A review. *J Biosyst Eng.* 2024;1–9. <https://doi.org/10.1007/s42853-024-00243-y>
 38. Popok VN, Kylián O. Gas-phase synthesis of functional nanomaterials. *Appl Nano.* 2020;1(1):4. <https://doi.org/10.3390/applnano1010004>
 39. Karakaya YH. *Mass spectrometric gas phase diagnostics in particle forming flames.* PhD [thesis]. Germany: Universität Duisburg-Essen; 2021. <https://doi.org/10.1016/j.pecs.2021.100927>
 40. Li L, Sun R, Zheng R. Tunable morphology and functionality of multicomponent self-assembly: A review. *Mater Des.* 2021;197:109209. <https://doi.org/10.1016/j.matdes.2020.109209>
 41. Dams M, Does-Sousa JL, Lamers RJ, Treumann A, Eeltink S. High-resolution nano-liquid chromatography with tandem mass spectrometric detection for the bottom-up analysis of complex proteomic samples. *Chromatographia.* 2019;82:101–10. <https://doi.org/10.1007/s10337-018-3647-5>
 42. El-Naggar ME, Shouair K. Recent advances in polymer/metal/metal oxide hybrid nanostructures for catalytic applications: A review. *J Environ Chem Eng.* 2020;8(5):104175. <https://doi.org/10.1016/j.jece.2020.104175>
 43. de Jong KP, editor. *Synthesis of solid catalysts.* Weinheim: Wiley-VCH; 2009. p. 422
 44. Pierre AC, editor. *Introduction to sol-gel processing.* New York: Springer Science+Business Media; 1998. p. 597–685 <https://doi.org/10.1007/978-1-4615-5659-6>

45. Mudhafar M, Zainol I, Alsailawic HA, Karhib MM, Zorah M, Alnagdi FH, et al. Bioactive chemical constituents of three crude extracts of *Polyalthia sclerophylla* using GC-mass and phytochemical screening and their antibacterial and cytotoxicity activities. *Eurasian Chem Commun.* 2023;5(8):675–90. <https://doi.org/10.22034/ecc.2023.387999.1602>
46. Aegerter MA, Almeida R, Soutar A, Tadanaga K, Yang H, Watanabe T. Coatings made by sol–gel and chemical nanotechnology. *J Solgel Sci Technol.* 2008;47:203–36. <https://doi.org/10.1007/s10971-008-1761-9>
47. Gradzielski M, Duvail M, de Molina PM, Simon M, Talmon Y, Zemb T. Using microemulsions: formulation based on knowledge of their mesostructure. *Chem Rev.* 2021;121(10):5671–740. <https://doi.org/10.1021/acs.chemrev.0c00812>
48. Karunaratne DN, Pamunuwa G, Ranatunga U. Introductory chapter: Microemulsions. In: *Properties and uses of microemulsions.* IntechOpen; 2017. <https://doi.org/10.5772/intechopen.68823>
49. Sharma G, Kumar D, Kumar A, Al-Muhtaseb AA, Pathania D, Naushad M, et al. Revolution from monometallic to trimetallic nanoparticle composites, various synthesis methods and their applications: A review. *Mater Sci Eng C.* 2017;71:1216–30. <https://doi.org/10.1016/j.msec.2016.11.002>
50. Xu C, Anusuyadevi PR, Aymonier C, Luque R, Marre S. Nanostructured materials for photocatalysis. *Chem Soc Rev.* 2019;48(14):3868–902. <https://doi.org/10.1039/C9CS00102F>
51. Omar S, Abu-Reziq R. Highly active ruthenium catalyst supported on magnetically separable mesoporous organosilica nanoparticles. *Appl Sci.* 2020;10(17):5769. <https://doi.org/10.3390/app10175769>
52. Ikram M, Rashid M, Haider A, Naz S, Haider J, Raza A, et al. A review of photocatalytic characterization and environmental cleaning, of metal oxide nanostructured materials. *Sustain Mater Technol.* 2021;30:e00343. <https://doi.org/10.1016/j.susmat.2021.e00343>
53. Serpone N, Emeline AV, Horikoshi S, Kuznetsov VN, Ryabchuk VK. On the genesis of heterogeneous photocatalysis: a brief historical perspective in the period 1910 to the mid-1980s. *Photochem Photobiol Sci.* 2012;11(7):1121–50. <https://doi.org/10.1039/c2pp25026h>
54. Vyas S. A short review on properties and applications of zinc oxide based thin films and devices: ZnO as a promising material for applications in electronics, optoelectronics, biomedical and sensors. *Johnson Matthey Technol Rev.* 2020;64(2):202–18. <https://doi.org/10.1595/205651320X15694993568524>
55. Hughes AE, Haque N, Northey SA, Giddey S. Platinum group metals: A review of resources, production and usage with a focus on catalysts. *Resources.* 2021;10(9):93. <https://doi.org/10.3390/resources10090093>
56. Rahman M. Magnetic resonance imaging and iron-oxide nanoparticles in the era of personalized medicine. *Nanotheranostics.* 2023;7(4):424. <https://doi.org/10.7150/ntno.86467>
57. Kusu M, Dinc E, Bilgin BA, Ramezani H, Akan OB. Transmitter and receiver architectures for molecular communications: A survey on physical design with modulation, coding and detection techniques. *Proc IEEE.* 2019;107(7):1302–41. <https://doi.org/10.1109/JPROC.2019.2916081>
58. Heinrich KFJ, Newbury D. *Electron probe quantitation.* Springer Science & Business Media; 2013. <https://doi.org/10.1007/978-1-4757-5581-7>
59. Jang SH, Kawashima S, Yin H. Influence of carbon nanotube clustering on mechanical and electrical properties of cement pastes. *Materials.* 2016;9(4):220. <https://doi.org/10.3390/ma9040220>
60. Zorah M, Mustapa IR, Daud N, Nahida JH, Sudin NAS. Thermomechanical study and thermal behavior of plasticized poly (lactic acid) nanocomposites. *Solid State Phenomena.* 2021;317:333–40. <https://doi.org/10.4028/www.scientific.net/SSP.317.333>
61. Park SH. Personal protective equipment for healthcare workers during the COVID-19 pandemic. *Infect Chemother.* 2020;52(2):165. <https://doi.org/10.3947/ic.2020.52.2.165>
62. Saini V, Sikri K, Batra SD, Kalra P, Gautam K. Development of a highly effective low-cost vaporized hydrogen peroxide-based method for disinfection of personal protective equipment for their selective reuse during pandemics. *Gut Pathog.* 2020;12:1–11. <https://doi.org/10.1186/s13099-020-00322-3>
63. Grant K, Andruchow JE, Conly J, Lee DD, Mazurik L, Atkinson P, et al. Personal protective equipment preservation strategies in the covid-19 era: A narrative review. *Infect Prev Pract.* 2021;3(3):100146. <https://doi.org/10.1016/j.infpip.2021.100146>
64. Zhu X, Li Y, Gu N. Application of artificial intelligence in the exploration and optimization of biomedical nanomaterials. *Nano Biomed Eng.* 2023;15(3). <https://doi.org/10.26599/NBE.2023.9290035>
65. Pagliaro M. Advancing nanochemistry education. *Chem–Eur J.* 2015;21(34):11931–6. <https://doi.org/10.1002/chem.20150103>
66. van Santen RA. *Chemical kinetics and catalysis.* Springer Science & Business Media; 2013.
67. Babudurai M. Heavy metal removal in aqueous phase using TiO₂/Iron-oxide nanocomposites. *Central Asian J Med Nat Sci.* 2021;5(4):533–8.
68. Zuliani A. Microwave-assisted synthesis of nanocatalysts in batch conditions; 2020. <http://hdl.handle.net/10396/19331>
69. Zorah M, Mudhafar M, Naser HA, Mustapa IR. The promises of the potential uses of polymer biomaterials in biomedical applications and their challenges. *Int J App Pharm.* 2023;15(4):27–36. <https://doi.org/10.22159/ijap.2023v15i4.45795>
70. Seyfi J, Jafari SH, Khonakdar HA, Sadeghi GM, Zohuri G, Hejazi I, et al. Fabrication of robust and thermally stable superhydrophobic nanocomposite coatings based on thermoplastic polyurethane and silica nanoparticles. *Appl Surf Sci.* 2015;347:224–30. <https://doi.org/10.1016/j.apsusc.2015.04.066>
71. Shi S, Si Y, Han Y, Wu T, Iqbal MI, Fei B, et al. Recent progress in protective membranes fabricated via electrospinning: Advanced materials, biomimetic structures and functional applications. *Adv Mater.* 2022;34(17):2107938. <https://doi.org/10.1002/adma.202107938>
72. Mansoori GA. An introduction to nanoscience and nanotechnology. In: *Nanoscience and plant–soil systems;* 2017. p. 3–20 https://doi.org/10.1007/978-3-319-46835-8_1
73. Mudhafar M, Zainol I, Alsailawi HA, Zorah M, Karhib MM. Preparation and characterization of FSHA/FsCol beads: Cell attachment and cytotoxicity studies. *Heliyon.* 2023;9(5). <https://doi.org/10.1016/j.heliyon.2023.e18756>
74. Bolanos Ch LC, Alvarez LX. Conductive polymers: Applications in photovoltaic cells and electronic devices. *Ciencia y Tecnologia.* 2018;34(1):18–38.
75. Castro E, Garcia AH, Zavala G, Echegoyen L. Fullerenes in biology and medicine. *J Mater Chem B.* 2017;5(32):6523–35. <https://doi.org/10.1039/C7TB01830F>
76. Nurazzi NM, Sabaruddin FA, Harussani MM, Kamarudin SH, Rayung M, Asyraf MRM, et al. Mechanical performance and applications of CNTs reinforced polymer composites-A review. *Nanomaterials.* 2021;11(9):2186. <https://doi.org/10.3390/nano11092186>
77. Karousis N, Tagmatarchis N, Tasis D. Current progress on the chemical modification of carbon nanotubes. *Chem Rev.* 2010;110(9):5366–97. <https://doi.org/10.1021/cr100094z>
78. Foladori G, Invernizzi N. A critical vision of disruptive nanotechnologies. *Perspect Glob Dev Technol.* 2018;17(5-6):614–31. <https://doi.org/10.1163/15691497-12341414>
79. Allan J, Belz S, Hoeveler A, Hugas M, Okuda H, Patri A, et al. Regulatory landscape of nanotechnology and nanoplastics from a global perspective. *Regul Toxicol Pharmacol.* 2021;122:104885. <https://doi.org/10.1016/j.yrtph.2021.104885>

80. Zorah M, Mudhafar M, Majhool AA, Abbood SF, Alsailawi HA, Karhib MM, et al. Review of the green composite: Importance of biopolymers, uses and challenges. *J Adv Res Fluid Mech Therm Sci*. 2023;111(1):194–216. <https://doi.org/10.37934/arfmts.111.1.194216>
81. Ortega-Nieto C, Losada-Garcia N, Prodan D, Furtos G, Palomo JM. Recent advances on the design and applications of antimicrobial nanomaterials. *Nanomaterials*. 2023;13(17):2406. <https://doi.org/10.3390/nano13172406>
82. Eker F, Duman H, Akdaşçı E, Bolat E, Sarıtaş S, Karav S, et al. A comprehensive review of nanoparticles: From classification to application and toxicity. *Molecules*. 2024;29(15):3482. <https://doi.org/10.3390/molecules29153482>
83. Ahmed SF, Kumar PS, Ahmed B, Mehnaz T, Shafiullah GM, Nguyen VN, et al. Carbon-based nanomaterials: Characteristics, dimensions, advances and challenges in enhancing photocatalytic hydrogen production. *Int J Hydrogen Energy*. 2024;52:424–42. <https://doi.org/10.1016/j.ijhydene.2023.03.185>
84. Feliczak-Guzik A. Nanomaterials as photocatalysts synthesis and their potential applications. *Materials*. 2022;16(1):193. <https://doi.org/10.3390/ma16010193>
85. Omran TZ, Jasmi FS, Obaid KM, Ghareeb AK, Alsailawi HA, Mudhafar M. The interleukin gene landscape: Understanding its influence on inflammatory mechanisms in apical periodontitis. *Mol Biol Rep*. 2025;52(1):365. <https://doi.org/10.1007/s10333-025-10477-4>
86. Thwala LN, Ndlovu SC, Mpofu KT, Lugongolo MY, Mthunzi-Kufa P. Nanotechnology-based diagnostics for diseases prevalent in developing countries: Current advances in point-of-care tests. *Nanomaterials*. 2023;13(7):1247. <https://doi.org/10.3390/nano13071247>
87. Obeed HH, Ridha NJ, Alosfur F, Tahir KJ, Madlol R, Hussein BM, editors. Comprehensive study on the effect of laser on human blood: Proceedings of the AIP Conference; 2022 Jan 11. Melville (NY): AIP Publishing; 2022. <https://doi.org/10.1063/5.0067072>
88. Sharma A, Jangra N, Dheer D, Jha SK, Gupta G, Puri V, et al. Understanding the journey of biopolymeric nanoformulations for oral drug delivery: Conventional to advanced treatment approaches. *Eur Polym J*. 2024;218:113338. <https://doi.org/10.1016/j.eurpolymj.2024.113338>
89. Preethi M, Adhav S, Kursunge H, Borse V. Introduction to nanoparticles as a potential carrier for brain targeting. In: Application of nanocarriers in brain delivery of therapeutics. Springer; 2024. p. 43–68 <https://doi.org/10.1007/978-981-97-2859-6>
90. Alshammari BH, Lashin MMA, Mahmood MA, Al-Mubaddel FS, Ilyas N, Rahman N, et al. Organic and inorganic nanomaterials: fabrication, properties and applications. *RSC Adv*. 2023;13(20):13735–85. <https://doi.org/10.1039/d3ra01421e>
91. Verma ML, Dhanya BS, Rani V, Thakur M, Jeslin J, Kushwaha R. Carbohydrate and protein based biopolymeric nanoparticles: Current status and biotechnological applications. *Int J Biol Macromol*. 2020;154:390–412. <https://doi.org/10.1016/j.ijbiomac.2020.03.106>
92. Khan S, Hossain MK. Classification and properties of nanoparticles. In: Nanoparticle-based polymer composites. Elsevier; 2022. p. 15–54 <https://doi.org/10.1016/C2020-0-01662-2>
93. Sajid M, Płotka-Wasyłka J. Nanoparticles: Synthesis, characteristics and applications in analytical and other sciences. *Microchem J*. 2020;154:104623. <https://doi.org/10.1016/j.microc.2020.104623>
94. Kharissova OV, Kharisov BI, Oliva González CM, Méndez YP, López I. Greener synthesis of chemical compounds and materials. *R Soc Open Sci*. 2019;6(11):191378. <https://doi.org/10.1098/rsos.191378>
95. Kim D, Shin K, Kwon SG, Hyeon T. Synthesis and biomedical applications of multifunctional nanoparticles. *Adv Mater*. 2018;30(49):1802309. <https://doi.org/10.1002/adma.201802309>
96. Gawande MB, Goswami A, Asefa T, Guo H, Biradar AV, Peng DL, et al. Core-shell nanoparticles: synthesis and applications in catalysis and electrocatalysis. *Chem Soc Rev*. 2015;44(21):7540–90. <https://doi.org/10.1039/C5CS00343A>
97. Senchukova M. A brief review about the role of nanomaterials, mineral-organic nanoparticles and extra-bone calcification in promoting carcinogenesis and tumor progression. *Biomedicines*. 2019;7(3):65. <https://doi.org/10.3390/biomedicines7030065>
98. Zhang Y, Bai Y, Jia J, Gao N, Li Y, Zhang R, et al. Perturbation of physiological systems by nanoparticles. *Chem Soc Rev*. 2014;43(10):3762–809. <https://doi.org/10.1039/c3cs60338e>
99. Yu Z, Gao L, Chen K, Zhang W, Zhang Q, Li Q, et al. Nanoparticles: A new approach to upgrade cancer diagnosis and treatment. *Nanoscale Res Lett*. 2021;16(1):88. <https://doi.org/10.1186/s11671-021-03489-z>
100. Rahmani S, Maroufkhani M, Mohammadzadeh-Komuleh S, Khoubi-Arani Z. Polymer nanocomposites for biomedical applications. In: Fundamentals of bionanomaterials. Elsevier; 2022. p. 175–215 <https://doi.org/10.1016/B978-0-12-822131-1.00014-2>
101. Tekade RK, Maheshwari R, Soni N, Tekade M, Chougule MB. Nanotechnology for the development of nanomedicine. In: Mishra V, Kesharwani P, Amin MC, Iyer AK, editors. Nanotechnology-based approaches for targeting and delivery of drugs and genes. Cambridge (MA): Elsevier; 2017. p. 3–61 <https://doi.org/10.1016/B978-0-12-804826-5.00001-9>
102. Domingues C, Lian X, Zhang Y, Smith J, Kumar R, Li H, et al. Where is nano today and where is it headed? A review of nanomedicine and the dilemma of nanotoxicology. *ACS Nano*. 2022;16(7):9994–10041. <https://doi.org/10.1021/acsnano.2c02965>
103. Sinha A, Simnani FZ, Singh D, Nandi A, Choudhury A, Patel P, et al. The translational paradigm of nanobiomaterials: Biological chemistry to modern applications. *Mater Today Bio*. 2022;17:100463. <https://doi.org/10.1016/j.mtbio.2022.100463>
104. Ambekar RS, Kandasubramanian B. Advancements in nanofibers for wound dressing: A review. *Eur Polym J*. 2019;117:304–36. <https://doi.org/10.1016/j.eurpolymj.2019.04.060>
105. Parham S, Zargar A, Bakhsheshi-Rad HR, Kharaziha M, Ismail AF, Sharif S, et al. Antimicrobial synthetic and natural polymeric nanofibers as wound dressing: A review. *Adv Eng Mater*. 2022;24(6):2101460. <https://doi.org/10.1002/adem.202101460>
106. Bhardwaj AK, Kant A, Rehalia A, Singh V, Sharma R. A review on nanomaterials for drug delivery systems and application of carbon-based nanomaterials. *ES Mater Manuf*. 2023;21(2):824. <https://doi.org/10.30919/esmm5f824>
107. Ahmed SF, Mofijur M, Rafa N, Chowdhury AT, Chowdhury S, Nahrin M, et al. Green approaches in synthesising nanomaterials for environmental nanobioremediation: Technological advancements, applications, benefits and challenges. *Environ Res*. 2022;204:111967. <https://doi.org/10.1016/j.envres.2021.111967>
108. Hezam MJ, Abbood MA, Shakir M, Mahmood AA, Mudhafar M, Alsailawi HA, et al. Optimal design and sizing of energy storage solution-based hybrid energy system considering economic and technical objective functions: A case study. *J Energy Storage*. 2025;30:125:117041. <https://doi.org/10.1016/j.est.2025.117041>
109. Gorgieva S, Zemljić LF, Strnad S, Kokol V. Textile-based biomaterials for surgical applications. In: Fundamental biomaterials: polymers. Amsterdam: Elsevier; 2018. p. 179–215 <https://doi.org/10.1016/B978-0-08-102755-7.00010-6>
110. M Matteucci F, Giannantonio R, Calabi F, Agostiano A, Gigli G, Rossi M. Deployment and exploitation of nanotechnology, nanomaterials and nanomedicine. In: AIP Conference Proceedings; 2018; Kuala Lumpur, Malaysia. Melville: AIP Publishing; 2018. <https://doi.org/10.1063/1.5080893>
111. Beg S, Rahman M, Barkat MA, Ahmad FJ. Nanomedicine for the treatment of disease: from concept to application. CRC Press; 2019. p. 6 <https://doi.org/10.1201/9780429425714>

112. Jamali MC, Mohamed AA, Jamal A, Kamal MA, Al Abdulmonem W, Saeed BA, et al. Biological mechanisms and therapeutic prospects of interleukin-33 in pathogenesis and treatment of allergic disease. *J Inflamm*. 2025;22(1):1–4. <https://doi.org/10.1186/s12950-025-00438-w>
113. Khan SH. Green nanotechnology for the environment and sustainable development. In: *Green materials for wastewater treatment*. 2020. p. 13–46 <https://doi.org/10.1016/B978-0-12-820199-3.00002-2>
114. Jain KK. Nanomolecular diagnostics. In: *The handbook of nanomedicine*. 3rd ed. Cham: Springer; 2017. p. 133–200 https://doi.org/10.1007/978-3-319-45108-1_7
115. Kemp JA, Kwon YJ. Cancer nanotechnology: current status and perspectives. *Nano Conver*. 2021;8(1):34. <https://doi.org/10.1186/s12951-021-00873-z>
116. Zonouri SA, Ali Alsailawi H, Mudhafar M. A high-sensitivity Wilkinson power divider sensor for detecting dielectric properties in edible oils. *Sensing Imaging*. 2025;26(1):1–34. <https://doi.org/10.1007/s11220-025-00567-9>
117. Adwani G, Bharti S, Kumar A. Engineered nanoparticles in non-invasive insulin delivery for precision therapeutics of diabetes. *Int J Biol Macromol*. 2024;233:133437. <https://doi.org/10.1016/j.jbiomac.2024.01.001>
118. Bhutta ZA, Kanwal A, Ali M, Kulyar MF-E-A, Yao W, Shoaib M, et al. Emerging nanotechnology role in the development of innovative solutions against COVID-19 pandemic. *Nanotechnology*. 2021;32(48):482001. <https://doi.org/10.1016/j.nano.2021.482001>
119. Zhang H, Tang J, Cao H, Wang C, Shen C, Liu J. Review of the applications of micro/nanorobots in biomedicine. *ACS Appl Nano Mater*. 2024;7(15):17151–92 <https://doi.org/10.1021/acsnm.4b01961>
120. Farooq MU, Lawrie CH, Deng NN. Engineering nanoparticles for cancer immunotherapy: current achievements, key considerations and future perspectives. *Chem Eng J*. 2024;150356. <https://doi.org/10.1016/j.cej.2024.150356>
121. Mandpe P, Prabhakar B, Gupta H, Shende P. Glucose oxidase-based biosensor for glucose detection from biological fluids. *Sensor Rev*. 2020;40(4):497–511. <https://doi.org/10.1108/SR-09-2019-0224>
122. Yang J, Yang J, Gong X, Zheng Y, Yi S, Cheng Y, et al. Recent progress in microneedles-mediated diagnosis, therapy and theranostic systems. *Adv Healthc Mater*. 2022;11(10):2102547. <https://doi.org/10.1002/adhm.202102547>
123. Tawiah B, Ofori EA, George SC. Nanotechnology in societal development. In: *Nanotechnology in societal development*. Springer; 2024. p. 1–64 https://doi.org/10.1007/978-3-030-34610-4_1
124. Liu Q, Zou J, Chen Z, He W, Wu W. Current research trends of nanomedicines. *Acta Pharm Sin B*. 2023;13(11):4391–416. <https://doi.org/10.1016/j.apsb.2023.06.004>
125. Desai N, Katare P, Makwana V, Salave S, Vora LK, Giri J. Tumor-derived systems as novel biomedical tools-turning the enemy into an ally. *Biomater Res*. 2023;27(1):113. <https://doi.org/10.1186/s43274-023-00039-6>
126. Burke MT. *Nanotechnology: the business*. CRC Press; 2018. <https://doi.org/10.1201/9781315219394>
127. Tibbals HF. *Medical nanotechnology and nanomedicine*. CRC Press; 2017. <https://doi.org/10.1201/b10151>
128. Cellina M, Rossi F, Bianchi L, Verdi A, Russo P, Conti G, et al. Digital twins: the new frontier for personalized medicine? *Appl Sci*. 2023;13(13):7940. <https://doi.org/10.3390/app13137940>
129. Kulkarni MB, Ayachit NH, Aminabhavi TM. Recent advancements in nanobiosensors: current trends, challenges, applications and future scope. *Biosensors (Basel)*. 2022;12(10):892. <https://doi.org/10.3390/bios12100892>
130. Xu H, Gao M, Tang X, Zhang W, Luo D, Chen M. Micro/nano technology for next-generation diagnostics. *Small Methods*. 2020;4(4):1900506. <https://doi.org/10.1002/smt.201900506>
131. Escobar M, Ghareeb M, Mudhafar M, Hezam MJ, Ghazaly NM, Zaki SH, et al. Enhancing quantum capacitance in BNYne/Graphene heterostructures through transition-metal dopants for high-performance supercapacitors. *J Organomet Chem*. 2024;1022:123404. <https://doi.org/10.1016/j.jorgchem.2024.123404>
132. Welch EC, Powell JM, Clevinger TB, Fairman AE, Shukla A. Advances in biosensors and diagnostic technologies using nanostructures and nanomaterials. *Adv Funct Mater*. 2021;31(44):2104126. <https://doi.org/10.1002/adfm.202104126>
133. Pirzada M, Altintas Z. Nanomaterials for healthcare biosensing applications. *Sensors*. 2019;19(23):5311. <https://doi.org/10.3390/s19235311>
134. Abd Elkodous M, El-Sayyad GS, Abdelrahman IY, El-Bastawisy HS, Mohamed AE, Mosallam FM, et al. Therapeutic and diagnostic potential of nanomaterials for enhanced biomedical applications. *Colloids Surf B Biointerfaces*. 2019;180:411–28. <https://doi.org/10.1016/j.colsurfb.2019.05.008>
135. Moura RP, Martins C, Pinto S, Sousa F, Samento B. Blood-brain barrier receptors and transporters: an insight on their function and how to exploit them through nanotechnology. *Expert Opin Drug Deliv*. 2019;16(3):271–85. <https://doi.org/10.1080/17425247.2019.1587204>
136. Martinelli C, Pucci C, Battaglini M, Marino A, Ciofani G. Antioxidants and nanotechnology: promises and limits of potentially disruptive approaches in the treatment of central nervous system diseases. *Adv Healthc Mater*. 2020;9(3):1901589. <https://doi.org/10.1002/adhm.201901589>
137. McLoughlin CD, Nevins S, Stein JB, Khakbiz M, Lee K. Overcoming the blood-brain barrier: multifunctional nanomaterial-based strategies for targeted drug delivery in neurological disorders. *Small Sci*. 2024;4(12):2400232. <https://doi.org/10.1002/smssc.202400232>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc. See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.