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REVIEW ARTICLE

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

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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 ($1x10^{-9}$ 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 C_{60} 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 C_{20}, but the most abundant and representative continues to be C_{60} (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

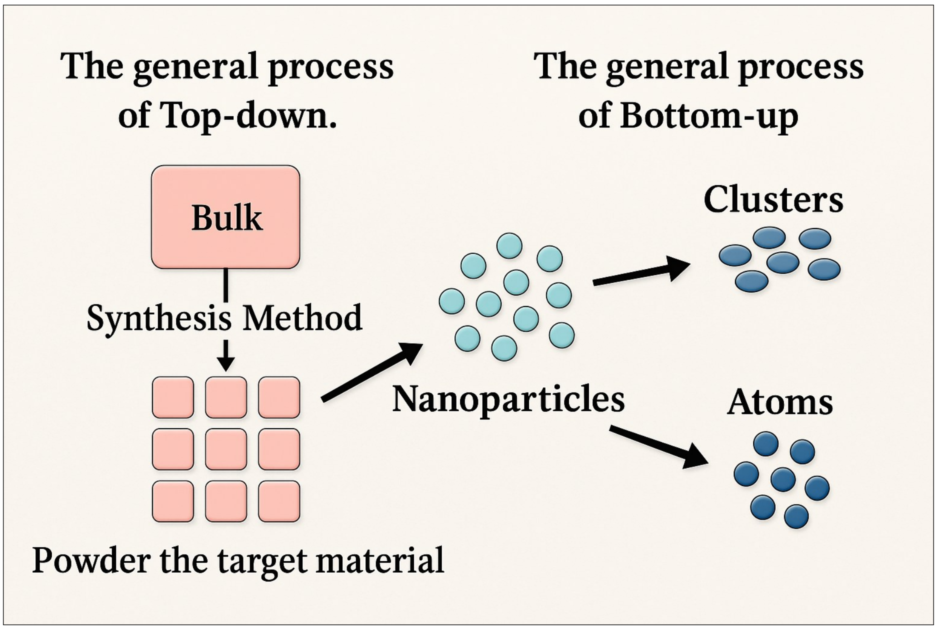

Fig. 1. The general mechanism of synthesis process of nanoparticles.

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

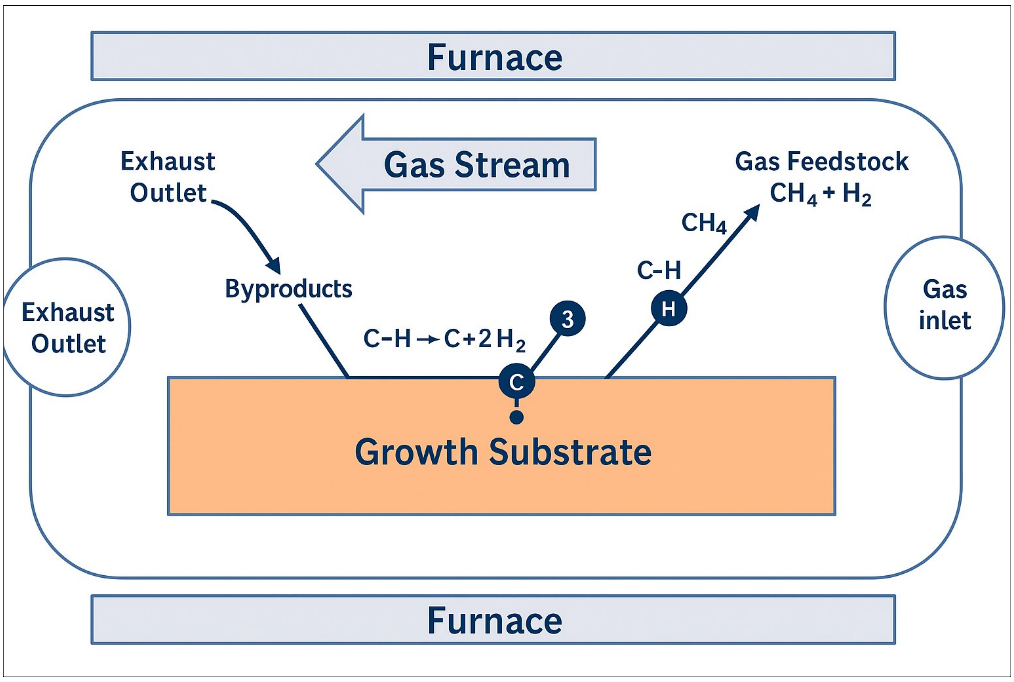

Fig. 2. Schematic diagram of thermal CVD growth of graphene (34).

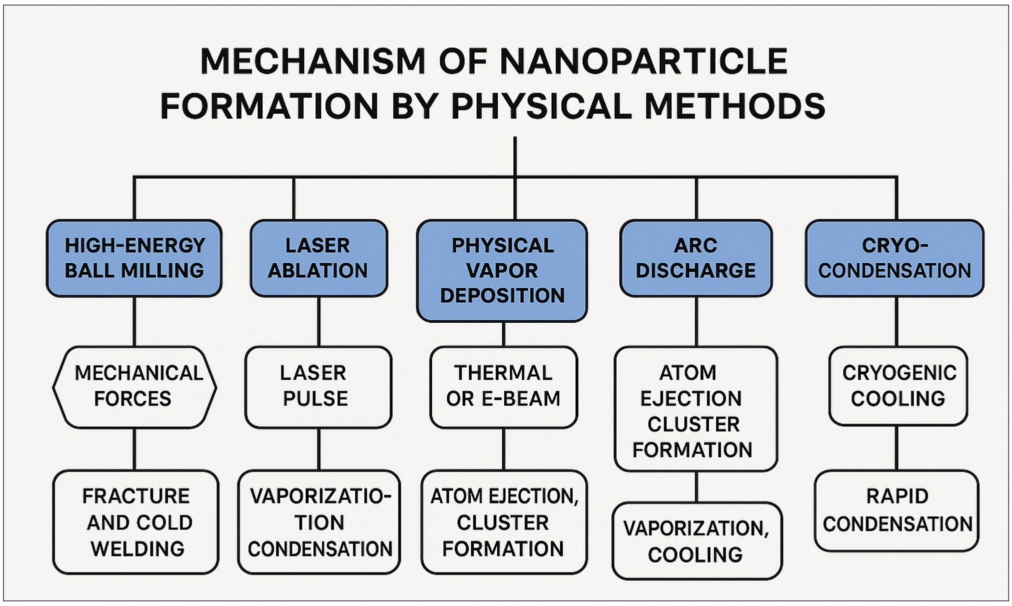

Fig. 3. Mechanisms of nanoparticles using physical methods.

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 photothermic 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 nano-physiochemistry 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

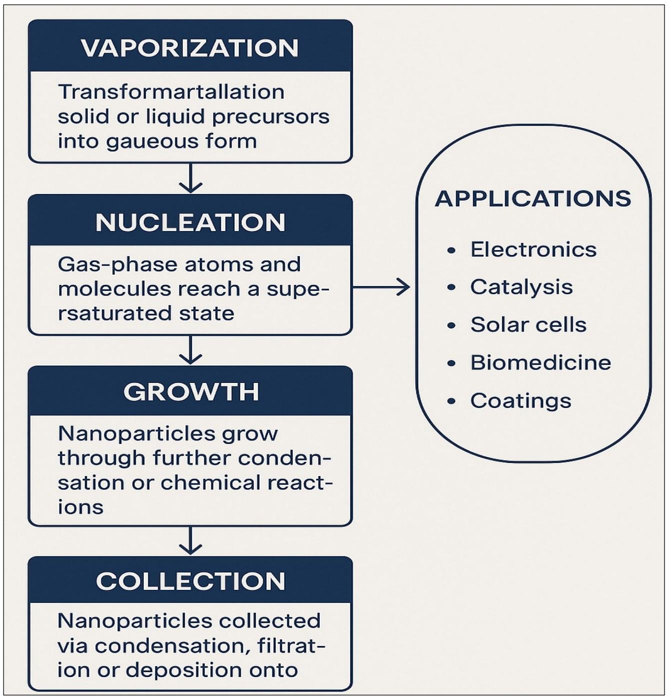

Fig. 4. Mechanism of gas phase techniques.

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 Nuclision 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 nuclear 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 drill hydride ($NaBH_4$) 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 nuclear control 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 nanotors (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.

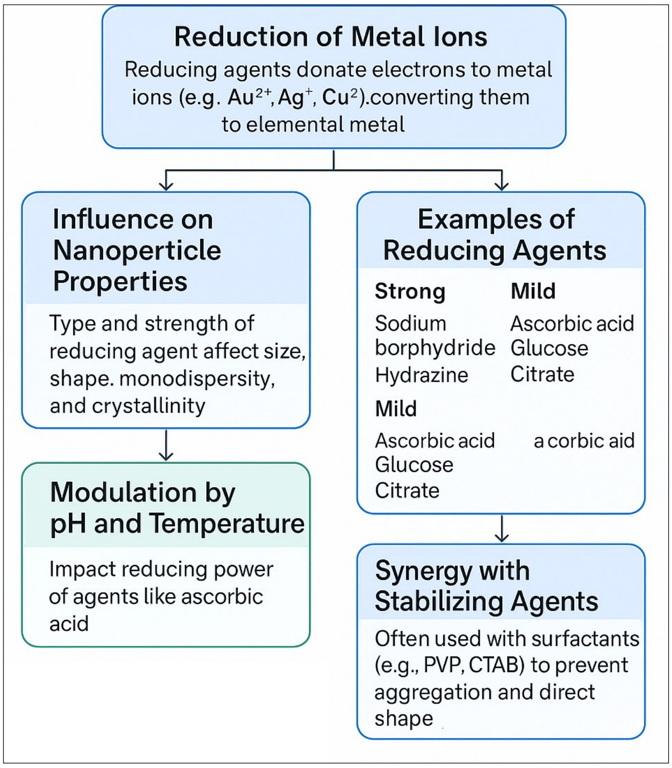

Fig.5. Role of reducing agents in the liquid phase techniques.

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.

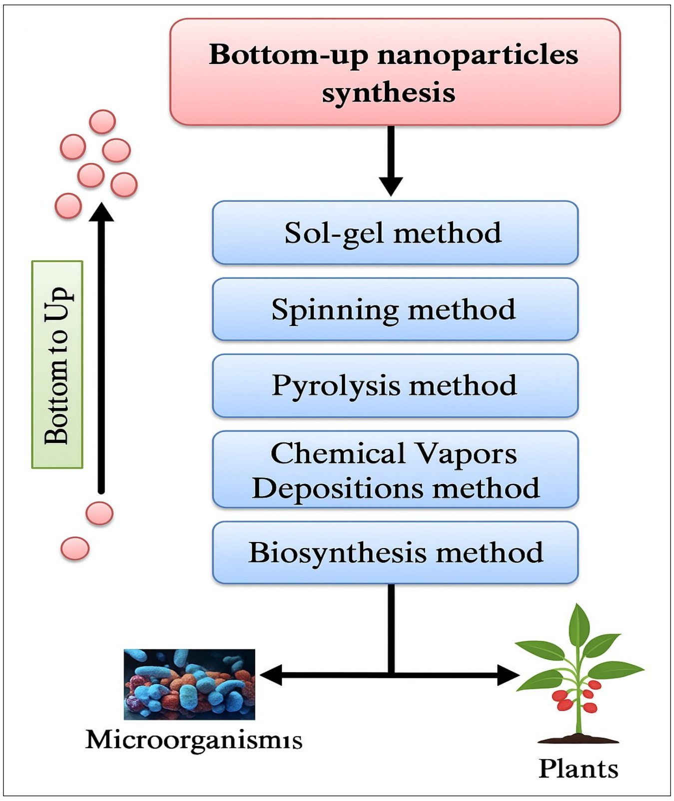

Fig. 6. The bottom-up process of nanoparticles.

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-C_3N_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 (•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).

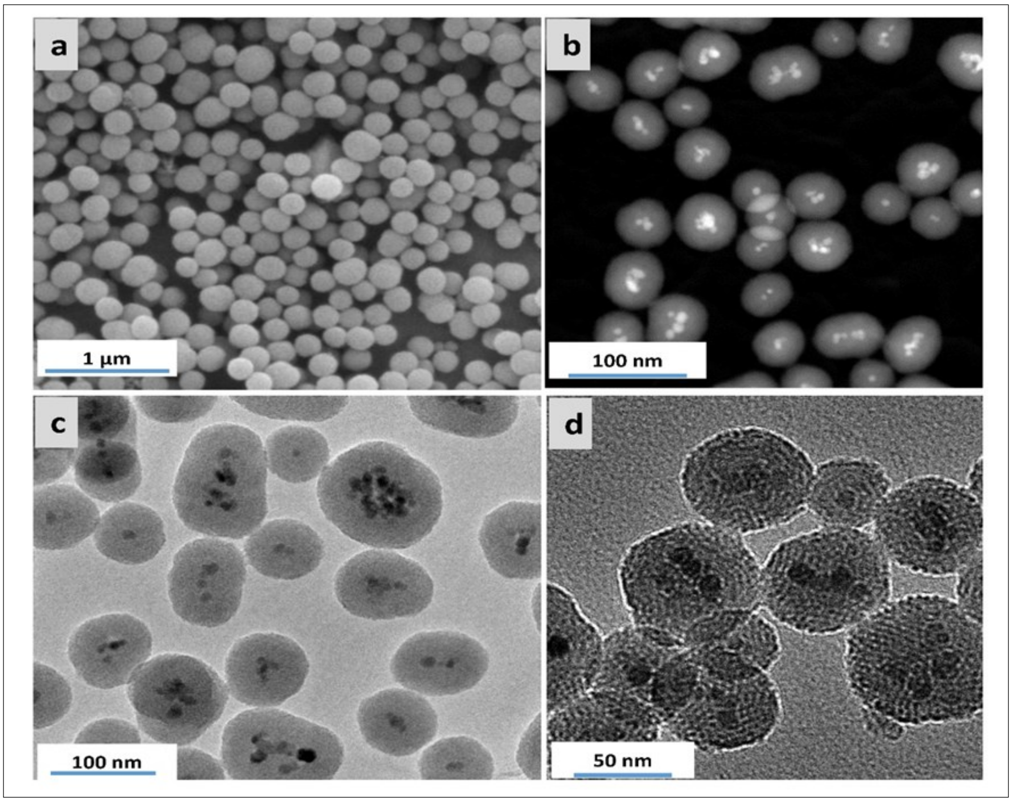

Fig. 7. Electron Microscopy Images of M-Ethylene PMO Nanoparticles (PMO NPs) (46).

(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

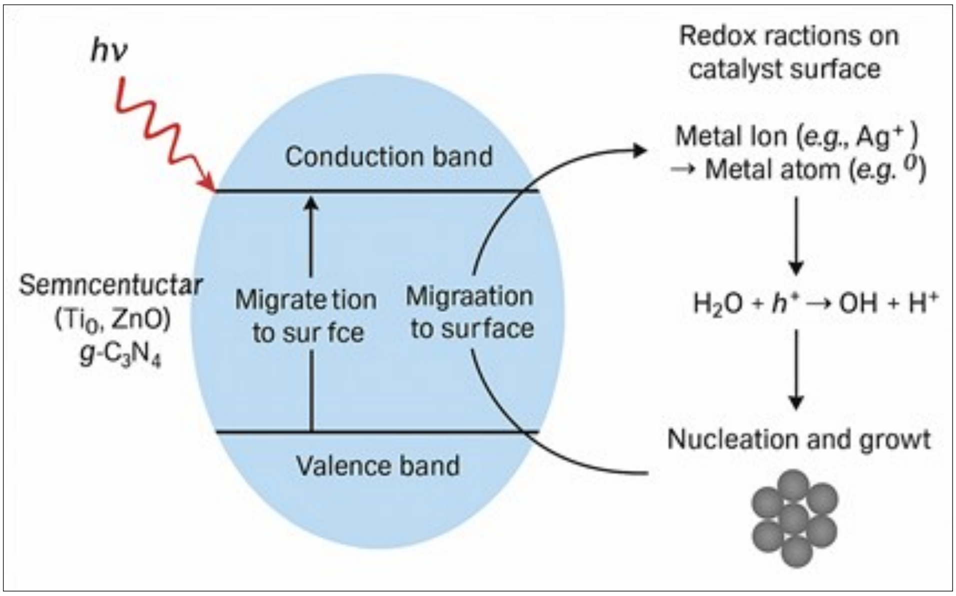

Fig. 8. Proposed mechanism of photocatalyst in the preparation of nanomaterials.

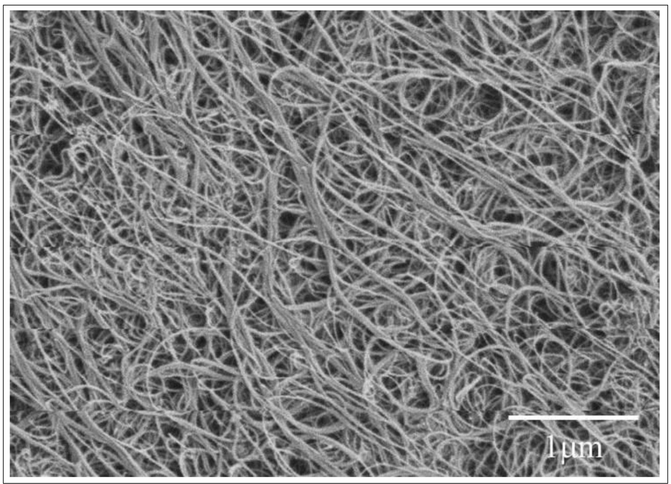

Fig. 9. SEM morphology of as- received Multi-Walled Carbon Nanotubes (MWCNTs) (51).

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

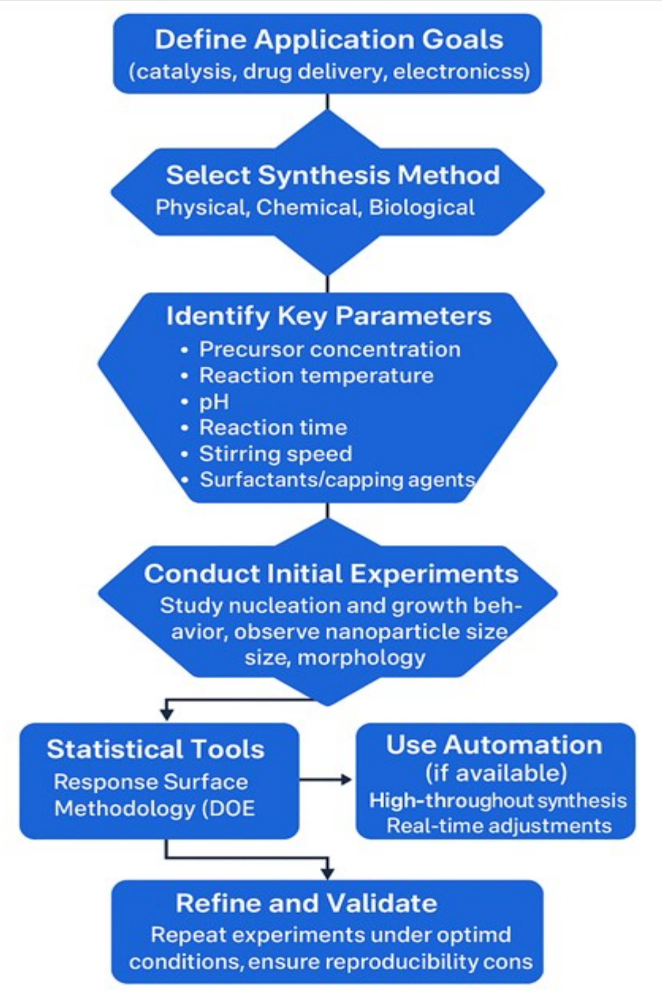

Fig.10. Optimisation processes in nanomaterial synthesis.

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 (TiO_2), 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).

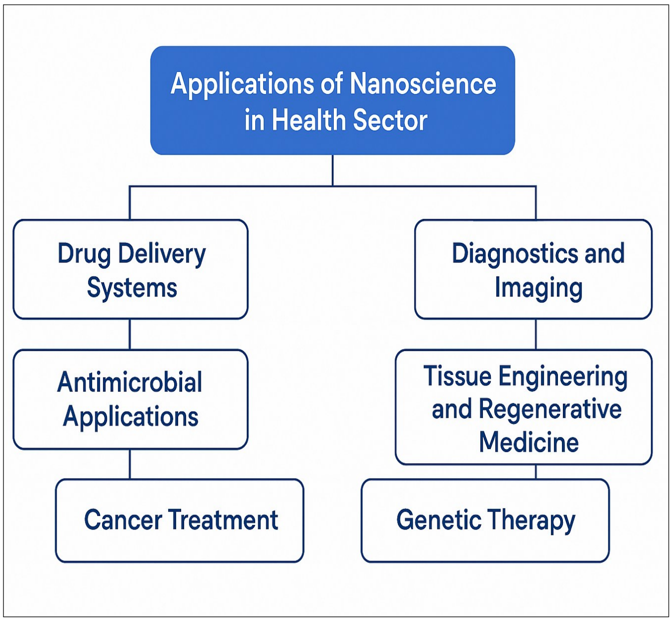

Fig.11. Applications of nanoscience in health sector.

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

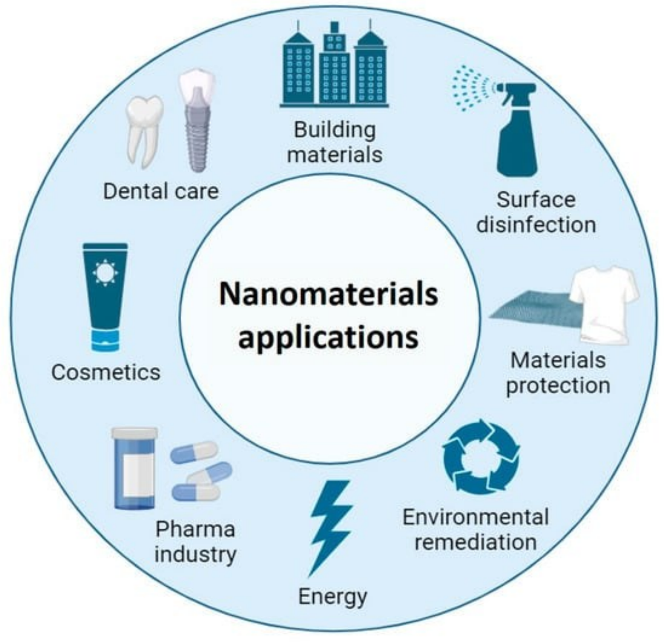

Fig. 12. Several nanomaterial applications (69).

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 scale (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.

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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

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