chemosensors

MDPI

Review

Synthesis and Modification of Magnetic Nanoparticles for Biosensing and Bioassay Applications: A Review

Soledad Carinelli, Maximina Luis-Sunga *, José Luis González-Mora and Pedro A. Salazar-Carballo

Laboratory of Sensors, Biosensors and Advanced Materials, Faculty of Health Sciences, University of La Laguna, Campus de Ofra s/n, 38071 La Laguna, Tenerife, Spain; scarinel@ull.edu.es (S.C.); jlgonzal@ull.edu.es (J.L.G.-M.); psalazar@ull.edu.es (P.A.S.-C.)

* Correspondence: mluissun@ull.edu.es

Abstract: Biosensors are analytical devices that use biological interactions to detect and quantify single molecules, clinical biomarkers, contaminants, allergens, and microorganisms. By coupling bioreceptors with transducers, such as nucleic acids or proteins, biosensors convert biological interactions into electrical signals. Electrochemical and optical transductions are the most widely used methods due to their high detection capability and compatibility with miniaturization. Biosensors are valuable in analytical chemistry, especially for health diagnostics, as they offer simplicity and sensitivity. Despite their usefulness, challenges persist in immobilizing biorecognition elements on the transducer surface, leading to issues such as loss of sensitivity and selectivity. To address these problems, the introduction of nanomaterials, in particular magnetic nanoparticles (MNPs) and magnetic beads, has been implemented. MNPs combine their magnetic properties with other interesting characteristics, such as their small size, high surface-to-volume ratio, easy handling, and excellent biocompatibility, resulting in improved specificity and sensitivity and reduced matrix effects. They can be tailored to specific applications and have been extensively used in various fields, including biosensing and clinical diagnosis. In addition, MNPs simplify sample preparation by isolating the target analytes via magnetic separation, thus reducing the analysis time and interference phenomena and improving the analytical performance of detection. The synthesis and modification of MNPs play a crucial role in adjusting their properties for different applications. This review presents an overview of the synthesis and surface modifications of magnetic nanoparticles and their contributions to the development of biosensors and bioassays for their applications across different areas. The future challenges of MNP synthesis and integration in assays are focused on their stability, multiplex detection, simplification and portability of test platforms, and in vivo applications, among other areas of development.

Keywords: magnetic nanoparticles; biosensor; bioassay; functionalization; nanomaterial synthesis; electrochemical detection; optical detection

Citation: Carinelli, S.; Luis-Sunga, M.; González-Mora, J.L.; Salazar-Carballo, P.A. Synthesis and Modification of Magnetic Nanoparticles for Biosensing and Bioassay Applications: A Review. *Chemosensors* **2023**, *11*, 533. https://doi.org/10.3390/chemosensors11100533

Academic Editors: Christos Kokkinos and Barbara Palys

Received: 18 July 2023
Revised: 11 September 2023
Accepted: 21 September 2023
Published: 10 October 2023

1. Introduction

In recent decades, biosensors have gained the attention of the research community and have improved the early/high sensitivity detection of different analytes in diverse application fields. A biosensor is an electronic device used to transform a biological interaction into an electrical signal that is processed by the transductor [1]. Among these approaches, electrochemical transduction has notable advantages, particularly its remarkable simplicity and sensitivity. This sensitivity can be further enhanced by introducing (bio)catalytic labels into the transducer or into the bioreceptor-target complex, amplifying the detection signal [2]. Other benefits include their potential for miniaturization, the low cost of production, multiplexed detection, and that they do not require expensive instrumentation for read-out [3]. As a result of these advantages, today, such technology is gradually supplanting standard sophisticated techniques, and they are set to become a vital tool in healthcare and other

application areas [4–6]. Undoubtedly, the most important biosensor, with a high impact on the health and control of diabetes, is the glucometer [7], and recent advancements have enabled the measurement of glucose from interstitial fluids just underneath the skin in continuous mode, avoiding the need to prickle the finger constantly to obtain a blood sample. However, in recent years' new advances and applications in various fields have been achieved; for example, in the detection of volatile organic compounds (VOCs) [8,9].

Another example where biosensors will have an important impact is in the diagnosis of infectious diseases (dengue, malaria, and chikungunya fever) [10]. According to the World Health Organization guidelines, the standard methods for these infections include microbiological isolation, serological tests, and molecular techniques such as polymerase chain reaction (PCR) [11,12]. However, although PCR is the most convenient method due to its high sensitivity and relatively short analysis time, it has an elevated cost of equipment and supplies. On the other hand, it requires specialized skills personnel for the execution and interpretation of results, which makes its use in routine analysis difficult and its integration into point-of-care (PoC) systems complicated. Moreover, they are prone to generating false positives due to nonspecific amplifications.

To overcome these problems, user-friendly, low-cost, and fast methods are still needed. In this context, the development of more efficient assays, including (bio)sensors, has the potential to significantly contribute to the development of enhanced and more effective analytical tools for biomedical diagnosis [13,14]. The main drawback of conventional nonstructured biosensors is associated with the proper immobilization of the biocatalytic or biorecognition element on the surface of the transducer. Non-oriented immobilization of biomolecules may produce reusability and reproducibility problems, and low sensitivity and selectivity due to the loss of catalytic activity or biorecognition reaction, which in turn hinders the electron transfer reaction and reduces the electrochemical signal. In addition, the stability of biological materials remains one of the main challenges in the development of such devices. Several problems arise from the lack of stability and degradation of the biological elements, leading to decreased sensitivity and accuracy of the biosensor. To address these issues, several strategies can be employed: improving stabilization techniques, controlling storage conditions, selecting more robust biological elements (or engineering them for enhanced stability), and implementing routine maintenance and calibration of biosensors to compensate for any stability loss and ensure consistent performance. To address these issues, different approaches have been introduced such as nanostructuration of the transducer and the utilization of carbon-based nanomaterials, organic polymers, magnetic nanoparticles (MNPs), and magnetic beads (MBs) as solid phases for the recognition/isolation reaction [15].

Nanomaterials, with dimensions ranging from 1 to 100 nm, have played a crucial role in science, technology, and medicine over the past two decades [16]. Their unique characteristics (small size, high surface-to-volume ratio, excellent biocompatibility, biodistribution, outstanding catalytic properties, etc.) offer great possibilities for their integration into new and better devices, analytical methods, and diagnostic tools, among others. [16]. One of the main properties of such materials is that their chemical and physical properties are drastically different from those of their bulk materials and can be tailor-made for a specific task [17,18].

Magnetic nanoparticles offer several significant advantages over other nanomaterials, making them attractive for a variety of markets and applications. The most important of these are listed here:

1. Magnetic properties: Due to their inherent magnetism, MNPs are easily manipulated and controlled by external magnetic fields, which is advantageous in biomedical applications, such as drug delivery and hyperthermia, where localization and targeted delivery are critical.
2. Biocompatibility: Many MNPs, especially those coated with biocompatible materials, such as polyethylene glycol (PEG), surfactants, and proteins, exhibit low toxicity, making them suitable for biomedical applications.

3. Drug delivery: MNPs can be functionalized with biomolecules or specific ligands to carry drugs or therapeutic agents. Magnetic guidance of these nanoparticles can improve the efficiency and precision of drug delivery, improving therapeutic outcomes and minimizing side effects.
4. Biomedical imaging and diagnostics: MNPs have exceptional capabilities for high-resolution imaging and early disease detection. In this regard, MNPs serve as contrast agents in various imaging modalities such as magnetic resonance imaging (MRI), magnetic particle imaging (MPI), magnetic particle spectroscopy (MPS), multimodal PET-MRI, SPECT-MRI, and OI-MRI.
5. Magnetic hyperthermia: MNPs exposed to alternating magnetic fields can generate heat due to hysteresis losses. This property can be used in magnetic hyperthermia treatments for cancer, where targeted heating of tumor cells can destroy them without affecting healthy tissue.
6. Environmental applications: MNPs can be used as sorbents in solid–liquid extraction. Due to their magnetic nature, they can be used for separation, treatment, and remediation processes to remove pollutants and contaminants from water and soil.
7. Nanotechnology integration: MNPs can be easily integrated into existing nanotechnology platforms, allowing them to be used together with other nanomaterials to create hybrid systems with enhanced functionalities, including hybrid analytical methods such as magnetic bioassays and biosensors.
8. Catalysis: MNPs can serve as effective catalysts in various chemical reactions due to their large surface area and unique magnetic properties. They can be easily separated and reused, which makes them attractive for catalytic applications.

Due to these advantages, MNPs have been successfully implemented in multiple areas such as energy and data storage [19,20], biosensing [21], catalysis [22], bioremediation [23], neural stimulation [24], pharmacological liberation [25,26], cancer treatment [27] and clinical diagnosis [14,28]. As mentioned above, the use of magnetic sorbents significantly simplifies sample manipulation by isolating the target by applying an external magnetic field [29,30]. Similar strategies may be integrated into other analytical procedures (protein purification [31,32], remediation [33,34], chromatography [35], atomic absorption spectrometry [36], and electroanalysis [37,38]) to improve the selectivity, sensitivity, and time for results [39]. However, the numerous advantages of nanomaterials are balanced by challenges related to safety, cost, regulations, and public perception. By implementing thorough safety measures, fostering collaboration, reducing production costs, and promoting education, we can maximize the benefits of nanomaterials while addressing their limitations.

On the other hand, the combination of MNPs and electrochemical read-out methods has allowed the development of new analytical techniques such as enzyme-linked immunomagnetic electrochemical (ELIME) methods [40]. Here, MNPs act as nanosized supports for the immobilization of biomolecules (antibodies, aptamers, and oligonucleotides) and are used for the isolation of the target from complex matrices and its concentration before detection. The utilization of MNPs enhances the effectiveness of analyte isolation and concentration, minimizes matrix effects due to simplified washing and separation procedures, allows faster assay kinetics, improves the sensitivity and limits of detection (LOD), and reduces the time for analysis [41]. Usually, ELIME bioassays are developed in a sandwich-type format, where two specific antibodies are used (capture-Ab and labeled-Ab). The read-out is performed using differential pulse voltammetry (DPV), constant potential amperometry (CPA), linear sweep voltammetry (LSV), or similar electrochemical techniques with screen-printed electrodes (SPEs) as transducers [42]. Moreover, the use of magnetic beads in combination with magneto-biosensing strategies can avoid individual electrode surface modifications with biological elements, which simplify storage and ensure proper pre-concentration of the sample on the transducer by applying a magnet under the working electrode area.

More recently, MNPs have gained great interest in microfluidic systems due to their extensive surface area and remarkable controllable characteristics [18,43]. The integration of MNPs into microfluidic systems improves analytical performance by introducing functionalized magnetic nanomaterials into microchip devices. Sun et al. employed a magnetic nanoparticle-assisted microfluidic system (MNPAMS) for high-recovery separation of low-abundance HeLa cells [44]. The system achieved a recovery ratio of 88.6% by labeling target cells with MNPs by cocultivation and using an additional magnetic field for separation. The MNPAMS offers advantages such as ease of microstructure design and fabrication, low-cost of permanent magnets, and successful cell separation with low damage rate during recovery, enabling further research.

Despite the many advantages of using MNPs, they still present some drawbacks for bioanalytical and biomedical applications. In this context, we have listed some challenges and advised possible solutions to address them.

1. Biocompatibility: Some MNPs may cause adverse reactions or toxicity in biological systems or suffer denaturation of the bioreceptor during the test. Because of this effect, the safe use of MNPs in the human body requires appropriate surface modification/coating and biocompatibility and toxicological testing prior to commercialization.
2. Aggregation: MNPs can aggregate or cluster together, which affects their stability and uniformity, modifying their interaction with biological tissues and leading to unpredictable behaviors, thereby reducing their efficacy. In addition, these phenomena may decrease analytical performance in bioassays, hindering electron transfer reactions or decreasing the number of active sites. Again, surface functionalization with adequate modifiers (silanizing agents, polymers, grafting specific functional groups) or the use of stabilizing solution, when possible, can improve stability and prevent aggregation.
3. Sensitivity and signal-to-noise ratio: Integration of MNPs may affect the test sensitivity and limit their effectiveness in detection systems. In recent years, many different approaches have been proposed to overcome these difficulties, such as the incorporation of (bio)catalytic labels, enzymatic amplifications, proximity ligation assays, nucleic acid-based amplification strategies such as PCR, hybridization chain reaction, rolling circle amplification, etc.
4. Interference with biological molecules: MNPs could interact/interfere with biological molecules, reducing their effectiveness and analytical performance. To overcome these difficulties, careful design of the MNP surface, its coating, and modifications are needed to minimize interference with biological molecules while maintaining their functionality.

The correct design and modification of MNPs offer a plethora of possibilities to create biocompatible and biomimetic surfaces for the biosensing of different analytes [45,46]. MNPs may be synthesized using different methods, grouped into top-down and bottom-up approaches [47,48]. The selection of the synthetic route and their later biofunctionalization are the determining steps to adjust the magnetic properties, phase composition, bio-distribution and biocompatibility, stability, aggregation effects, degradation, toxicity, and size distribution of the MNPs.

In the following section, we discuss (1) the most widely employed synthesis methods for magnetic nanomaterials and (2) their adequate modification and development to address the main challenges and introduce novel properties to MNPs. Special attention is given to the functionalization of nanomaterials, which plays a crucial role in enhancing the sensitivity, chemical stability, catalytic efficiency, and biocompatibility of biosensing platforms. In particular, this review highlights the use of different functionalizing agents, such as chitosan, polyethylene glycol, and silica, along with the widespread application of organic coatings such as polyaniline, polydopamine, polypyrrole, and inorganic coatings.

Moreover, this review delves into the successful applications of MNPs in biomedicine, the environment, and food safety, underscoring their versatility and wide-ranging utility. Each section of the review introduces examples of the synthesis and functionalization methods employed, illustrating their applications in analytical and biomedical fields. In

addition, the present review focuses mainly on the electrochemical applicability of such MNPs and in the design of different biosensors and bioassays (the reader can find other very interesting reviews in the literature focusing on other areas [14,18,23,28,33,43]).

2. Synthesis and Modification of MNPs

2.1. Synthesis of MNPs

Depending on their applications, different synthetic and modification protocols can be used [49,50]. The choice of such methods depends on the specific requirements of the bioassay/application and the desired properties of the MNPs, such as their morphology, size, biocompatibility, stability, and magnetic properties.

Nanoparticle synthesis has become a crucial area of research, unlocking endless possibilities for innovation and applications in various fields. A large number of methods can be found in the literature, although they can be grouped under two general approaches: (1) bottom-up methods, where nanostructures are built from individual atoms, molecules, or smaller building blocks, and (2) top-down methods, where the fabrication of nanostructures starts with the manipulation of bulk materials and is then reduced to the desired nanosized structure. In addition, another interesting classification is based on the synthetic methods used: (1) physical and (2) chemical approaches. In many cases, it is feasible to associate chemical methods with the bottom-up approach and physical methods with the top-down technique. However, it is important to note that this association is not a strict rule and that, in some cases, there may be overlaps or combinations of approaches in the synthesis route. Briefly, we can summarize such methods as follows:

Physical approaches:

1. Vapor Condensation: In this technique, vaporized metal atoms or compounds are rapidly cooled to form nanoparticles through condensation. The size of nanoparticles depends on the temperature, pressure, and cooling rate.
2. Laser Ablation: High-energy laser pulses are used to vaporize a target material, and the ejected material condenses to form nanoparticles. This method allows the synthesis of nanoparticles without the need for chemical reagents.
3. Sputtering: In this process, energetic ions are bombarded onto a solid target material, causing the ejection of atoms and their deposition on a substrate, resulting in the formation of nanoparticles.
4. Ball Milling: This mechanical method consists of grinding and mixing solid materials, which results in the formation of nanoparticles due to high-energy collisions between the particles.

Chemical approaches:

1. Co-precipitation or chemical reduction: In this method, metal ions are dissolved in a solution and reduced to form nanoparticles by the addition of a reducing agent. The size and shape of the nanoparticles can be controlled by adjusting the reaction conditions and stabilizing agents.
2. Solvothermal method: This technique involves the hydrolysis and condensation of metal alkoxides or metal chlorides in a solution to produce a colloidal suspension of nanoparticles. The process allows precise control of nanoparticle composition and size.
3. Thermal decomposition: In this procedure, high temperatures are used to decompose precursors and produce nuclei, followed by their subsequent growth into NPs. Several factors such as temperature, solvent, reactant ratio, reflux time, and seed concentration are important to determine the size and morphology of nanoparticles.
4. Micro-emulsion: Nanoparticles are formed into a stable microemulsion, where the core contains the reaction precursors and the surfactants control the particle size and prevent aggregation.
5. Green synthesis: This approach uses plant extracts or other natural sources as reducing and stabilizing agents to produce nanoparticles. It offers an eco-friendly alternative to conventional chemical methods.

In the following sections, we describe the most employed chemical methods within the bottom-up approaches [17]. Table 1 depicts a small selection of works indicating the synthetic routes, target, and the main analytical parameters. Other protocols under the top-down approach or physical methods can be found in the literature [51].

2.1.1. Co-Precipitation

This procedure involves the addition of an aqueous solution of metal salts to a basic medium of an alkaline agent in the presence of a reductant, resulting in the formation of MNPs (see Equation (1), described for iron-based magnetic particles).

$$2FeSO_4 + N_2H_4 \text{ (reducing agent)} + 4NaOH \rightarrow 2Fe_3O_4 + N_2 + 4H_2O \quad (1)$$

This approach is simple and cost-effective. Due to their scalability, low cost, and user-friendly reaction, these methods are widely used in biosensing applications. The main drawback of this method is the precise stoichiometry, which can lead to the formation of large particles and agglomerates, which can affect their further application.

Another frequently employed synthetic route for magnetite or maghemite (Fe_3O_4 and Fe_2O_3, respectively) nanoparticles involves using an aqueous solution of Fe(II) and Fe(III) salts that is added dropwise to an alkaline (pH~9–12) solution (NaOH, KOH, or NH_4OH) under vigorous stirring. Following the reaction (see Equation (2)), the resulting precipitate is subsequently magnetically decanted and washed with deionized water until neutrality and dried overnight at 60–80 °C.

$$2Fe^{2+} + Fe^{3+} + 8OH^- \rightarrow Fe_3O_4 + 4H_2O \quad (2)$$

The co-precipitation technique has been used in several works during the last ten years [52,53]. This method was employed to synthesize zinc-substituted Fe_3O_4 nanoparticles ($Zn_xFe_{3-x}O_4$) with a spinel structure to create a novel electrochemical nonenzymatic glucose sensing system [54]. For this purpose, a two-step procedure followed by hydrothermal treatment in a microwave field was used to develop modified carbon paste electrodes. The results showed a linear detection range of 0.1 to 2 mM with a LOD of 0.03 mM, and a short response time of less than 3 s, making these NPs a potential nanomaterial for biosensing and magnetic hyperthermia applications. In the same way, the co-precipitation method was used to synthesize Fe_3O_4 nanoparticles and coat them with varying concentrations of polyethylene glycol (PEG), resulting in a smaller particle size and solving the agglomeration phenomenon [55].

Furthermore, the synthesis of $MnFe_2O_4$@chitosan/MWCNTs/PDMS composite films via chemical co-precipitation has also been reported (Figure 1) [56]. The sensing platform was constructed to detect alpha2-macroglobulin (α2-M), which is critical in diabetic nephropathy diagnosis. This synthesis approach yielded numerous sites for highly efficient binding of the α2 m antibody. The results revealed a detection limit of 0.13 ng/mL and a linear range from 10 ng/mL to 100 µg/mL, which is significantly lower than the limit required for clinical assessment. In this work, $MnFe_2O_4$@chitosan NPs were synthesized by chemical co-precipitation and integrated into a biomedical sensing strategy due to the excellent magnetoelectric effect of this material and its interesting properties for building flexible biosensing surfaces. $MnFe_2O_4$@chitosan NPs were mixed (a) with MWCNTs to enhance the electrical conductivity and improve the sensitivity of the biosensor and (b) with PDMS to form a flexible film-based biosensor. On the one hand, the chitosan-coated $MnFe_2O_4$ particles provided biological modification sites for the capture antibody (α2 m antibody). This work showed that the synthesis of ferrite materials such as $MnFe_2O_4$ can be used to manufacture flexible biosensors, which have an enormous impact on biomedical device development.

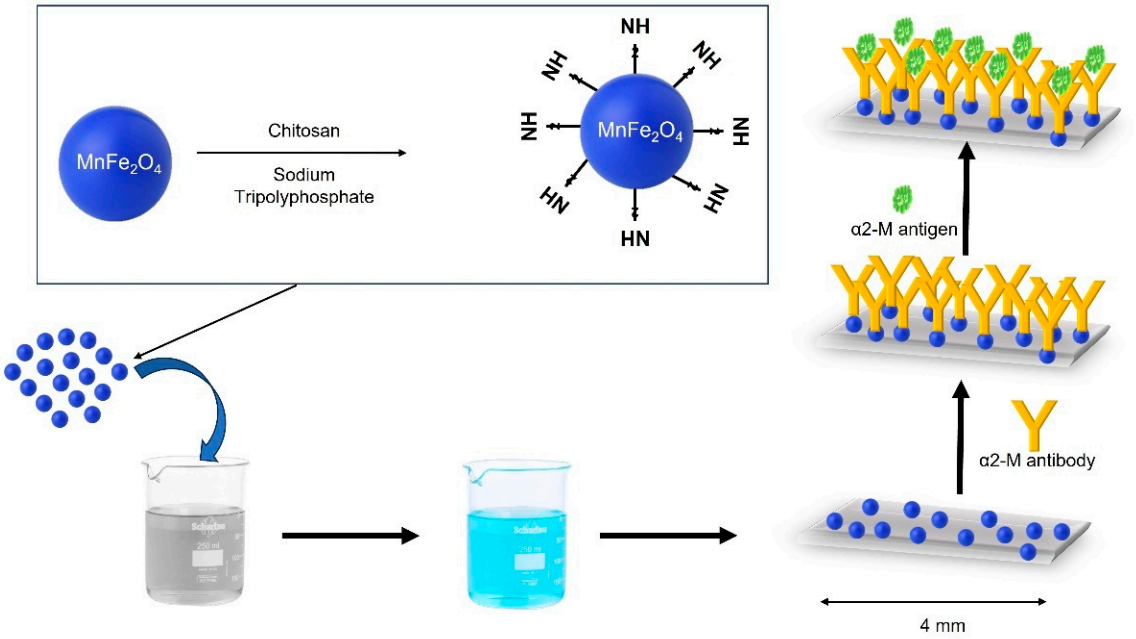

Figure 1. Schematic diagram for the synthesis of the $MnFe_2O_4$@chitosan/MWCNTs/PDMS composite film and its integration in an α2 m sensing platform. Adapted with permission from Ref. [56]. Copyright 2023. Creative Commons license.

Finally, cerium-doped magnetite nanoparticles were synthesized by the co-precipitation method and then used as a co-reactant in a luminol-$K_3Fe(CN)_6$ chemiluminescence system [57]. The effective quenching of metronidazole resulted in a linear detection range of 3.47 to 93.7 µmol/L and a LOD of 0.391 µmol/L. The simple and fast synthesis route combined with the highly sensitive and selective detection of α2 m demonstrates great potential for use of this material in PoC devices. Although these particles have shown superparamagnetic behavior, this property was not taken advantage of by the developed strategy. However, the synthesis of magnetic nanomaterials has great versatility for integration into different detection systems.

2.1.2. Solvothermal Synthesis

This method involves the use of a high-pressure autoclave to carry out the synthesis reaction in a high-boiling-point organic solvent. A common precursor under this approach is iron pentacarbonyl ($Fe(CO)_5$). Usually, such a reactive compound is dissolved in a high-boiling-point organic solvent, such as oleylamine or oleic acid. Then, the solution is heated under high-pressure conditions in an autoclave at a temperature between 200 and 300 °C. In the presence of a reducing agent, the iron pentacarbonyl is reduced to form magnetite (Fe_3O_4) nanoparticles (see Equation (3)). The main advantage of this synthesis is that high temperature and pressure conditions facilitate the formation of MNPs with uniform characteristics, in which particle size and shape can be easily controlled. The reaction time varies from several hours to days. However, excessively long reaction times can lead to the formation of large particles or agglomerates, which can be detrimental to their application in analysis techniques.

$$5Fe(CO)_5 + 20NaOH \rightarrow Fe_3O_4 + 25CO_2 + 10Na_2CO_3 + 10H_2O \quad (3)$$

The solvothermal method was employed by Wang et al. [58] to produce a Fe_3O_4@Cu@Cu_2O nanocomposite with demonstrated peroxidase-like activity. This nanocomposite was able to facilitate the oxidation of common peroxidase substrates such as o-phenylenediamine and 3,3′,5,5′-tetramethylbenzidine in the presence of hydrogen peroxide (H_2O_2), and it also revealed excellent recyclability and reusability without a significant loss of catalytic activity.

Likewise, the same solvothermal method was employed to obtain Au@Fe_3O_4 nanoparticles with the aim of enhancing peroxidase-like activity via a synergistic effect between Fe_3O_4 NPs and gold nanoparticles (Au@Fe_3O_4 NPs) [59]. These nanoparticles were used to create an aptasensor for detecting ochratoxin A (OTA). The designed biosensor exhibited adequate LOD detecting concentrations as low as 30 pg/mL OTA, demonstrating excellent sensitivity due to these NPs. Furthermore, a hybrid nanocomposite, Fe_3O_4@ZIF-8/RGO, was created by a facile one-step solvothermal approach, followed by the fabrication of MOFs (ZIF-8) on the surface of Fe_3O_4 [60]. The developed biosensor displayed exceptional properties for the determination of dopamine in PBS, including a broad linear range of 2.0 nM to 10 μM, and a very low LOD of 0.667 nM. Additionally, the ability to selectively detect dopamine even in the presence of interferents such as ascorbic acid and uric acid highlights its potential for their detection in biological fluids. This result demonstrated the advantages of the Fe_3O_4@ZIF-8/RGO in enhancing the effect of the voltammetric measurement of dopamine.

2.1.3. Thermal Decomposition

This method involves the thermal decomposition of a metal precursor in a high-boiling-point organic solvent in the presence of a stabilizing agent. This technique requires heating the precursor material (iron salts, such as iron chlorides, iron carboxylates, or iron acetylacetonate ($Fe(acac)_3$) to a high temperature in the presence of a solvent. Typically, benzyl alcohol, trioctylamine, or dodecanethiol ($C_{12}H_{25}SH$), which serve as reducing agents and a medium for the thermal decomposition reaction, are used as solvents (see Equation (4)). The solution is heated, usually in the range of 200–400 °C, under a controlled atmosphere (e.g., argon or nitrogen) for several hours. During the heating process, the precursor decomposes to form iron oxide nanoparticles, which are stabilized by the surfactant or stabilizing agents present in the solution.

$$Fe(acac)_3 + 3C_{12}H_{25}SH \rightarrow Fe_3O_4 + 3C_{12}H_{25}SCH_3 + 3CH_3COCH_3 \quad (4)$$

The resulting magnetite nanoparticles, with high-quality and narrow size distributions, are typically coated with a surfactant or stabilizing agent, which can be removed by washing or thermal treatment. As in other methods described above, precise control over the size and shape of the MNPs may be obtained by adjusting the reaction parameters; however, the correct removal of a surfactant or stabilizing agent is a critical point that has consequences in downstream applications.

The synthesis of Fe_3O_4 nanoparticles by thermal decomposition for the development of a sensor composed of MNPs and cetyltrimethylammonium bromide was reported by Guivar et al. [61]. This sensor operates as a peroxidase mimetic system and could achieve an amperometric detection limit of H_2O_2 of 103 μmol/L and a linear response in the range from 100 μmol/L to 1.8 mmol/L (R^2 = 0.994) with a sensitivity of 16 nA/mol L. Moreover, a narrow and monodisperse size distribution (diameter of 4.8 ± 0.6 nm and polydispersity index: 13%) was achieved by this synthesis. The absence of agglomeration indicated high stability in inorganic media, and the tested interfering agents (K^+, Na^+, Cl^-, Mg^{2+}, Ca^{2+}, and uric acid) verified the selectivity toward H_2O_2, being comparable with some enzyme-based biosensors. The peroxidase biomimetic sensor presented a performance comparable to that of some peroxidase-based biosensors, but without any concern about the lack of stability or loss of catalytic activity that occurs after enzyme immobilization.

2.1.4. Microemulsion Method

This method involves the use of a microemulsion, which is a dispersion of two immiscible liquids (usually oil and water) stabilized by a surfactant. The microemulsion method can be used to synthesize a variety of MNPs, including iron oxide, cobalt oxide, and nickel ferrite nanoparticles. The precursors of the MNPs are dissolved in one of the phases of the microemulsion, typically the oil phase. The surfactant stabilizes the resulting droplets of the oil phase in the water phase, creating a highly homogeneous reaction environment

for NP synthesis. Since the reaction takes place in the confined space of the droplets, the resulting MNPs present a uniform size. The resulting particles can be coated with various organic and inorganic materials to enhance their stability and biocompatibility, making them a valuable tool in various fields, including biomedicine, electronics, and catalysis.

Overall, the microemulsion method is a versatile and effective technique for synthesizing monodisperse MNPs with controlled size, microstructure, and properties [62]. However, in some cases, NPs prepared by the microemulsion method present a low yield, difficult scale-up procedures, and problems related to the effect of residual surfactant.

The microemulsion method has been 'tili'ed by Rivas et al. [63] to produce stable, monodisperse core–shell Fe@Au NPs with good morphological and structural properties. This one-pot successive reaction method in microemulsions can easily obtain nanoparticles with a diameter of approximately 6 nm and a 3 nm Fe core, with a saturation magnetization of 1.13 emu/g. The resulting Fe@Au nanoparticles exhibit excellent stability even in the air after magnetic separation, indicating a proper coating of the largely reactive iron core by the Au shell. Furthermore, the same technique was employed to develop a new type of multifunctional nanomaterial, FePt/Fe_3O_4-CdSe heteronanostructures coated in silica, which displayed both luminescent and magnetic properties [64]. The reverse micelle microemulsion technique was used to coat the heteronanostructures, combining magnetic and luminescent properties, making them water dispersible, highly colloidally stable, and capable of emitting photoluminescence in the blue–green region. All these properties confirm that this bifunctional nanomaterial has great potential for (bio)sensing/biomedical applications.

2.1.5. Green Synthesis

This method involves the use of natural resources, such as plants, bacteria, and fungi, to synthesize MNPs [65]. This synthesis pathway is eco-friendly and avoids the use of toxic solvents and hazardous reagents, making it a sustainable alternative to traditional synthesis methods. Nevertheless, parameter optimizations (pH, temperature, and reaction time) are required to improve the reproducibility and stability of the particles. In addition, the use of natural resources can lead to batch-to-batch variation in the properties of the synthesized MNPs, which can be a challenge for large-scale production. In the near future, the advancement and refinement of more efficient, scalable, and reproducible green synthesis protocols are expected to significantly contribute to the sustainable production of nanoparticles for a wide range of applications, including biomedical imaging, drug delivery, and environmental remediation [66], reducing the environmental impact associated with traditional synthesis methods.

A green and ultrafast technique was developed for synthesizing iron oxide MNPs using a high-energy sonochemical approach, considering the amplitude (energy) of the ultrasound probe and sonication time [67]. This combination enables the development of an innovative one-minute green synthesis process, resulting in a significant reduction in energy consumption, solvents and reagents, time, and the generation of waste materials. These MNPs were evaluated for mercury detection in water and as a carrier on which to anchor polyclonal antibodies against TRIB2 protein (Tribbles Pseudokinase 2) as part of an immunoprecipitation assay. Additionally, a green approach was also applied to enhance electrode electron transfer via the deposition of carbon and silver on the Fe_3O_4 NP core, resulting in the formation of core–shell Fe_3O_4@C@Ag NPs on the electrode surface [68]. Core–shell Fe_3O_4@C@Ag NPs were synthesized and employed to improve the electron transfer between enzymes and the electrode surface. The biosensor exhibited high sensitivity with a value of 0.0346 μA/mM cm and a LOD of 0.5 mM. The excellent biosensor performance was attributed to the large surface area of the NPs, which allows effective loading of HRP and high electron communication capacity. Last, Ahmadian-Fard-Fini et al. [69] aimed to develop a novel photoluminescence and magnetic nanocomposite for the detection of bacterial pathogens based on magnetite–carbon dots. Carbon quantum dot NPs were obtained using extracts of lemon, grapefruit, and turmeric. These nanoparticles were employed as a nontoxic sensor for the detection of *E. coli* bacteria, and it was observed

that the photoluminescence of the nanocomposite was quenched by increasing the quantity of bacteria detection confirming its effectiveness for biosensor applications.

Table 1. Electrochemical sensor performance comparison with magnetic nanoparticles: categorized based on synthesis methods.

Sensor Material	Synthesis Method	Analyte	LoD (nM)	Linear Range	Reference
$Zn_xFe_{3-x}O_4$	co-precipitation	glucose	0.03 mM	0.1 to 2 mM	[54]
$MnFe_2O_4$@chitosan/MWCNTs/PDMS	co-precipitation	alpha2-macroglobulin	0.13 ng/mL	10 ng/mL to 100 µg/mL	[56]
Cerium-doped magnetite nanoparticles	co-precipitation	metronidazole	0.391 mol/L	3.47 to 93.7 µmol/L	[57]
Fe_3O_4@Cu@Cu_2O	solvothermal	H_2O_2	0.2 mM	0.4 to 1.5 mM	[58]
Au@Fe_3O_4	solvothermal	ochratoxin A	30 pg/mL	0.5–100 ng/mL	[59]
Fe_3O_4@ZIF-8/RGO	solvothermal	dopamine	0.667 nM	2.0 nM to 10 µM	[60]
Fe_3O_4@CTAB	thermal decomposition	H_2O_2	103 µmol/L	100 µmol/L to 1.8 mmol/L	[61]
Iron oxide MNPs	green synthesis	mercury	0.004 ppm	0.030 to 0.060 ppm	[67]
silica/Fe_3O_4@C@Ag	green synthesis	cholesterol	0.5 mM	0.5 to 22.5 mM	[68]

2.2. Surface Modifications of MNPs

The appropriate modification of MNPs confers them with special properties for their integration in different applications such as solubility, biocompatibility, low toxicity, stability against oxidation processes, and electrical properties. The chemical stability, hydrophobicity, catalytic properties, and biocompatibility of NPs can be improved by conjugating different organic and inorganic chemical compounds, such as silica, gold, platinum, ceria, chitosan, polyethylene glycol, polyvinyl alcohol, poly(lactic-co-glycolic acid), and polyethylenimine), during or after the synthesis of NPs [70]. Table 2 depicts a selection of works categorized by the surface modification/coating, target, and the main analytical parameters.

2.2.1. Organic Coatings/Ligands

MNP synthesis based on organic coatings/ligands may confer hydrophobic properties to the nanomaterial. Therefore, additional modifications are needed to improve its dispersion in water-based media, such as the ligand exchange method or core–shell structures. Additionally, organic ligands can provide new functional groups for conjugation with bioreceptors such as antibodies or peptides, enabling specific targeting of cells or biomolecules [71]. Within the current approach, the biorecognition element can be modified with fluorescent probes (e.g., fluorescein, rhodamine, and cyanine) [72] for sensing applications. These fluorescent dyes emit light when they are excited by a specific wavelength, allowing the detection of biomolecules in biological samples with high sensitivity and specificity. Particles synthesized by this technique have been applied in several areas, including disease diagnosis, drug discovery, and imaging diagnosis.

A very interesting approach for core–shell methodology is the use of organic polymers, such as polydopamine (pDA), polypyrrole (PPy), polyaniline (PANI). MNPs coated with conductive polymers (e.g., PANI and PPy) can be used for biosensing applications [53]. For example, DNA or aptamer probes immobilized on polypyrrole or polyaniline-modified transducers/nanoparticles [73–75] may offer a conductive coating with high stability and biocompatibility for biorecognition.

Chitosan

Recent MNP functionalization with chitosan (CS) has been reported, including the creation of a chitosan-functionalized graphene (CG) material via the combination of car-

boxylic chitosan and graphite using the ball milling technique [76]. The incorporation of nitrogen, derived from chitosan, significantly enhances the catalytic activity, improving its sensing performance and creating a favorable environment for enzyme immobilization. Moreover, this cationic polymer confers hydrophilic properties and biocompatibility to the nanoparticle core. For example, Fe_3O_4 MNPs were added to the CG to create multifunctional nanocomposites with potential use as magnetic resonance imaging agents and in vivo biosensors. Then, glucose oxidase was immobilized on the CG via covalent binding, resulting in a biosensor with high sensitivity (5.658 $mA \cdot mM^{-1} \cdot cm^{-2}$), a low detection limit of 16 µM, and a linear detection range of up to 26 mM.

Similarly, Peng et al. [77] also reported a chitosan-functionalized nanocomposite for glucose determination. This nanocomposite consists of magnetic nanoparticles, chitosan, β-cyclodextrin (Fe_3O_4-CS-CD), and multiwalled carbon nanotubes. The nanoparticle synthesis and the electrode modification are represented in Figure 2. The results showed that the abundant amino and hydroxyl groups of chitosan combined with β-cyclodextrin conferred to the electrode excellent properties such as good biocompatibility, nontoxicity, and high mechanical strength, which are necessary for enzyme immobilization. This glucose sensor, tested on human serum samples, presented a low detection limit (19.30 µM), broad linear range (40 µM to 1.04 mM), high sensitivity (23.59 $\mu A \cdot mM^{-1} \cdot cm^{-1}$), excellent selectivity, and long-term stability.

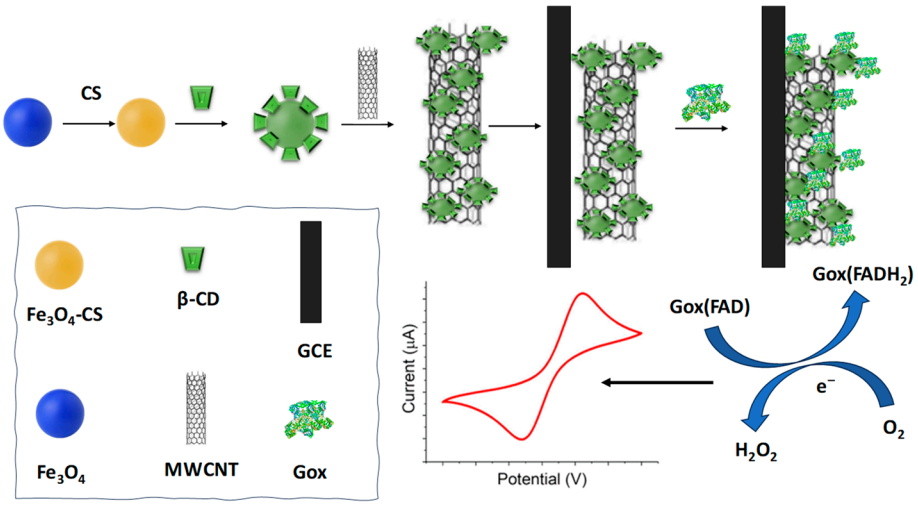

Figure 2. Schematic illustration of the fabrication of the glucose biosensor. Reproduced with permission from Ref. [77] Copyright 2020. Electroanalysis.

Moreover, a functionalized electrochemical biosensor for the determination of TGs was reported by Di Tocco et al. [78]. The biosensor developed in this study consisted of lipase immobilization on chitosan-coated magnetic nanoparticles (MNPs) dispersed in a matrix of multiwalled carbon nanotubes/pectin (MWCNT/Pe) modified with copper oxide on a GCE. The sensitivity of the sensors is significantly enhanced by employing a modified electrode incorporating electroactive materials. Furthermore, the presence of chitosan-coated nanomaterial greatly facilitates the immobilization of lipase onto the electrode surface, optimizing its functionality. According to theoretical studies, the detection and quantification limits were 3.2–3.6 mg/L and 9.6–11 mg/L, respectively, confirming its viability for determining TGs in human serum clinical samples.

Poly-(Ethylene Glycol)

Poly (ethylene glycol) (PEG) is a nonionic polyether compound with a wide application in various fields, including food products, cosmetics, and pharmaceuticals, due to its exceptional properties as a solvent, plasticizer, surfactant, base, and lubricant [79]. PEG offers several advantages, such as prolonging the circulation time of drugs and reducing their immunogenicity. By increasing the molecular weight (MW) of pharmaceutical

products such as proteins or peptides, PEG decreases renal clearance and protects them from proteolytic degradation, thus altering their pharmacokinetic profile. In addition, PEG improves drug solubility by creating a water cloud around the polymer. In particular, the use of PEG to modify the surface of MNPs has been found to decrease protein adsorption, which reduces their recognition by the mononuclear phagocytic system [80] and increases their blood circulation and biodistribution [81]. Moreover, PEG-modified MNPs enhance biocompatibility and hydrophilicity and improve the immobilization of other modifiers such as silver NPs [82], antibodies [83], and enzymes [84].

A recent study reported the functionalization of Fe_3O_4@Au nanoparticles with PEG and hyaluronic acid (HA) for the development of an immunosensor for brusellosis detection [85]. Fe_3O_4@Au@PEG@HA-modified electrodes demonstrated high selectivity, sensitivity for antibody detection (LOD of 0.36 fg/mL; response range from 10 fg/mL to 10 pg/mL), and high capacity to prevent biofouling. Despite the good results obtained, the coating of the nanoparticles with PEG was insufficient, as was the prevention of nonspecific protein absorption. Similarly, Shin et al. [86] developed a colorimetric assay for the detection of H_2O_2 and glucose using Fe_3O_4 magnetic nanoparticles functionalized with PEG ligands. PEG functionalization led to a significant increase in the catalytic activity of the MNPs, which act as enzyme mimetics with peroxidase-like activity. Furthermore, PEG ligands prevent self-aggregation of the nanoparticles and facilitate the transfer of H_2O_2 and diammonium salt substrate toward the MNPs via hydrophilic interactions. The glucose bioassay using this functionalized system exhibited a limit of detection of 3 μM, demonstrating high potential for practical applications.

In addition, PEG was also utilized as a mediator to prepare a novel PEG-mediated APBA (m-aminophenylboronic acid)-functionalized magnetic nanomaterial (APBA-PEG-MN) for detecting *Staphylococcus aureus* by using magnetic separation and fluorescence analysis (Figure 3) [87]. The LOD in several matrices such as fruit juice, spinach, pure culture, and pool water were 270 CFU/mL. APBA-PEG-MNs confirmed good stability and could maintain good capture efficiency at 4 °C and different pH values. The collected results indicate that the magnetic separation–fluorescence sensor system can achieve fast, accurate, and specific detection of *S. aureus*.

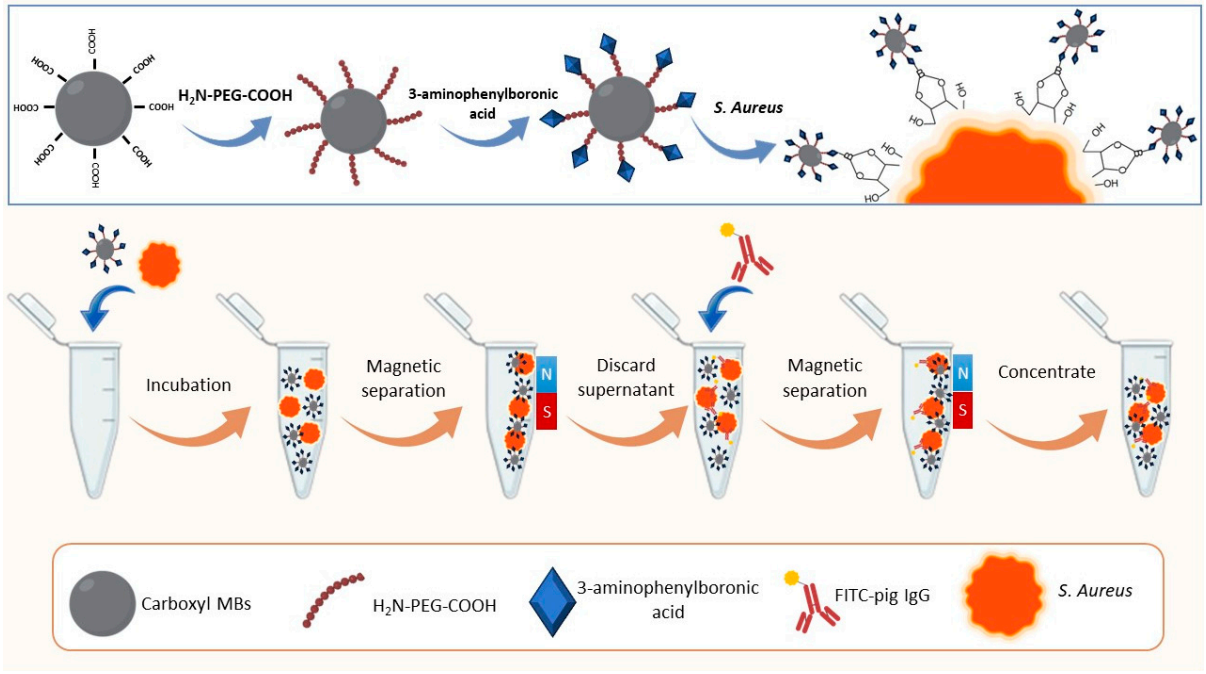

Figure 3. Schematic diagram of fluorescence assays combined with APBA-PEG-MNs for S. aureus detection. Adapted with permission from Ref. [87]. Copyright 2022. Microchemical Journal.

Polypyrrole (Ppy)

Polypyrrole polymers have been studied as coating materials because of their high conductivity and potential use as supports for immobilizing enzymes and as substrates for cell adhesion. Ppy has also demonstrated its usefulness in the development of electrochemical sensors and in biomedical applications such as hyperthermia. However, one of the challenges in the synthesis of NPs composed of a single inorganic core and polymer shell is the control of the thickness layer, whose aggregation problems during synthesis can become a limitation for certain applications. Synthesis strategies for iron oxide cores and Ppy shells have involved emulsion polymerization by using micelles as templates to produce iron oxide@Ppy core–shell nanoparticles [88]. The thickness of the shell can be easily adjusted, obtaining NPs with magnetic core and conductive shell properties that can be promising for their use as photothermal agents and electrochemical biosensors. Moreover, Ppy and chitosan-coated Fe_3O_4 were electrochemically polymerized onto pencil graphite electrodes and used as a platform to immobilize glucose-6-phosphate dehydrogenase for chronopotentiometric detection of glucose-6-phosphate (G6P) [89]. The advantages of Ppy are that it can be used in a neutral pH region, and it is stable enough to be polymerized onto different substrate materials. The results exhibited a good linear response (0.0025–0.05 mM) and high selectivity and recovery, making this biosensor suitable for G6P measurements. Additionally, a photothermal biosensor based on polypyrrole NPs was reported for C-reactive protein detection [90]. This biosensor allowed for dual temperature and pressure readouts for the detection of the protein. The Ppy study confirmed the easy polymerization using pyrrole and Fe^{3+}, efficient light-to-heat conversion due to strong absorption in the near-infrared region, high photothermal stability, and good reproducibility. These properties demonstrated that this dual-mode biosensor has significant potential for PoC testing and biomarker detection.

Polyaniline (PANI)

Polyaniline is a conductive polymer that presents abundant amino groups. The PANI polymeric matrix promotes electron transfer, a property that makes them nanomaterials of great interest for integration into platforms.

PANI was recently utilized for the synthesis of polyaniline–iron oxide magnetic nanohybrids for the amperometric detection of catechol [91]. The conjugated structure of PANI, along with its electrical and proton conductivity in acidic media, provides efficient electron transfer for catechol oxidation and stability. This sensor demonstrated high sensitivity, a low detection limit, and successful recovery of catechol from tap water samples. In addition, a new sensing platform employing Fe_3O_4@PANI NPs has been synthesized for the determination of creatinine in biological fluids [92]. The Fe_3O_4@PANI NPs are hydrophilic and stable, revealing a detection limit of 0.35 nmol/L. This nanomaterial provides many functionalized sites where creatinine molecules can bind by hydrogen bonding with the amino groups of the PANI matrix. Furthermore, PANI/magnetic graphene (MG) composites were also synthesized with the aim of immobilizing laccase, a multicopper polyphenol oxidase used to determine phenols in food, environment, and biological fluids (Figure 4) [93]. The obtained biosensing platform showed superior electrical properties, high sensitivity between the linear ranges of 0.4–337.2 μM, and a detection limit of 2.94 μM. These results hold great potential for the prepared biosensor as a phenolic biosensor in real water samples.

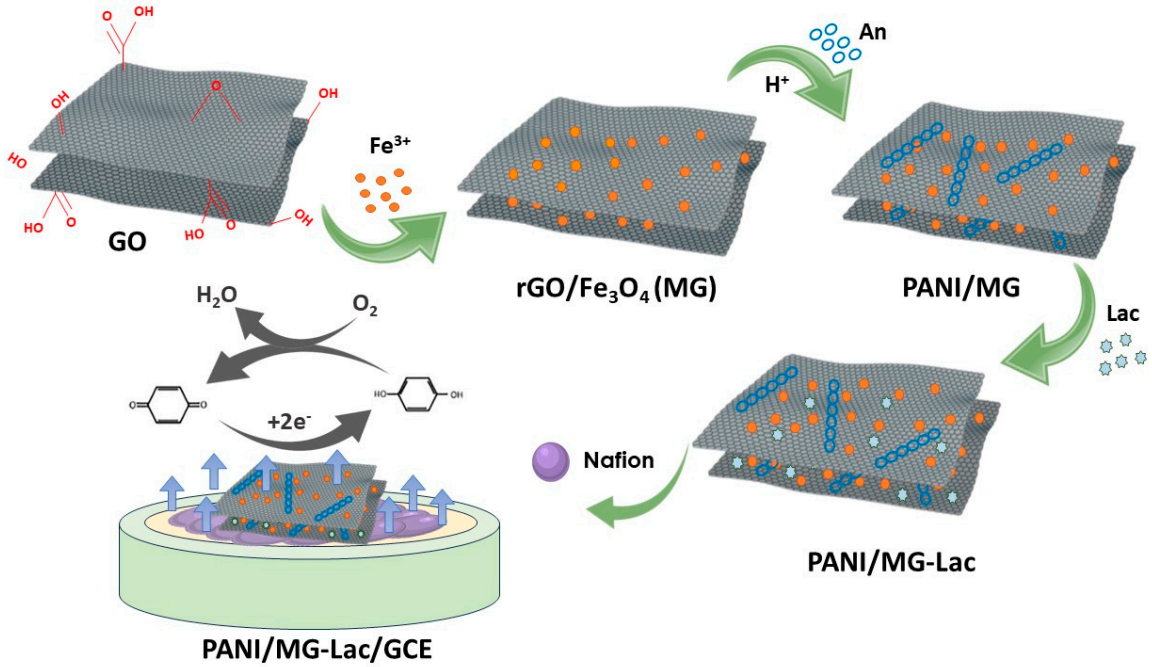

Figure 4. Schematic illustration of the synthesis of polyaniline/magnetic graphene-Lac-GCE, along with the enzymatic oxidation of hydroquinone using laccase and its subsequent electrochemical reduction on the GCE. Adapted with permission from Ref. [93]. Copyright 2020. Int J Biol Macromol.

Polydopamine (pDA)

The use of polydopamine coating on nanoparticles for biosensing has several advantages. First, polydopamine is a biocompatible material that does not induce an immune response, making it safe for use in vivo applications. Second, the polydopamine coating increases the stability of the nanoparticles, reducing the possibility of aggregation and being easily deposited on virtually all types of organic and inorganic materials [94]. Third, the coating enhances the ability of nanoparticles to bind to biological molecules, improving the sensitivity and selectivity of biosensors. Finally, the coating can be easily modified to introduce functional groups or biomolecules for specific targeting and detection. The most common method for producing pDA is the oxidation method under slightly alkaline conditions (aqueous solution at approximately pH 8.5). The self-polymerization reaction is mild and does not require complicated instrumentation or harsh conditions. The thickness of the polymer can be easily controlled by adjusting several factors, such as pH, concentration of monomer, presence of copper ions, and reaction time. Many examples of its applications in biomedicine, biosensing, separation methods, and remediation are reported in the literature.

For instance, core–shell glucose oxidase-Au-polydopamine-Fe_3O_4 magnetic bionanoparticles (GOx-Au-pDA-Fe_3O_4 MBNPs) for glucose detection were synthesized by using a one-pot chemical polymerization method [95]. In this system, MNPs permit easy manipulation, PDA provides biocompatibility to sustain the native structure of GOx, and AuNPs facilitate direct electron transfer of GOx. The amperometric results showed a good linear response from 0.02 to 1.87 mM, confirming its great potential for application in biocatalysis and biosensing. Moreover, a magnetoimmunoassay in which core–shell MNPs were modified with polydopamine (MNPs@pDA-Ab) was reported for the detection of *Legionella pneumophila* SG1, a human pathogen that can be found in natural and artificial freshwater systems [96]. To accomplish this, a specific capture antibody was attached to MNPs@pDA and incubated with bacteria. The bacteria were captured and sandwiched between an antibody labeled with horseradish peroxidase (Ab-HRP) and the modified MNPs@pDA. Finally, the MNPs@pDA-Ab-*Legionella pneumophila*-Ab-HRP complex was held by a magnetic field onto the electrode surface. Electrochemical detection

was performed on disposable SPCEs, achieving a LOD of 10 CFU/mL, which is suitable for the analysis of moderately to severely contaminated samples. In addition, other PDA-modified MNPs for the enzymatic biosensing of H_2O_2 in human plasma samples were reported [97]. The proposed strategy, shown in Figure 5, consists of the immobilization of HRP on MNPs@pDA and the electrochemical polymerization of L-arginine and toluidine blue (Tb) onto the GCE surface to obtain HRP/MNPs@pDA/(L-Arg/Tb). The obtained hybrid thin film provides efficient grafting of MNPs@pDA and facilitates the covalent immobilization of HRP due to the presence of many active functionalization sites. The biosensor performance revealed that it was able to reduce H_2O_2 in a range of 0.5 to 30 µM with a limit of detection of 0.23 µM, confirming its high potential for H_2O_2 analysis.

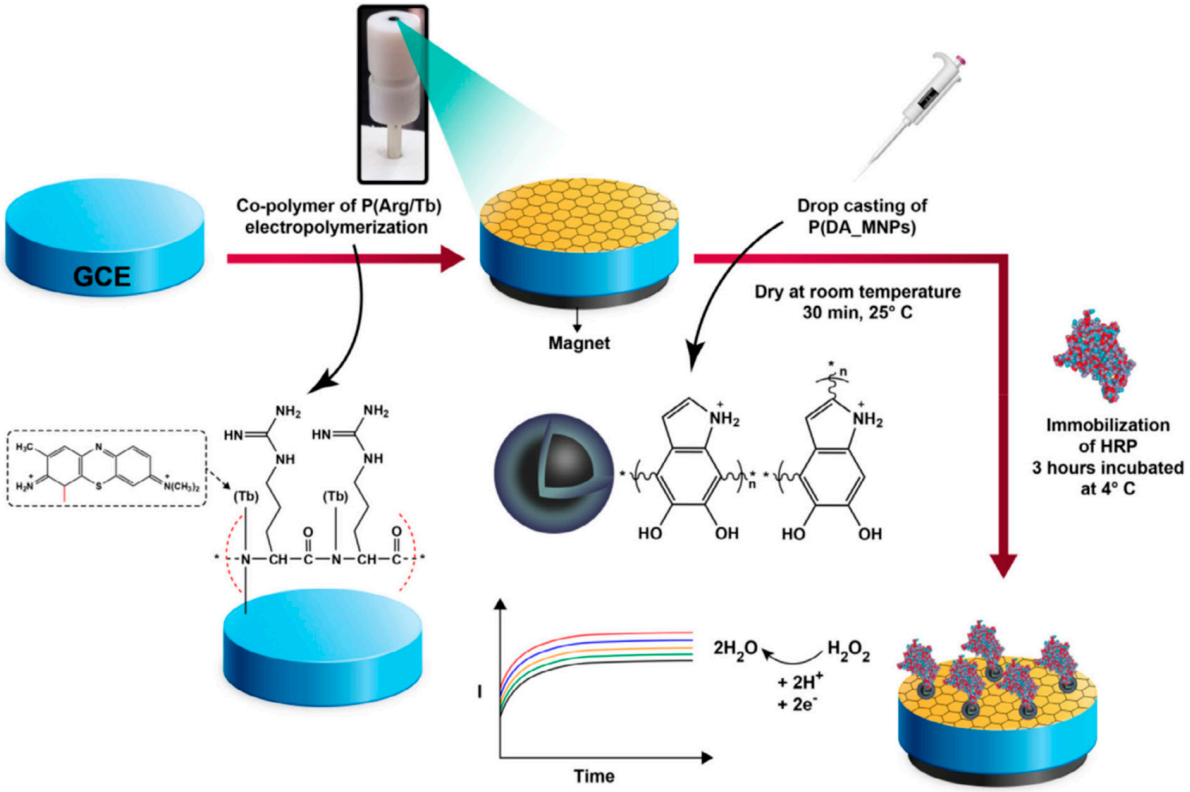

Figure 5. Synthesis procedure of HRP/PDA-MNPs/(L-Arg/Tb) hybrid thin film for H_2O_2 detection. Taken with permission from Ref. [97]. Copyright 2021. Journal of Molecular recognition.

2.2.2. Inorganic Coatings and Modifications

Inorganic coatings (silica, carbonaceous materials, gold, and platinum) also improve catalytic properties and increase the stability and biocompatibility of magnetic nanoparticles while offering unique magnetic, electrical, and optical properties for imaging and sensing applications. For example, iron oxide nanoparticles can be used for magnetic resonance imaging of cells and tissues, while gold-coated nanoparticles can be used for surface-enhanced Raman scattering sensing of biomolecules. The combination of the magnetic properties of NPs with the large surface-to-volume ratio of graphene has also been used to improve the electrocatalytic properties of many magnetic nanocomposites, especially when they are also modified with catalytic materials such as Pt, Co, Ni, and Au. The use of Au-modified MNPs in electrochemical biosensing applications offers the advantage of further modifications with many biomolecules such as nucleic acids (RNA, ssDNAs, and dsDNA), aptamers, and others that may be used for the biorecognition or catalytic conversion of the target analyte.

Silica

Silica coating has been utilized to obtain manganese ferrite nanoparticles for efficient anti-prostate specific membrane antigen (PSMA) immobilization [98]. The $MnFe_2O_4$ nanoparticles were prepared by co-precipitation and then suspended in an ethanol–water solution with tetraethyl orthosilicate to form core–shell structures ($MnFe_2O_4$@SiO_2). The silica coating prevents oxidation and agglomeration, and confers –OH groups for further functionalization. Subsequently, the NPs were linked to a specific antibody to PSMA, validating their potential for improving ELISA-based assays.

Another study related to MNP silica coating is the synthesis of ZnO-capped mesoporous silica nanoparticles for the construction of a microfluidic biosensor for detecting *Salmonella typhimurium* (*S. typhimurium*) [99]. Samples with higher bacterial concentrations revealed a more pronounced color change and higher fluorescence, shown in Figure 6a,b, respectively. Figure 6c,d show the absorbance and fluorescence measurements, respectively, for different bacterial concentrations. In addition, quantitative detection of *S. Typhimurium* was possible in a wide range from 10^2 to 10^7 CFU/mL, with a detection limit of 63 CFU/mL for the colorimetric measurement and 40 CFU/mL for the fluorescent read-out (see Figure 6e,f). The use of mesoporous silica provided a wide surface area, which facilitated the loading of a larger number of (bio)molecules, increasing the sensitivity [99].

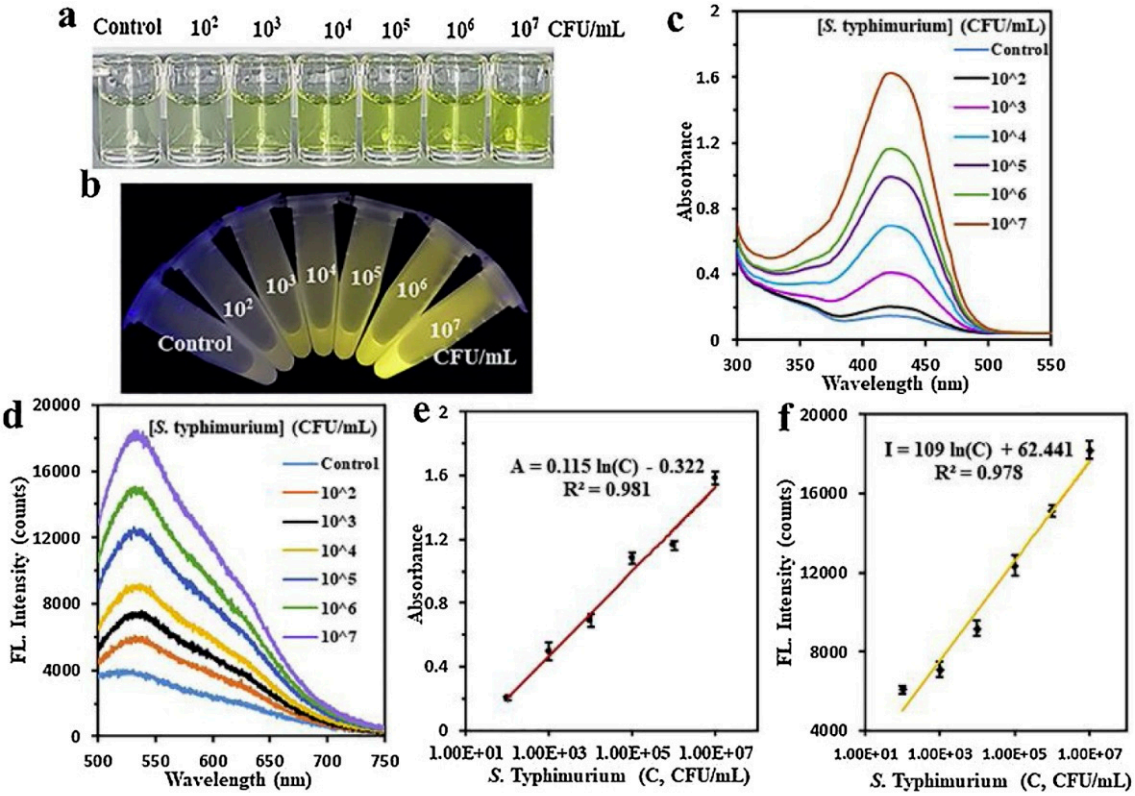

Figure 6. Results of ZnO-capped mesoporous silica NPs as a biosensor platform for *S. Typhimurium* detection: (**a**) absorbance and (**b**) fluorescence photographs; (**c**) absorbance and (**d**) fluorescence spectra; calibration curve of (**e**) absorbance and (**f**) fluorescence intensity. Taken with permission from Ref. [99]. Copyright 2020. Sensors and Actuators B: Chemical.

Finally, silica coating of MNPs was performed to create an effective sensing platform for the immobilization of hemoglobin for multiplex detection of dopamine, uric acid, and folic acid [100]. The procedure consisted of the modification of a carbon paste electrode with MWCNTs and Hb immobilized on silica-coated MNPs, which can enhance Hb stability. This system was successfully evaluated for dopamine, uric acid, and folic acid, showing detection limits of 12, 14, and 18 nM and linear ranges of 1–30.6, 1–286, and 1–369 μM,

respectively. However, the applicability of the biosensor in serum samples was only verified for dopamine analyte.

Gold (Au)

Among the latest research, the modification of NP surfaces with gold NPs was described. Innovative hierarchically porous tridimensional magnetic molybdenum trioxide–pDA-gold functionalized nanospheres (3D mag-MoO_3–pDA@Au nanospheres) have been reported as a multifunctional hybrid composed of plasmonic, semiconductor, and magnetic NPs [101]. This structure has been used to develop a magnetically induced nanogap-enhanced Raman scattering (MINERS) sensing platform for ultrasensitive detection of SARS-CoV-2 (Figure 7a). The introduction of metal Au NPs with complex morphologies and dimensions into SERS detection technology is due to the propensity of these nanostructures to resonantly couple to light with intense scattering at the nanoscale, resulting in increased electromagnetic field strength for "hotspot" generation. By utilizing a magnetic actuation process, the MINERS system enhances Raman signal stability and reproducibility, facilitating the highly sensitive detection of the SARS-CoV-2 spike protein. The sandwich-type immunoreaction carried out resulted in a highly reliable biosensing system, showing that the detection of SARS-CoV-2 spike protein is viable in the range of fg/mL with a broad linear dynamic detection range spanning from 10 fg/mL to 1 ng/mL (Figure 7b,c).

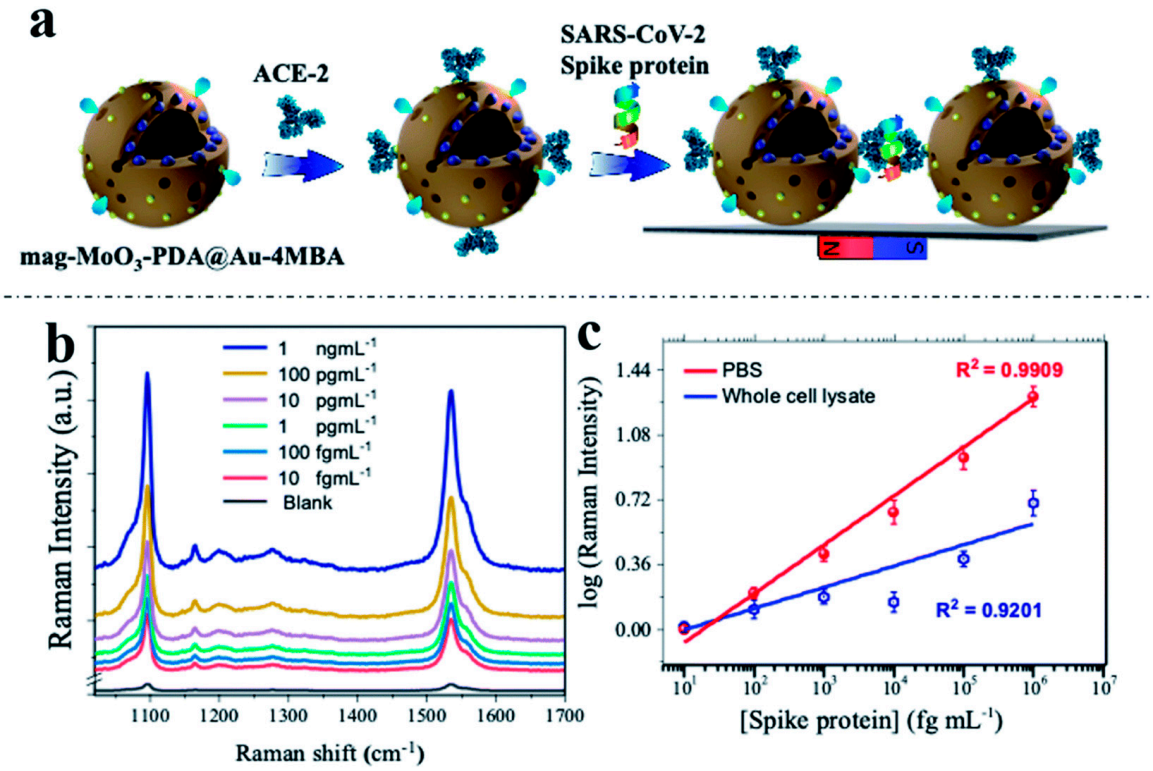

Figure 7. Magnetic nanogap-enhanced Raman scattering (MINERS) bioassay for detection of SARS-CoV-2 spike protein. (**a**) Scheme of the functionalization of the 3D mag-MoO_3–PDA@Au nanostructure with ACE-2, followed by capture/immunoreaction with spike protein on the MINERS substrate. (**b**) MINERS spectra obtained by varying the concentration of SARS-CoV-2 spike protein. (**c**) The calibration plots corresponding to the MINERS bioassay of SARS-CoV-2 spike protein in both PBS and whole cell lysate media. Taken with permission from Ref. [101]. Copyright 2022. Nanoscale Advances Journal.

Another platform based on gold coating consists of a biosensor platform using AuNP-coated magnetic beads for the determination of alkaline phosphatase [102]. Its performance was tested using extracellular vesicle detection, showing its potential as a biosensor in

biological environments. Moreover, an aptamer-based electrochemical biosensor was prepared for the detection of leukemic cancer cells [103]. For this purpose, a thiolated specific aptamer was immobilized on gold-coated magnetic Fe_3O_4 NPs acting as a substrate, and nitrogen-doped graphene as the detection electrode. The gold coating significantly increased the chemical stability and improved the sensitivity. The results showed a linear response from 10 to 1×10^6 cells/mL, which implies a wide dynamic range for leukemic cancer cells, confirming its use for detection in human blood plasma.

In addition, a sandwich-type biosensor with magnetic Fe_3O_4 particles and dithiobis(sulfosuccinimidylpropionate)-modified gold nanoparticles (DTSSP-AuNPs) was developed for dopamine analysis [104]. The method was based on the color change of the DTSSP-Gold NPs and the UV/Vis signal measurement obtaining a detection limit of 10 nM for dopamine. A novel biosensor was also created by using gold nanoparticle-loaded magnetic reduced graphene oxide (MrGO@AuNPs) for detecting the endocrine disruptor bisphenol A (BPA). The biosensor displayed good sensitivity under optimal conditions, with a detection limit as low as 0.141 pg/mL. The design consisted of a combination of BPA aptamer-MrGO@AuNPs and methylene blue-loaded gold nanoparticles to form a stable complex for synergistic signal amplification [105].

Another interesting recent report is a simple method to synthesize AuNPs/bovine serum albumin/Fe_3O_4 composite nanoparticles for electrochemical glucose sensing. In this case, gold NPs contribute to enhancing the electron transfer. High reproducibility, sensitivity, and stability were obtained, with a short response time (0.8 s), linear dynamic range from 0.25 to 7.0 mM, and a low detection limit of 3.54 μM. All these characteristics make this composite a great material for amperometric biosensor design [106]. Alternatively, the specificity of AuNPs in biosensors has been used to increase the sensitivity of quartz-crystal microbalances and as optical transducers for colorimetric biosensors. For this purpose, gold-coated core–shell magnetic NPs were functionalized with a photochemical immobilization technique in order to bind antibodies vertically on the gold surface, which could improve the detection limit of colorimetric biosensors [107]. Finally, Fe_3O_4@Au NPs were used for Pb^{2+} detection obtaining a detection limit of 15 pM. The design of these NPs allows their magnetic control and interference reduction with an increase in the specific surface area, also providing the possibility to detect other heavy metal ions [108].

Platinum (Pt)

Among the platinum-modified magnetic materials that have been reported in recent years, a novel biosensor design based on a 1,1′-oxalyldiimidazole chemiluminescent enzyme immune assay can be found [109]. The system consisted of using a thyroid stimulant hormone (TSH) capture antibody attached to MB and TSH detection antibody-conjugated HRP immobilized on Pt nanoparticles. A detection limit of 0.004 mU/L and a wide dynamic range from 0.013 to 12 mU/L were achieved, confirming that it can effectively quantify TSH in human serum for the early diagnosis of thyroid cancer. In addition, Fe_3O_4-Pt/core–shell nanoparticles (MPt/CS NPs) in the aqueous phase were synthesized using citrate as a surface-stabilizing and reducing agent for their integration in lateral flow immunoassay (LFIA) strips [110]. In this case, the incorporation of Pt into the outer layer of Fe_3O_4 NPs increases the catalytic properties to act as a nanozime. The results show a two-fold increase in sensitivity compared to commercially available Au NP-LFIA (LOD: 3.7 ng/mL) versus the low detection limit of 0.039 ng/mL with the synthesized nanoparticles. It was proven that MPt/CS NPs exhibit high catalytic efficiency, high affinity for the colorimetric substrate, and great potential for PoC testing.

Finally, a layer-by-layer biosensor for the amperometric detection of xanthine was constructed. Its design was based on pDA-modified MNPs coated with four-generation ethylenediamine core polyamidoamine G-4 dendrimers that were decorated with Pt-NPs. The material was deposited on a GCE coated with a graphene oxide-carboxymethylcellulose nanomaterial, and xanthine oxidase was successfully immobilized on the scaffold. Xanthine

could be detected in the range of 50 nM to 12 µM and a LOD of 13 nM was obtained with good reproducibility and repeatability results in real fish samples [111].

Quantum Dots (QDs)

Quantum dots are semiconductor nanoparticles (such as CdSe and InAs, among others) that present unique optical and electrical properties depending on their size. They are brighter, more stable, and have a longer fluorescence lifetime. The emission wavelength of QDs can be tuned by changing their size, enabling multicolor imaging and detection of biomolecules or cells in complex biological samples. QDs have several advantages over traditional organic dyes and other electrochemical labels for bioimaging and biodetection. QDs can enhance the immobilization of biomolecules and labels, facilitate electron transfer, and amplify electrochemical signals. Due to these advantages, QDs can significantly improve the performance of immunological sensors [112]. A very interesting advancement in the use of QDs is multiplexing, where multiple types of QDs with different emission wavelengths/redox responses can be used simultaneously for multiplexed imaging or detection, allowing for the detection of multiple biomolecules or cells at once.

QDs have also been incorporated in the synthesis of magnetic nanomaterials and have been used for the construction of a prototype biosensor for the detection of E. coli in water samples [113]. For this purpose, superparamagnetic Fe_3O_4 NPs were conjugated with an E. coli-specific aptamer, which facilitated the separation of *E. coli* cells due to magnetic separation, obtaining fluorescence intensity values from 100 to 400 µg/mL. The ATmega 328P prototype biosensor developed with this system successfully detected low bacterial counts in water samples, also enabling the possibility of its application to food samples.

Finally, quantum dots were also used to develop an optical sensor platform for the fluorescence determination of histamine [114]. Histamine can be found in contaminated food and is used as a signal of food safety. The system consists of a cysteine-containing peptide incorporated into gold-coated magnetic nanoparticles (MNP@Au NPs) and can be used for the purification and inspection of fish samples. The synthesis of the QDs was performed by the hydrothermal one-pot method, allowing their fluorescence to be efficiently quenched by peptides due to electron transfer exchanges but recovering it with the addition of histamine. The biosensor was investigated on real fish samples, demonstrating a detection range of 0.1 to 100 ppm and a detection limit of 21.15 ppb and showing great potential as a histamine sensor for food protection.

Table 2. Electrochemical sensor performance comparison with magnetic nanoparticles: categorized based on surface modifications/coatings.

Sensor Material	MNPs Surface Modification/ Coatings	Analyte	LoD	Linear Range	Reference
MNP/CG	chitosan	glucose	16 µM	Up to 26 mM	[76]
Fe_3O_4-chitosan-β-cyclodextrin/MWCNTs	chitosan	glucose	19.30 µM	40 µM to 1.04 mM	[77]
CNP-L/CuONP/MWCNT/Pe/GC	chitosan	triglycerides	3.2 mg/L	9.6 to 11 mg/L	[78]
Fe_3O_4@Au@PEG@HA	polyethylene glycol	brucellosis antibodies	0.36 fg/mL	10 fg/mL to 10 pg/mL	[85]
PEG-MNPs	poly ethylene glycol	glucose	3 µM	5 to 1000 µM	[86]
APBA-PEG-MNs	polyethylene glycol	*Staphylococcus aureus*	270 CFU/mL	100 to 100,000 CFU/mL	[87]
PPy and PPy-containing CS/Fe_3O_4	polypyrrole	glucose-6-phosphate	0.002 mM	0.0025 to 0.05 mM	[89]
Ppy NPs	polypyrrole	C-reactive protein	0.45 mg/L	0.75 to 12 mg/L	[90]
Fe_3O_4@PANI	polyaniline	catechol	0.2 nM	-	[91]
Fe_3O_4@PANI NPs	polyaniline	creatinine	0.35 nM	0.02 to 1 µM	[92]
PANI/MG	polyaniline	hydroquinone	2.94 µM	0.4 to 337.2 µM	[93]
GOx-Au-pDA-Fe_3O_4 MBNPs	polydopamine	glucose	6.5 mM	0.02 to 1.87 mM	[95]
MNPs@pDA-Ab	polydopamine	*Legionella pneumophila*	10,000 CFU/mL	10 to 100,000 CFU/mL	[96]
MNPs@pDA	polydopamine	H_2O_2	0.23 µM	0.5 to 30 µM	[97]

Table 2. *Cont.*

Sensor Material	MNPs Surface Modification/ Coatings	Analyte	LoD	Linear Range	Reference
MNP-MSN@CUR@ZnO@pAbs	silica	*Salmonella Typhimurium*	Colorimetric: 63 CFU/mL Fluorescent: 40 CFU/mL	10^2 to 10^7 CFU/mL	[99]
Silica-coated MNPs	silica	dopamine, uric acid and folic acid	12, 14 and 18 nM	1 to 30.6, 1 to 286 and 1 to 369 μM	[100]
3D mag-MoO_3–PDA@Au NS	gold	SARS-CoV-2	10 fg/mL	10 fg/mL to 1 ng/mL	[101]
gold-coated magnetic nanoparticles	gold	leukemia cells	10 cells/mL	10 to 1,000,000 cells/mL	[103]
DTSSP-AuNPs	gold	dopamine	10 nM	0.02 to 0.80 μM	[104]
MrGO@AuNPs	gold	bisphenol A	0.141 pg/mL	0.01 ng/mL to 100 ng/mL	[105]
AuNPs/BSA/Fe_3O_4	gold	glucose	3.54 μM	0.25 to 7.0 mM	[106]
Fe_3O_4@Au NPs	gold	Pb^{2+}	15 pM	50 pM to 1 μM	[108]
Magnetic beads and Pt NPs	platinum	thyroid stimulant hormone	0.004 mU/L	0.013 to 12 mU/L	[109]
MPt/CS NPs	platinum	Human chorionic gonadotropin	0.039 ng/mL	-	[110]
PtNP-PAMAM-MNP/GO-CMC[w]	platinum	Xanthine	13 nM	50 nM to 12 μM	[111]
SPIONs and CdTe-MPA QDs[x]	QD	*Escherichia coli*	100 bacterial cells	100 to 400 μg/mL	[113]
NAC-CQDs[y]	QD	histamine	21.15 ppb	0.1 to 100 ppm	[114]

3. Conclusions

In recent years, several strategies have been developed for the synthesis of magnetic nanoparticles, and the most popular approaches are co-precipitation, solvothermal, microemulsion, and green synthesis methods. Here, we presented the most commonly used synthesis methods, including the appropriate modification or development of new magnetic nanomaterials to overcome the main difficulties and add novel properties to MNPs. In this regard, the functionalization of nanomaterials improves the chemical stability, catalytic efficiency, biocompatibility, and sensitivity for their integration in biosensing platforms. Briefly, the most widespread functionalizing agents presented in this review are chitosan, polyethylene glycol, and silica, among others. In addition, various organic (polyaniline, polydopamine, and polypyrrole) and inorganic coatings (gold, silica, or platinum) are also broadly employed. Despite existing problems such as aggregation, toxicity, and oxidation, advances in MNP research highlight their great potential for biomedical, environmental, and food safety applications, among others. Finally, each section of this review has presented a wide variety of papers illustrating synthesis and functionalization methods and their application in different fields of science, mainly focused on analytical and biomedical aspects. Looking ahead, the future applications and prospects of MNPs are set to continue revolutionizing fields such as diagnostics, drug delivery, and environmental monitoring. These advances may contribute to innovative solutions encompassing trends such as simultaneous detection of multiple analytes, further miniaturization and portability of devices, in-vivo applications, and and increased focus on improving sensitivity and selectivity for detection purposes, among other areas of development.

Author Contributions: Conceptualization, S.C., M.L.-S., J.L.G.-M. and P.A.S.-C.; methodology, P.A.S.-C. and M.L.-S.; investigation, M.L.-S.; formal analysis S.C.; writing original draft preparation P.A.S.-C.; writing-review and editing, S.C., M.L.-S. and J.L.G.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Interreg MAC 2014–2020 program (MAC2/1.1b/352 MacBioidi 2 Project). Soledad Carinelli gratefully acknowledges the financial support of the "Juan de la Cierva Programme" (FJC2020-043734-I) financed by the "Ministerio de Ciencia e Innovación" and the "Agencia Estatal de Investigación" of the Spanish Government.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Nagel, B.; Dellweg, H.; Gierasch, L.M. Glossary for chemists of terms used in biotechnology (IUPAC Recommendations 1992). *Pure Appl. Chem.* **1992**, *64*, 143–168. [CrossRef]
2. Sumitha, M.S.; Xavier, T.S. Recent advances in electrochemical biosensors—A brief review. *Hybrid Adv.* **2023**, *2*, 100023. [CrossRef]
3. Ronkainen, N.J.; Halsall, H.B.; Heineman, W.R. Electrochemical biosensors. *Chem. Soc. Rev.* **2010**, *39*, 1747–1763. [CrossRef]
4. Choi, J.R. Development of Point-of-Care Biosensors for COVID-19. *Front. Chem.* **2020**, *8*, 517. [CrossRef]
5. Pioz, M.J.; Espinosa, R.L.; Laguna, M.F.; Santamaria, B.; Murillo, A.M.M.; Hueros, Á.L.; Quintero, S.; Tramarin, L.; Valle, L.G.; Herreros, P.; et al. A review of Optical Point-of-Care devices to Estimate the Technology Transfer of These Cutting-Edge Technologies. *Biosensors* **2022**, *12*, 1091. [CrossRef]
6. Qazi, S.; Raza, K. Chapter 4—Smart biosensors for an efficient point of care (PoC) health management. In *Smart Biosensors in Medical Care*; Chaki, J., Dey, N., De, D., Eds.; Academic Press: Cambridge, MA, USA, 2020; pp. 65–85.
7. Zafar, H.; Channa, A.; Jeoti, V.; Stojanović, G.M. Comprehensive Review on Wearable Sweat-Glucose Sensors for Continuous Glucose Monitoring. *Sensors* **2022**, *22*, 638. [CrossRef]
8. Calabrese, A.; Battistoni, P.; Ceylan, S.; Zeni, L.; Capo, A.; Varriale, A.; D'Auria, S.; Staiano, M. An Impedimetric Biosensor for Detection of Volatile Organic Compounds in Food. *Biosensors* **2023**, *13*, 341. [CrossRef]
9. Hurot, C.; Brenet, S.; Buhot, A.; Barou, E.; Belloir, C.; Briand, L.; Hou, Y. Highly sensitive olfactory biosensors for the detection of volatile organic compounds by surface plasmon resonance imaging. *Biosens. Bioelectron.* **2019**, *123*, 230–236. [CrossRef]
10. Cheon, J.; Qin, J.; Lee, L.P.; Lee, H. Advances in Biosensor Technologies for Infection Diagnostics. *Acc. Chem. Res.* **2022**, *55*, 121–122. [CrossRef] [PubMed]
11. Muñoz-San Martín, C.; Montero-Calle, A.; Garranzo-Asensio, M.; Gamella, M.; Pérez-Ginés, V.; Pedrero, M.; Pingarrón, J.M.; Barderas, R.; de-Los-Santos-Álvarez, N.; Lobo-Castañón, M.J.; et al. First bioelectronic immunoplatform for quantitative secretomic analysis of total and metastasis-driven glycosylated haptoglobin. *Anal. Bioanal. Chem.* **2023**, *415*, 2045–2057. [CrossRef] [PubMed]
12. Brady, N.; O'Reilly, E.L.; McComb, C.; Macrae, A.I.; Eckersall, P.D. An immunoturbidimetric assay for bovine haptoglobin. *Comp. Clin. Pathol.* **2019**, *28*, 21–27. [CrossRef] [PubMed]
13. Lou, D.; Fan, L.; Jiang, T.; Zhang, Y. Advances in nanoparticle-based lateral flow immunoassay for point-of-care testing. *View* **2022**, *3*, 20200125. [CrossRef]
14. Materón, E.M.; Miyazaki, C.M.; Carr, O.; Joshi, N.; Picciani, P.H.; Dalmaschio, C.J.; Davis, F.; Shimizu, F.M. Magnetic nanoparticles in biomedical applications: A review. *Appl. Surf. Sci. Adv.* **2021**, *6*, 100163. [CrossRef]
15. Naresh, V.; Lee, N. A review on biosensors and recent development of nanostructured materials-enabled biosensors. *Sensors* **2021**, *21*, 1109. [CrossRef] [PubMed]
16. Diez-Pascual, A.M.; Rahdar, A. Functional Nanomaterials in Biomedicine: Current Uses and Potential Applications. *ChemMedChem* **2022**, *17*, e202200142. [CrossRef]
17. Baig, N.; Kammakakam, I.; Falath, W. Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges. *Mater. Adv.* **2021**, *2*, 1821–1871. [CrossRef]
18. Zhong, Z.; He, J.; Li, G.; Xia, L. Recent Advances in Magnetic Nanoparticles-Assisted Microfluidic Bioanalysis. *Chemosensors* **2023**, *11*, 173. [CrossRef]
19. Kumar, N.S.; Suvarna, R.P.; Naidu, K.C.B.; Reddy, B.V.S. 19—Magnetic nanoparticles for high energy storage applications. In *Fundamentals and Industrial Applications of Magnetic Nanoparticles*; Hussain, C.M., Patankar, K.K., Eds.; Woodhead Publishing: Sawston, UK, 2022; pp. 601–618.
20. Salazar-Carballo, P.A.; López-Pérez, M.; Martín-González, M.E.; Hernández-Suarez, F.; Martín-Luis, M.C. Radon Dynamics and Effective Dose Estimation in a Touristic Volcanic Cave: La Cueva del Viento, Tenerife (Canary Islands, Spain). *GeoHealth* **2023**, *7*, e2022GH000704. [CrossRef]
21. Carinelli, S.; Fernández, I.; González-Mora, J.L.; Salazar-Carballo, P.A. Hemoglobin-modified nanoparticles for electrochemical determination of haptoglobin: Application in bovine mastitis diagnosis. *Microchem. J.* **2022**, *179*, 107528. [CrossRef]
22. Ghorbani-Choghamarani, A.; Rabiei, H.; Tahmasbi, B.; Ghasemi, B.; Mardi, F. Preparation of DSA@MNPs and application as heterogeneous and recyclable nanocatalyst for oxidation of sulfides and oxidative coupling of thiols. *Res. Chem. Intermed.* **2016**, *42*, 5723–5737. [CrossRef]
23. Mohammed, L.; Gomaa, H.G.; Ragab, D.; Zhu, J. Magnetic nanoparticles for environmental and biomedical applications: A review. *Particuology* **2017**, *30*, 1–14. [CrossRef]

24. Wu, S.; Li, H.; Wang, D.; Zhao, L.; Qiao, X.; Zhang, X.; Liu, W.; Wang, C.; Zhou, J. Genetically magnetic control of neural system via TRPV4 activation with magnetic nanoparticles. *Nano Today* **2021**, *39*, 101187. [CrossRef]
25. El-Boubbou, K. Magnetic iron oxide nanoparticles as drug carriers: Preparation, conjugation and delivery. *Nanomedicine* **2018**, *13*, 929–952. [CrossRef] [PubMed]
26. Goyal, A.K.; Ramchandani, M.; Basak, T. Recent Advancements, Challenges, and Future Prospects in Usage of Nanoformulation as Theranostics in Inflammatory Diseases. *J. Nanotheranostics* **2023**, *4*, 106–126. [CrossRef]
27. Huang, J.; Li, Y.; Orza, A.; Lu, Q.; Guo, P.; Wang, L.; Yang, L.; Mao, H. Magnetic Nanoparticle Facilitated Drug Delivery for Cancer Therapy with Targeted and Image-Guided Approaches. *Adv. Funct. Mater.* **2016**, *26*, 3818–3836. [CrossRef]
28. Mukhtar, M.; Bilal, M.; Rahdar, A.; Barani, M.; Arshad, R.; Behl, T.; Brisc, C.; Banica, F.; Bungau, S. Nanomaterials for Diagnosis and Treatment of Brain Cancer: Recent Updates. *Chemosensors* **2020**, *8*, 117. [CrossRef]
29. Conde-Díaz, A.; Rodríguez-Ramos, R.; Socas-Rodríguez, B.; Salazar-Carballo, P.Á.; Rodríguez-Delgado, M.Á. Application of polyaniline-based magnetic-dispersive-solid-phase microextraction combined with liquid chromatography tandem mass spectrometry for the evaluation of plastic migrants in food matrices. *J. Chromatogr. A* **2022**, *1670*, 462988. [CrossRef]
30. Molinero-Fernández, Á.; Moreno-Guzmán, M.; López, M.Á.; Escarpa, A. Magnetic Bead-Based Electrochemical Immunoassays On-Drop and On-Chip for Procalcitonin Determination: Disposable Tools for Clinical Sepsis Diagnosis. *Biosensors* **2020**, *10*, 66. [CrossRef]
31. Schwaminger, S.P.; Fraga-García, P.; Blank-Shim, S.A.; Straub, T.; Haslbeck, M.; Muraca, F.; Dawson, K.A.; Berensmeier, S. Magnetic One-Step Purification of His-Tagged Protein by Bare Iron Oxide Nanoparticles. *ACS Omega* **2019**, *4*, 3790–3799. [CrossRef]
32. Peuker, U.A.; Thomas, O.; Hobley, T.J.; Franzreb, M.; Berensmeier, S.; SchÄFer, M.; Hickstein, B. Bioseparation, Magnetic Particle Adsorbents. *Encycl. Ind. Biotechnol.* **2010**, 1–31. [CrossRef]
33. Phouthavong, V.; Yan, R.; Nijpanich, S.; Hagio, T.; Ichino, R.; Kong, L.; Li, L. Magnetic Adsorbents for Wastewater Treatment: Advancements in Their Synthesis Methods. *Materials* **2022**, *15*, 1053. [CrossRef]
34. Maharana, M.; Sen, S. Magnetic zeolite: A green reusable adsorbent in wastewater treatment. *Mater. Today Proc.* **2021**, *47*, 1490–1495. [CrossRef]
35. Rodríguez-Ramos, R.; Socas-Rodríguez, B.; Santana-Mayor, Á.; Salazar-Carballo, P.Á.; Rodríguez-Delgado, M.Á. Sustainable polypyrrole-based magnetic-microextraction of phthalates from jellies and apple-based beverages prior to tandem mass spectrometry analysis. *J. Chromatogr. A* **2021**, *1637*, 461858. [CrossRef]
36. Villafañe, G.; Bazán, V.; Brandaleze, E.; López, A.; Pacheco, P.; Maratta, A. Solid phase extraction of arsenic on modified MWCNT/Fe3O4 magnetic hybrid nanoparticles from copper ores samples with ETAAS determination. *Talanta Open* **2022**, *6*, 100149. [CrossRef]
37. Zhang, M.; Zou, Y.; Zhou, X.; Yan, F.; Ding, Z. Vertically-Ordered Mesoporous Silica Films for Electrochemical Detection of Hg(II) Ion in Pharmaceuticals and Soil Samples. *Front. Chem.* **2022**, *10*, 952936. [CrossRef]
38. Abdulla, M.; Ali, A.; Jamal, R.; Bakri, T.; Wu, W.; Abdiryim, T. Electrochemical Sensor of Double-Thiol Linked PProDOT@Si Composite for Simultaneous Detection of Cd(II), Pb(II), and Hg(II). *Polymers* **2019**, *11*, 815. [CrossRef] [PubMed]
39. Scigalski, P.; Kosobucki, P. Recent Materials Developed for Dispersive Solid Phase Extraction. *Molecules* **2020**, *25*, 4869. [CrossRef]
40. Fernández, I.; Carinelli, S.; González-Mora, J.L.; Villalonga, R.; Lecuona, M.; Salazar-Carballo, P.A. Electrochemical bioassay based on l-lysine-modified magnetic nanoparticles for Escherichia coli detection: Descriptive results and comparison with other commercial magnetic beads. *Food Control* **2023**, *145*, 109492. [CrossRef]
41. Campuzano, S.; Pedrero, M.; Gamella, M.; Serafin, V.; Yanez-Sedeno, P.; Pingarron, J.M. Beyond Sensitive and Selective Electrochemical Biosensors: Towards Continuous, Real-Time, Antibiofouling and Calibration-Free Devices. *Sensors* **2020**, *20*, 3376. [CrossRef] [PubMed]
42. Campuzano, S.; Pedrero, M.; González-Cortés, A.; Yáñez-Sedeño, P.; Pingarrón, J.M. Electrochemical biosensors for autoantibodies in autoimmune and cancer diseases. *Anal. Methods* **2019**, *11*, 871–887. [CrossRef]
43. Abedini-Nassab, R.; Miandoab, M.P.; Şaşmaz, M. Microfluidic Synthesis, Control, and Sensing of Magnetic Nanoparticles: A Review. *Micromachines* **2021**, *12*, 768. [CrossRef]
44. Sun, Y.; Li, H.; Cui, G.; Wu, X.; Yang, M.; Piao, Y.; Bai, Z.; Wang, L.; Kraft, M.; Zhao, W.; et al. A magnetic nanoparticle assisted microfluidic system for low abundance cell sorting with high recovery. *Micro Nano Eng.* **2022**, *15*, 100136. [CrossRef]
45. Campuzano, S.; Ruiz-Valdepeñas Montiel, V.; Serafin, V.; Yanez-Sedeno, P.; Pingarron, J.M. Cutting-Edge Advances in Electrochemical Affinity Biosensing at Different Molecular Level of Emerging Food Allergens and Adulterants. *Biosensors* **2020**, *10*, 10. [CrossRef]
46. Mohsin, A.; Hussain, M.H.; Mohsin, M.Z.; Zaman, W.Q.; Aslam, M.S.; Shan, A.; Dai, Y.; Khan, I.M.; Niazi, S.; Zhuang, Y.; et al. Recent Advances of Magnetic Nanomaterials for Bioimaging, Drug Delivery, and Cell Therapy. *ACS Appl. Nano Mater.* **2022**, *5*, 10118–10136. [CrossRef]
47. Ma, K.; Xu, S.; Tao, T.; Qian, J.; Cui, Q.; Rehman, S.U.; Zhu, X.; Chen, R.; Zhao, H.; Wang, C.; et al. Magnetosome-inspired synthesis of soft ferrimagnetic nanoparticles for magnetic tumor targeting. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2211228119. [CrossRef]
48. Ali, A.; Shah, T.; Ullah, R.; Zhou, P.; Guo, M.; Ovais, M.; Tan, Z.; Rui, Y. Review on Recent Progress in Magnetic Nanoparticles: Synthesis, Characterization, and Diverse Applications. *Front. Chem.* **2021**, *9*, 629054. [CrossRef]

49. Tripathy, A.; Nine, M.J.; Silva, F.S. Biosensing platform on ferrite magnetic nanoparticles: Synthesis, functionalization, mechanism and applications. *Adv. Colloid Interface Sci.* **2021**, *290*, 102380. [CrossRef] [PubMed]
50. Schladt, T.D.; Schneider, K.; Schild, H.; Tremel, W. Synthesis and bio-functionalization of magnetic nanoparticles for medical diagnosis and treatment. *Dalton Trans.* **2011**, *40*, 6315–6343. [CrossRef]
51. Abid, N.; Khan, A.M.; Shujait, S.; Chaudhary, K.; Ikram, M.; Imran, M.; Haider, J.; Khan, M.; Khan, Q.; Maqbool, M. Synthesis of nanomaterials using various top-down and bottom-up approaches, influencing factors, advantages, and disadvantages: A review. *Adv. Colloid Interface Sci.* **2022**, *300*, 102597. [CrossRef]
52. Alromi, D.A.; Madani, S.Y.; Seifalian, A. Emerging Application of Magnetic Nanoparticles for Diagnosis and Treatment of Cancer. *Polymers* **2021**, *13*, 4146. [CrossRef]
53. Bustamante-Torres, M.; Romero-Fierro, D.; Estrella-Nunez, J.; Arcentales-Vera, B.; Chichande-Proano, E.; Bucio, E. Polymeric Composite of Magnetite Iron Oxide Nanoparticles and Their Application in Biomedicine: A Review. *Polymers* **2022**, *14*, 752. [CrossRef]
54. Ognjanović, M.; Stanković, D.M.; Ming, Y.; Zhang, H.; Jančar, B.; Dojčinović, B.; Prijović, Ž.; Antić, B. Bifunctional $(Zn,Fe)_3O_4$ nanoparticles: Tuning their efficiency for potential application in reagentless glucose biosensors and magnetic hyperthermia. *J. Alloys Compd.* **2019**, *777*, 454–462. [CrossRef]
55. Antarnusa, G.; Suharyadi, E. A synthesis of polyethylene glycol (PEG)-coated magnetite Fe_3O_4 nanoparticles and their characteristics for enhancement of biosensor. *Mater. Res. Express* **2020**, *7*, 056103. [CrossRef]
56. Guo, J.H.X.; Ge, Y.; Zhao, D.; Sang, S.; Ji, J. Highly Sensitive Magnetoelastic Biosensor for Alpha2-Macroglobulin Detection Based on $MnFe_2O_4$@chitosan. *Micromachines* **2023**, *14*, 401. [CrossRef] [PubMed]
57. Orooji, Y.; Irani-Nezhad, M.H.; Hassandoost, R.; Khataee, A.; Pouran, S.R.; Joo, S.W. Cerium doped magnetite nanoparticles for highly sensitive detection of metronidazole via chemiluminescence assay. *Spectrochim. Acta A Mol. Biomol. Spectrosc.* **2020**, *234*, 118272. [CrossRef] [PubMed]
58. Wang, Z.; Chen, M.; Shu, J.; Li, Y. One-step solvothermal synthesis of Fe_3O_4@Cu@Cu_2O nanocomposite as magnetically recyclable mimetic peroxidase. *J. Alloys Compd.* **2016**, *682*, 432–440. [CrossRef]
59. Wang, C.; Qian, J.; Wang, K.; Yang, X.; Liu, Q.; Hao, N.; Wang, C.; Dong, X.; Huang, X. Colorimetric aptasensing of ochratoxin A using Au@ Fe_3O_4 nanoparticles as signal indicator and magnetic separator. *Biosens. Bioelectron.* **2016**, *77*, 1183–1191. [CrossRef]
60. Wang, Y.; Zhang, Y.; Hou, C.; Liu, M. Magnetic Fe_3O_4@MOFs decorated graphene nanocomposites as novel electrochemical sensor for ultrasensitive detection of dopamine. *RSC Adv.* **2015**, *5*, 98260–98268. [CrossRef]
61. Guivar, J.A.; Fernandes, E.G.; Zucolotto, V. A peroxidase biomimetic system based on Fe_3O_4 nanoparticles in non-enzymatic sensors. *Talanta* **2015**, *141*, 307–314. [CrossRef]
62. Okoli, C.; Sanchez-Dominguez, M.; Boutonnet, M.; Jaras, S.; Civera, C.; Solans, C.; Kuttuva, G.R. Comparison and functionalization study of microemulsion-prepared magnetic iron oxide nanoparticles. *Langmuir* **2012**, *28*, 8479–8485. [CrossRef]
63. Rivas, J.; Redondo, Y.P.; Iglesias-Silva, E.; Vilas-Vilela, J.M.; León, L.M.; López-Quintela, M.A. Air-stable Fe@Au nanoparticles synthesized by the microemulsion's methods. *J. Korean Phys. Soc.* **2013**, *62*, 1376–1381. [CrossRef]
64. Souza, C.G.S.d.; Souza, J.B.; Beck, W.; Varanda, L.C. Luminomagnetic Silica-Coated Heterodimers of Core/Shell FePt/Fe_3O_4 and CdSe Quantum Dots as Potential Biomedical Sensor. *J. Nanomater.* **2017**, *2017*, 2160278. [CrossRef]
65. Ying, S.; Guan, Z.; Ofoegbu, P.C.; Clubb, P.; Rico, C.; He, F.; Hong, J. Green synthesis of nanoparticles: Current developments and limitations. *Environ. Technol. Innov.* **2022**, *26*, 102336. [CrossRef]
66. Samuel, M.S.; Ravikumar, M.; John, J.A.; Selvarajan, E.; Patel, H.; Chander, P.S.; Soundarya, J.; Vuppala, S.; Balaji, R.; Chandrasekar, N. A Review on Green Synthesis of Nanoparticles and Their Diverse Biomedical and Environmental Applications. *Catalysts* **2022**, *12*, 459. [CrossRef]
67. Perez-Beltran, C.H.; Garcia-Guzman, J.J.; Ferreira, B.; Estevez-Hernandez, O.; Lopez-Iglesias, D.; Cubillana-Aguilera, L.; Link, W.; Stanica, N.; da Costa, A.M.R.; Palacios-Santander, J.M. One-minute and green synthesis of magnetic iron oxide nanoparticles assisted by design of experiments and high energy ultrasound: Application to biosensing and immunoprecipitation. *Mater. Sci. Eng. C Mater. Biol. Appl.* **2021**, *123*, 112023. [CrossRef]
68. Satvekar, R.K.; Pawar, S.H. Multienzymatic Cholesterol Nanobiosensor Using Core–Shell Nanoparticles Incorporated Silica Nanocomposite. *J. Med. Biol. Eng.* **2018**, *38*, 735–743. [CrossRef]
69. Ahmadian-Fard-Fini, S.; Salavati-Niasari, M.; Ghanbari, D. Hydrothermal green synthesis of magnetic Fe(3)O(4)-carbon dots by lemon and grape fruit extracts and as a photoluminescence sensor for detecting of *E. coli* bacteria. *Spectrochim. Acta A Mol. Biomol. Spectrosc.* **2018**, *203*, 481–493. [CrossRef] [PubMed]
70. Ali, A.; Zafar, H.; Zia, M.; Haq, I.u.; Phull, A.R.; Ali, J.S.; Hussain, A. Synthesis, characterization, applications, and challenges of iron oxide nanoparticles. *Nanotechnol. Sci. Appl.* **2016**, *9*, 49–67. [CrossRef] [PubMed]
71. Yang, H.Y.; Li, Y.; Lee, D.S. Functionalization of Magnetic Nanoparticles with Organic Ligands toward Biomedical Applications. *Adv. NanoBiomed Res.* **2021**, *1*, 2000043. [CrossRef]
72. García, R.S.; Stafford, S.; Gun'ko, Y.K. Recent Progress in Synthesis and Functionalization of Multimodal Fluorescent-Magnetic Nanoparticles for Biological Applications. *Appl. Sci.* **2018**, *8*, 172. [CrossRef]
73. Kulikova, T.; Porfireva, A.; Evtugyn, G.; Hianik, T. Electrochemical DNA Sensors with Layered Polyaniline-DNA Coating for Detection of Specific DNA Interactions. *Sensors* **2019**, *19*, 469. [CrossRef]

74. Gong, Q.; Han, H.; Yang, H.; Zhang, M.; Sun, X.; Liang, Y.; Liu, Z.; Zhang, W.; Qiao, J. Sensitive electrochemical DNA sensor for the detection of HIV based on a polyaniline/graphene nanocomposite. *J. Mater.* **2019**, *5*, 313–319. [CrossRef]
75. Zhang, X.; Tan, X.; Wang, P.; Qin, J. Application of Polypyrrole-Based Electrochemical Biosensor for the Early Diagnosis of Colorectal Cancer. *Nanomaterials* **2023**, *13*, 674. [CrossRef] [PubMed]
76. Zhang, W.; Li, X.; Zou, R.; Wu, H.; Shi, H.; Yu, S.; Liu, Y. Multifunctional glucose biosensors from Fe(3)O(4) nanoparticles modified chitosan/graphene nanocomposites. *Sci. Rep.* **2015**, *5*, 11129. [CrossRef] [PubMed]
77. Peng, L.; Luo, Y.; Xiong, H.; Yao, S.; Zhu, M.; Song, H. A Novel Amperometric Glucose Biosensor Based on Fe_3O_4-Chitosan-β-Cyclodextrin/MWCNTs Nanobiocomposite. *Electroanalysis* **2020**, *33*, 723–732. [CrossRef]
78. Di Tocco, A.; Robledo, S.N.; Osuna, Y.; Sandoval-Cortez, J.; Granero, A.M.; Vettorazzi, N.R.; Martinez, J.L.; Segura, E.P.; Ilina, A.; Zon, M.A.; et al. Development of an electrochemical biosensor for the determination of triglycerides in serum samples based on a lipase/magnetite-chitosan/copper oxide nanoparticles/multiwalled carbon nanotubes/pectin composite. *Talanta* **2018**, *190*, 30–37. [CrossRef] [PubMed]
79. D'Souza, A.A.; Shegokar, R. Polyethylene glycol (PEG): A versatile polymer for pharmaceutical applications. *Expert Opin. Drug Deliv.* **2016**, *13*, 1257–1275. [CrossRef] [PubMed]
80. Zhang, X.; Wang, H.; Ma, Z.; Wu, B. Effects of pharmaceutical PEGylation on drug metabolism and its clinical concerns. *Expert Opin. Drug Metab. Toxicol.* **2014**, *10*, 1691–1702. [CrossRef]
81. Patsula, V.; Horák, D.; Kučka, J.; Macková, H.; Lobaz, V.; Francová, P.; Herynek, V.; Heizer, T.; Páral, P.; Šefc, L. Synthesis and modification of uniform PEG-neridronate-modified magnetic nanoparticles determines prolonged blood circulation and biodistribution in a mouse preclinical model. *Sci. Rep.* **2019**, *9*, 10765. [CrossRef]
82. Zomorodian, K.; Veisi, H.; Mousavi, S.M.; Ataabadi, M.S.; Yazdanpanah, S.; Bagheri, J.; Mehr, A.P.; Hemmati, S.; Veisi, H. Modified magnetic nanoparticles by PEG-400-immobilized Ag nanoparticles (Fe_3O_4@PEG–Ag) as a core/shell nanocomposite and evaluation of its antimicrobial activity. *Int. J. Nanomed.* **2018**, *13*, 3965–3973. [CrossRef]
83. Nagasaki, Y.; Kobayashi, H.; Katsuyama, Y.; Jomura, T.; Sakura, T. Enhanced immunoresponse of antibody/mixed-PEG co-immobilized surface construction of high-performance immunomagnetic ELISA system. *J. Colloid Interface Sci.* **2007**, *309*, 524–530. [CrossRef]
84. Ahmad, N.; Colak, B.; Zhang, D.-W.; Gibbs, M.J.; Watkinson, M.; Becer, C.R.; Gautrot, J.E.; Krause, S. Peptide Cross-Linked Poly (Ethylene Glycol) Hydrogel Films as Biosensor Coatings for the Detection of Collagenase. *Sensors* **2019**, *19*, 1677. [CrossRef] [PubMed]
85. Lv, S.; Sheng, J.; Zhao, S.; Liu, M.; Chen, L. The detection of brucellosis antibody in whole serum based on the low-fouling electrochemical immunosensor fabricated with magnetic Fe_3O_4@ Au@ PEG@ HA nanoparticles. *Biosens. Bioelectron.* **2018**, *117*, 138–144. [CrossRef]
86. Shin, H.Y.; Kim, B.-G.; Cho, S.; Lee, J.; Na, H.B.; Kim, M.I. Visual determination of hydrogen peroxide and glucose by exploiting the peroxidase-like activity of magnetic nanoparticles functionalized with a poly(ethylene glycol) derivative. *Microchim. Acta* **2017**, *184*, 2115–2122. [CrossRef]
87. Wang, Z.; Feng, X.; Xiao, F.; Bai, X.; Xu, Q.; Xu, H. A novel PEG-mediated boric acid functionalized magnetic nanomaterials based fluorescence biosensor for the detection of Staphylococcus aureus. *Microchem. J.* **2022**, *178*, 107379. [CrossRef]
88. Cha, B.G.; Lee, D.; Kim, T.; Piao, Y.; Kim, J. Iron Oxide@Polypyrrole Core–Shell Nanoparticles as the Platform for Photothermal Agent and Electrochemical Biosensor. *J. Nanosci. Nanotechnol.* **2016**, *16*, 6942–6948. [CrossRef]
89. Sahin, S.; Ozmen, I.; Bastemur, G.Y.; Ozkorucuklu, S.P. Development of Voltammetric Glucose-6-phosphate Biosensors Based on the Immobilization of Glucose-6-phosphate Dehydrogenase on Polypyrrole- and Chitosan-Coated Fe(3)O(4) Nanoparticles/Polypyrrole Nanocomposite Films. *Appl. Biochem. Biotechnol.* **2019**, *188*, 1145–1157. [CrossRef] [PubMed]
90. Song, E.; Tao, Y.; Shen, H.; Yang, C.; Tian, T.; Yang, L.; Zhu, Z. A polypyrrole-mediated photothermal biosensor with a temperature and pressure dual readout for the detection of protein biomarkers. *Analyst* **2022**, *147*, 2671–2677. [CrossRef]
91. Chandra, S.; Lang, H.; Bahadur, D. Polyaniline-iron oxide nanohybrid film as multi-functional label-free electrochemical and biomagnetic sensor for catechol. *Anal. Chim. Acta* **2013**, *795*, 8–14. [CrossRef] [PubMed]
92. Wen, T.; Zhu, W.; Xue, C.; Wu, J.; Han, Q.; Wang, X.; Zhou, X.; Jiang, H. Novel electrochemical sensing platform based on magnetic field-induced self-assembly of Fe_3O_4@Polyaniline nanoparticles for clinical detection of creatinine. *Biosens. Bioelectron.* **2014**, *56*, 180–185. [CrossRef] [PubMed]
93. Lou, C.; Jing, T.; Zhou, J.; Tian, J.; Zheng, Y.; Wang, C.; Zhao, Z.; Lin, J.; Liu, H.; Zhao, C.; et al. Laccase immobilized polyaniline/magnetic graphene composite electrode for detecting hydroquinone. *Int. J. Biol. Macromol.* **2020**, *149*, 1130–1138. [CrossRef]
94. Hsine, Z.; Mlika, R.; Jaffrezic-Renault, N.; Korri-Youssoufi, H. Recent progress in graphene based modified electrodes for electrochemical detection of dopamine. *Chemosensors* **2022**, *10*, 249. [CrossRef]
95. Peng, H.P.; Liang, R.P.; Zhang, L.; Qiu, J.D. Facile preparation of novel core-shell enzyme-Au-polydopamine-Fe(3)O(4) magnetic bionanoparticles for glucosesensor. *Biosens. Bioelectron.* **2013**, *42*, 293–299. [CrossRef]
96. Martin, M.; Salazar, P.; Jimenez, C.; Lecuona, M.; Ramos, M.J.; Ode, J.; Alcoba, J.; Roche, R.; Villalonga, R.; Campuzano, S.; et al. Rapid Legionella pneumophila determination based on a disposable core-shell Fe_3O_4@poly(dopamine) magnetic nanoparticles immunoplatform. *Anal. Chim. Acta* **2015**, *887*, 51–58. [CrossRef]

97. Sardaremelli, S.; Hasanzadeh, M.; Seidi, F. Enzymatic recognition of hydrogen peroxide (H_2O_2) in human plasma samples using HRP immobilized on the surface of poly(arginine-toluidine blue)- Fe_3O_4 nanoparticles modified polydopamine: A novel biosensor. *J. Mol. Recognit.* **2021**, *34*, e2928. [CrossRef] [PubMed]
98. Rashid, Z.; Soleimani, M.; Ghahremanzadeh, R.; Vossoughi, M.; Esmaeili, E. Effective surface modification of $MnFe_2O_4$ @SiO_2 @PMIDA magnetic nanoparticles for rapid and high-density antibody immobilization. *Appl. Surf. Sci.* **2017**, *426*, 1023–1029. [CrossRef]
99. Huang, F.; Guo, R.; Xue, L.; Cai, G.; Wang, S.; Li, Y.; Liao, M.; Wang, M.; Lin, J. An Acid-Responsive Microfluidic Salmonella Biosensor Using Curcumin as Signal Reporter and ZnO-Capped Mesoporous Silica Nanoparticles for Signal Amplification. *Sens. Actuators B Chem.* **2020**, *312*, 127958. [CrossRef]
100. Ghodsi, J.; Hajian, A.; Rafati, A.A.; Shoja, Y.; Yurchenko, O.; Urban, G. Electrostatically immobilized hemoglobin on silica-coated magnetic nanoparticles for simultaneous determination of dopamine, uric acid, and folic acid. *J. Electrochem. Soc.* **2016**, *163*, B609. [CrossRef]
101. Achadu, O.J.; Nwaji, N.; Lee, D.; Lee, J.; Akinoglu, E.M.; Giersig, M.; Park, E.Y. 3D hierarchically porous magnetic molybdenum trioxide@gold nanospheres as a nanogap-enhanced Raman scattering biosensor for SARS-CoV-2. *Nanoscale Adv.* **2022**, *4*, 871–883. [CrossRef]
102. Lee, S.E.; Jeong, S.E.; Hong, J.S.; Im, H.; Hwang, S.Y.; Oh, J.K.; Kim, S.E. Gold-Nanoparticle-Coated Magnetic Beads for ALP-Enzyme-Based Electrochemical Immunosensing in Human Plasma. *Materials* **2022**, *15*, 6875. [CrossRef]
103. Khoshfetrat, S.M.; Mehrgardi, M.A. Amplified detection of leukemia cancer cells using an aptamer-conjugated gold-coated magnetic nanoparticles on a nitrogen-doped graphene modified electrode. *Bioelectrochemistry* **2017**, *114*, 24–32. [CrossRef]
104. Wang, Z.; Bai, Y.; Wei, W.; Xia, N.; Du, Y. Magnetic Fe_3O_4-Based Sandwich-Type Biosensor Using Modified Gold Nanoparticles as Colorimetric Probes for the Detection of Dopamine. *Materials* **2013**, *6*, 5690–5699. [CrossRef] [PubMed]
105. Hu, L.; Cui, J.; Wang, Y.; Jia, J. An ultrasensitive electrochemical biosensor for bisphenol A based on aptamer-modified MrGO@AuNPs and ssDNA-functionalized AuNP@MBs synergistic amplification. *Chemosphere* **2022**, *311*, 137154. [CrossRef] [PubMed]
106. He, C.; Xie, M.; Hong, F.; Chai, X.; Mi, H.; Zhou, X.; Fan, L.; Zhang, Q.; Ngai, T.; Liu, J. A Highly Sensitive Glucose Biosensor Based on Gold Nanoparticles/Bovine Serum Albumin/Fe_3O_4 Biocomposite Nanoparticles. *Electrochim. Acta* **2016**, *222*, 1709–1715. [CrossRef]
107. Della Ventura, B.; Campanile, R.; Cimafonte, M.; Elia, V.; Forente, A.; Minopoli, A.; Scardapane, E.; Schiattarella, C.; Velotta, R. Gold Coated Nanoparticles Functionalized by Photochemical Immobilization Technique for Immunosensing. In *Sensors and Microsystems. AISEM 2020. Lecture Notes in Electrical Engineering*; Springer: Cham, Switzerland, 2021; Volume 753, pp. 113–118.
108. Weng, C.; Li, X.; Lu, Q.; Yang, W.; Wang, J.; Yan, X.; Li, B.; Sakran, M.; Hong, J.; Zhu, W.; et al. A label-free electrochemical biosensor based on magnetic biocomposites with DNAzyme and hybridization chain reaction dual signal amplification for the determination of Pb(2). *Mikrochim. Acta* **2020**, *187*, 575. [CrossRef]
109. Choi, G.; Kim, E.; Park, E.; Lee, J.H. A cost-effective chemiluminescent biosensor capable of early diagnosing cancer using a combination of magnetic beads and platinum nanoparticles. *Talanta* **2017**, *162*, 38–45. [CrossRef]
110. MKim, S.; Kweon, S.H.; Cho, S.; An, S.S.A.; Kim, M.I.; Doh, J.; Lee, J. Pt-Decorated Magnetic Nanozymes for Facile and Sensitive Point-of-Care Bioassay. *ACS Appl. Mater. Interfaces* **2017**, *9*, 35133–35140.
111. Borisova, B.; Sánchez, A.; Jiménez-Falcao, S.; Martín, M.; Salazar, P.; Parrado, C.; Pingarrón, J.M.; Villalonga, R. Reduced graphene oxide-carboxymethylcellulose layered with platinum nanoparticles/PAMAM dendrimer/magnetic nanoparticles hybrids. Application to the preparation of enzyme electrochemical biosensors. *Sens. Actuators B Chem.* **2016**, *232*, 84–90. [CrossRef]
112. Šafranko, S.; Goman, D.; Stanković, A.; Medvidović-Kosanović, M.; Moslavac, T.; Jerković, I.; Jokić, S. An Overview of the Recent Developments in Carbon Quantum Dots—Promising Nanomaterials for Metal Ion Detection and (Bio) Molecule Sensing. *Chemosensors* **2021**, *9*, 138. [CrossRef]
113. Pandit, C.; Alajangi, H.K.; Singh, J.; Khajuria, A.; Sharma, A.; Hassan, M.S.; Parida, M.; Semwal, A.D.; Gopalan, N.; Sharma, R.K.; et al. Development of magnetic nanoparticle assisted aptamer-quantum dot based biosensor for the detection of *Escherichia coli* in water samples. *Sci. Total Environ.* **2022**, *831*, 154857. [CrossRef]
114. Shi, R.; Feng, S.; Park, C.Y.; Park, K.Y.; Song, J.; Park, J.P.; Chun, H.S.; Park, T.J. Fluorescence detection of histamine based on specific binding bioreceptors and carbon quantum dots. *Biosens. Bioelectron.* **2020**, *167*, 112519. [CrossRef] [PubMed]