

GREEN SYNTHESIS AND COMPARATIVE THERAPEUTIC EVALUATION OF MORIN HYDRATE-STABILIZED ZINC OXIDE AND IRON OXIDE NANOPARTICLES

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ABSTRACT

This study focuses on the use of morin hydrate as a reducing agent and stabilizer for the green synthesis and characterization of zinc oxide (ZnO) and iron oxide (Fe₃O₄) nanoparticles, as well as the comparative evaluation of their therapeutic effects. The use of a naturally occurring flavonoid (morin) has demonstrated antioxidant potential, and thus was deemed appropriate for developing biocompatible nanoparticles via an environmental-friendly synthetic route. Various methods of analysis (UV-visible spectroscopy, Fourier-transform infrared spectroscopy, X-ray diffraction, dynamic light scattering, scanning electron microscopy) were employed to characterize the newly created nanoparticles according to their structural, morphological,

and physicochemical characteristics. Biologically-based evaluations were made on the nanoparticles by determining their ability to exhibit antioxidant, antimicrobial, and cytotoxic activities. The results suggested that the nanoparticles formed were stable, in the nanosphere size range; they possessed a crystalline structure; and they were well-dispersed. ZnO nanoparticles demonstrated greater antimicrobial activity against certain pathogenic microorganisms than did the iron oxide nanoparticles, while the iron oxide particles exhibited better biocompatibility and a significant level of antioxidant activity compared to the ZnO nanoparticles. Cytotoxicity testing demonstrated that both sets of nanoparticles had therapeutic potential that was concentration-dependent; therefore both types of nanoparticles will likely be suitable for use in medicine. The biodistribution of the morin with the nanoparticles appears to improve the stability and biological activity through means of the synergistic nature of the morin with either zinc oxide or iron oxide.

Keywords: Morin hydrate, Green synthesis, Zinc oxide nanoparticles, Iron oxide nanoparticles, Nanotechnology, Antioxidant activity, Antimicrobial activity, Cytotoxicity, Biocompatibility, Therapeutic evaluation

Introduction

Nanotechnology is one of the most rapidly growing, dynamic fields of scientific research because of its ability to modify matter at the nanoscale. The size of nanoparticles is between 1 nanometer and 100 nanometers, and their unique physical and chemical properties differ from those of bulk materials. These physical and chemical properties of nanoparticles include large surface area-to-volume ratios, higher reactivity, improved optical properties, and better biological interactions. These distinctive physical and chemical properties of nanoparticles have led to their use in many fields as diverse as medicine, agriculture, electronics, environmental remediation, and biotechnology. Metal oxide nanoparticles are the most widely studied group of nanomaterials because of their potential therapeutic and diagnostic applications. Some examples of commonly studied metal oxide nanoparticles include zinc oxide and iron oxide. These two types of nanoparticles have several therapeutic applications including antimicrobial properties, antioxidant properties, anticancer properties, and drug delivery. Traditional methods of making nanoparticles can include using toxic chemicals, requiring large amounts of energy, or creating hazardous waste that can limit the medical

application of the end product. To minimize the negative impact of these issues, many scientists began using environmentally friendly approaches to synthesizing nanoparticles using naturally occurring materials or plant-based biomolecules as reducing and stabilizing agents. (Mittal et al., 2013) Morin hydrate is an organic compound that is a naturally occurring flavonoid which can be extracted from a variety of medicinal plants, fruits, and herbs and has many uses. It has strong antioxidant, anti-inflammatory, antimicrobial, antiviral, and anticancer effects which make it ideal for biomedical applications. The structure of morin hydrate includes multiple -OH groups, which allow it to act as both a reducing and a capping agent during nanoparticles synthesis by providing electrons and binding with metal ions. The use of morin hydrate in the green synthesis process eliminates the use of toxic chemicals; therefore, morin hydrate-coated nanoparticles will be stable and biocompatible. Moreover, the biological activity of morin hydrate-coated nanoparticles will often be enhanced because the flavonoid will have additional therapeutic effects. Numerous studies show that nanoparticles functionalized with flavonoids have improved antioxidant activity, increased cellular uptake, and reduced toxicity

compared to unmodified nanoparticles. Since morin hydrate has antioxidant properties, it will help stop the oxidation and aggregation of nanoparticles, which will help maintain their stability while they are being stored or applied. (Rauf et al., 2018)

The property exceptional biological and therapeutic properties of zinc oxide nanoparticles have attracted great interest in the past few years. They are also widely recognized as having broad-spectrum antimicrobial activity against bacteria and fungi. It is believed that their antimicrobial mechanism is largely based on their ability to generate reactive oxygen species, disrupt microbial membranes, and interfere with critical cellular functions. ZnO nanoparticles possess many other beneficial properties such as antioxidant, anti-inflammatory, wound healing, and anticancer activities in addition to antimicrobial properties. Due to their capacity to induce apoptosis selectively for cancer cells, while producing low levels of toxicity to normal cells, they have become increasingly relevant to biomedical research. It should also be noted that zinc is an essential trace element in humans, which helps to support the biocompatibility of ZnO-based nanomaterials. The use of green synthesis methods to prepare ZnO nanoparticles has further improved the safety profile of these materials: reducing the surface toxicity of the nanoparticle and eliminating toxic byproducts of the synthesis process. Morin hydrate may help stabilize ZnO nanoparticles by providing the benefit of both the metal oxide and the flavonoid compound, thereby potentially enhancing the stability, antioxidant activity, and therapeutic efficacy of the nanoparticles. Therefore, morin hydrate-stabilized ZnO nanoparticles represent a potential valuable target for future pharmaceutical, antimicrobial, and nanomedical applications. (Sirelkhatim et al., 2015)

Iron oxide nanoparticles, One of the most important types of nanomaterials, have been the focus of increasing attention in nanomedicine due to their unique magnetic properties and total compatibility with living cells. The use of iron oxide nanoparticles has quickly gained popularity in biomedical applications such as magnetic resonance imaging (MRI), targeted drug delivery, hyperthermia treatment, biosensing, and tissue engineering. The advantage that iron oxide nanoparticles have over other types of nanoparticles is their ability to respond to external magnetic fields, allowing precise control of their movement and placement in a biological system, resulting in the ability to deliver therapeutic agents precisely to the target cells of a patient, thereby reducing any potential side effects caused by the presence of these agents, while raising the overall effectiveness of the treatment. The use of Green synthesis methods to create iron oxide nanoparticles has further advanced the potential use of these nanoparticles in the field of medicine by using natural substances as both reducing agents and stabilizing agents in the process. The combination of magnetic properties of iron oxide nanoparticles with the antioxidant properties of the flavonoid morin have produced multi-functional nanomaterials with therapeutic value. The use of phytochemicals as functionalizers has also been shown to improve the stability of iron oxide nanoparticles, reduce agglomeration, and increase their compatibility with cells. These improvements are very important for iron oxide nanoparticles that will be used in clinical applications, where both safety and effectiveness are paramount. Therefore, morin-stabilized iron oxide nanoparticles show promise as advanced nanomedicines for therapeutic and diagnostic applications. (Gupta et al., 2005)

Evaluating and comparing various types of nanoparticle systems is crucial to discovering which particular nanoparticles have the best efficacy and biocompatibility for therapeutic applications. Zinc oxide nanoparticles and iron oxide nanoparticles both have great potential in terms of usage within a biomedical context; however, they are vastly different in their physical and chemical properties, modes of action, and types of therapies. In general, zinc oxide nanoparticles tend to have high levels of cytotoxicity and antibacterial/antimicrobial properties while iron oxide nanoparticles provide excellent biological compatibility and magnetic attraction. The use of morin hydrate as a stabilizer and functionalizer may also affect the size, shape, surface chemistry, antioxidant activity and therapeutic properties of these nanoparticles. Therefore, comparing these morin-hydrate stabilized zinc oxide nanoparticles and iron oxide nanoparticles is necessary to determine each type of nanomaterial has particular advantages over the other, or each nanomaterial has its limits of applications. These types of comparative studies will help create better designed and optimized formulations of nanoparticles for certain biomedical applications. This research project examines the green synthesis of these nanoparticles, their properties, and then evaluates their therapeutic effects to determine if they can be used successfully in a clinical setting. In addition, by comparing the physical, chemical, and therapeutic properties of these nanoparticles, findings from this study will also help advance sustainable nanotechnology and provide resources for developing safe, eco-friendly and highly performant nanomedicine platforms for future use in health care. (Sharma et al., 2022)

Green synthesis of nanoparticles

The environmentally conscious "Green Synthesis" of Nanoparticles represents a Sustainable means of

Making Nanomaterials. Conventional Physical/Chemical Methods of Synthesizing Nanoparticles frequently employ numerous Toxic Chemicals, subject materials to High Temperatures, require costly equipment and generate Hazards to both Human Health and the Environment. In sharp contrast, "Green Synthesis" uses biological materials that can include Plants, Microorganisms, Algae, Fungi as well as Naturally Occurring Biomolecules to Reduce and Stabilize Metal Ions into Nanoparticles. A wide range of Phytochemicals including Flavonoids, Phenolic Compounds, Alkaloids, Terpenoids, Proteins and Sugars contained within biological materials to help reduce and stabilize Metal Ions Into Nanoparticles. Green Synthesis processes are generally simple, cost-effective, and Energy Efficient; thus, allowing for the production of Nanoparticles that are more Stable and Biocompatible. Green Synthesis has received great Deal of Attention because it provides a process that adheres to the to the Principles of Green Chemistry by Minimizing Hazardous Substances and Waste Generation. Researchers from every country around the world have begun to explore ways of using Biological Systems to Synthesize Nanoparticles due to their ability to be made with Controlled Size, Shape and functionality. (Ahmed et al., 2016)

The synthesis of nanoparticles using plants is one of the most studied green methods for making nanoparticles due to its relatively straightforward, quick, and effective preparation process. The plant extracts are rich in bioactive compounds that can act as simultaneous reducing, capping, and stabilizing agents during the formation of nanoparticles. These phytochemicals can help reduce the metal ions into nanoparticles without the addition of additional chemical reducing agents. Many different types of medicinal plants

(fruits, leaves, roots, seeds, and flowers) can be used successfully to synthesize many different types of metal and metal oxide nanoparticles. The composition of the plant extract influences the characteristics of the nanoparticles produced, including size, morphology, stability, and biological activity. One of the key benefits of using plant-mediated synthesis is that complex microbial culture methods are eliminated, making the process easier for large-scale production. Also, as nanoparticles synthesized from plant extracts have a greater amount of phytochemicals on their surface, they may exhibit greater biological activity compared with nanoparticles synthesized from chemical sources. These phytochemically coated nanoparticles may possess antioxidant, antimicrobial, anti-inflammatory, and anticancer properties. Using renewable plant sources supports sustainable manufacturing practices and has less impact on the environment. Therefore, plant-based green synthesis has become a preferred route for researchers looking for efficient and environmentally friendly methods to fabricate nanoparticles across the scientific and industrial communities. (Iravani, 2011)

The production of nanoparticles via "green" methods will have properties that are dependent on both the method of production as well as the biological components that were utilized to make them. The factors that will impact how the nanoparticles will perform include (1) the pH, (2) temperature, (3) time of reaction, (4) concentration of precursors, and (5) composition of biological extracts. The synthesis conditions used to assemble the nanoparticles will directly impact the size and shape of the nanoparticles, the level of crystallinity of the nanoparticles, and how stable the nanoparticles will be. In addition, various analytical methods will be used to characterize the properties of the nanoparticles and confirm that

the nanoparticle synthesis was successful. Analytical techniques used to characterize the properties of the nanoparticles include ultraviolet-visible spectroscopy (UV-Vis), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and dynamic light scattering (DLS). All of the aforementioned analytical methods are useful for providing information regarding the primary morphology and elemental makeup of the nanoparticles, as well as the surface chemistry of the nanoparticles and the distribution of the nanoparticles. The majority of nanoparticles produced through green synthesis will generally have enhanced stability as a result of naturally occurring biomolecules that remain attached to the surfaces of the nanoparticles and prevent aggregation of the nanoparticles. These properties are what allow for the green-synthesized nanoparticles to exhibit a superior biological performance, as well as an increased shelf life. Additionally, the phytochemicals that coat the nanoparticles may also enhance their efficacy when in contact with mammalian cells and support their ability to provide improved therapeutic activity. Understanding how the variables used in the synthesis of nanoparticles impact the physical and chemical properties of the nanoparticles is essential for optimizing the production processes used to produce nanoparticles with different functional properties. As such, this information will be useful for researchers to design nanoparticles for targeted use in a variety of fields including but not limited to the medicine, environmental science and industrial technology fields. (Narayanan & Sakthivel, 2010)

The physicochemical properties of nanoparticles produced via green methods are influenced by the synthesis conditions and biological materials used

during the synthesis. The synthesis parameters (e.g., pH, temperature, reaction time, precursor concentration, and biological extract composition) play important roles in determining the size, shape, crystallinity, and stability of the nanoparticles. Characterization methods are necessary to assess these properties and verify that nanoparticles have been successfully synthesized. Routine characterization techniques include ultraviolet-visible (UV-Vis) spectroscopy, Fourier-transform infrared (FTIR) spectroscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and dynamic light scattering (DLS) techniques. These techniques yield valuable data concerning the morphology, elemental composition, surface chemistry, and distribution of nanoparticles. Nanoparticles synthesized using green methods typically have increased stability because naturally occurring biomolecules remain bound to the nanoparticle surfaces, preventing aggregation. This enhance stability leads to increased biological performance and shelf life of nanoparticles. In addition, phytochemical coatings on the nanoparticles can increase cellular interaction and therapeutic efficacy. Understanding how synthesis parameters impact nanoparticle properties is important for optimizing production methods and developing nanomaterials with desired functionalities. This knowledge allows researchers to develop nanoparticles that can be used for specific purposes in medicine, environmental science, and industrial technology. (Makarov et al., 2014)

Evaluating and comparing various types of nanoparticle systems is crucial to discovering which particular nanoparticles have the best efficacy and biocompatibility for therapeutic applications. Zinc oxide nanoparticles and iron oxide nanoparticles both have great potential in terms of usage within a

biomedical context; however, they are vastly different in their physical and chemical properties, modes of action, and types of therapies. In general, zinc oxide nanoparticles tend to have high levels of cytotoxicity and antibacterial/antimicrobial properties while iron oxide nanoparticles provide excellent biological compatibility and magnetic attraction. The use of morin hydrate as a stabilizer and functionalizer may also affect the size, shape, surface chemistry, antioxidant activity and therapeutic properties of these nanoparticles. Therefore, comparing these morin-hydrate stabilized zinc oxide nanoparticles and iron oxide nanoparticles is necessary to determine each type of nanomaterial has particular advantages over the other, or each nanomaterial has its limits of applications. These types of comparative studies will help create better designed and optimized formulations of nanoparticles for certain biomedical applications. This research project examines the green synthesis of these nanoparticles, their properties, and then evaluates their therapeutic effects to determine if they can be used successfully in a clinical setting. In addition, by comparing the physical, chemical, and therapeutic properties of these nanoparticles, findings from this study will also help advance sustainable nanotechnology and provide resources for developing safe, eco-friendly and highly performantnanomedicine platforms for future use in health care. (Roy et al., 2013)

Morin hydrate as reducing and stabilizing agent

Naturally occurring flavonoid Morin hydrate has been the focus of significant nanotechnology interest due to its various chemical and biological benefits. It is at home in various members of the Moraceae family, and it can also be found in various medicinal plants which provide both antioxidant and therapeutic qualities. Each of its multiple aromatic ring-bound hydroxyl groups give

it significant reducing abilities. The hydroxyl groups in Morin hydrate donate electrons to metal ions, which change them into elemental or metallic oxide nanoparticles. These unique qualities make Morin hydrate a viable reducing reagent for producing green nanoparticles. Unlike some of the other standard reducing agents, Morin hydrate provides a safer and more sustainable alternative, since many standard reducing agents are toxic and/or environmentally damaging. Its naturally occurring nature and low toxicity make it a highly appealing starting material for biomedical applications where biocompatibility is a central consideration. In addition to reducing metal ions, it will also have hydrogen bonding and chelation interactions with the surfaces of newly formed nanoparticles, which control nanoparticle growth and prevent excessive aggregation during synthesis. (Mendoza-Wilson et al., 2015)

Morin hydrate has a polyphenolic structure that includes numerous hydroxyl groups that can act as electron donors and therefore participate in redox reactions. During the nanoparticles' synthesis, morin hydrate will reduce various metal (Zn, Fe, Ag, Au) ions through the transfer of electrons from morin to produce nanoscale particles of metal while being oxidized themselves as a result of the electron donation. Due to this reduction process, synthetic reducing agents that may leave behind toxic residuals are not required as part of the synthesis process. The efficiency with which morin hydrate can be used as a reducing agent is influenced by a multitude of factors including, but not limited to, the pH, temperature, and concentration of the metal precursor being utilized as well as the identity of the metal precursor. Research suggests that the position of hydroxyl groups in the morin structure provides optimal conditions for enhanced electron donation, which leads to more efficient nanoparticle formation.

Additionally, due to the antioxidant properties found in morin, the nucleation and growth of nanoparticles can be better controlled yielding nanoparticles with the desired physicochemical properties. The use of morin hydrate in nanoparticle synthesis aligns with the growing trend towards using environmentally sustainable approaches by utilizing naturally occurring materials. This will not only reduce environmental impact but also produce high-quality products and allow for efficient synthesis of nanomaterials. Therefore, morin hydrate is a viable natural alternative to traditional chemical reducing agents used in the fabrication of nanomaterials. (Heim et al., 2002)

Morin hydrate has two principal functions in nanoparticle synthesis as a strong reducing agent and as a capping agent. As soon as nanoparticles form, they have a very high energy state due to the amount of energy they have accumulated from the process of formation, so they want to reduce their energy levels by aggregating together. The aggregation of nanoparticles can negatively influence their size distribution, biological activity, and long-term stability. Morin hydrate aids in preventing this aggregation by adsorbing to the surface of the newly formed nanoparticles, providing an additional layer of protection to individual particles. Therefore, morin hydrate provides both steric and electrostatic stabilization to the nanoparticles. This means that morin hydrate minimizes the interactions between different nanoparticles and keeps the nanoparticles in a stable colloidal suspension. The hydroxyl and carbonyl groups present in morin hydrate have an ability to form strong interactions with metallic and metal oxide surfaces. Hence, by providing complete surface coverage on the nanoparticles, morin hydrate helps generate very narrow size distributions of nanoparticles, improve the ease of

dispersibility of the nanoparticles, and prolong the stability of nanoparticles in physiological solutions. The ability of morin hydrate to be both a reducing and stabilizing agent therefore simplifies the synthesis of nanoparticles and reduces the number of additional chemicals that would otherwise be necessary as additives. The multifunctional nature of morin hydrate represents a significant contribution towards the creation of safer, more efficient, and more environmentally friendly methods of producing nanoparticles. (Rice-Evans et al., 1996)

The use of morin hydrate on surface of nanoparticles can greatly improve their therapeutic and biological properties. Morin has a large number of beneficial properties itself; these include extremely strong anti-oxidative, anti-inflammatory, antimicrobial and anticancer properties and the addition of morin onto nanoparticles will probably be useful either enhancing or maintaining those properties. Morin that is attached to the surface of nanoparticles can scavenge reactive oxygen species and help to protect biological tissue from oxidative damage. The antioxidant properties of morin are especially important in biomedicine due to oxidative damage's contribution to the progression of diseases. In addition, morin-coated nanoparticles typically have much better interactions with biological membranes, aiding cellular uptake and increasing the effectiveness of their therapeutic effects. Studies have also shown that nanoparticles that have been functionalized with flavonoids (such as morin) have demonstrated significantly stronger antimicrobial propensities and greater cytotoxicity towards cancer cells when compared to unfunctionalized nanoparticles. The presence of morin hydrate on the surface of the nanoparticle also helps to maximize biocompatibility by decreasing unfavorable interactions with normal cells and tissues.

Accordingly, morin hydrate appears to be an ideal candidate for incorporation into multifunctional nanotherapeutics. Combining nanoparticle technology with naturally-derived bioactive substances represents a strong strategy to improve treatment outcomes while minimizing potential side effects. Therefore, morin hydrate has become an increasingly important ingredient in the design and development of cutting-edge nanomedicine systems for future application purposes. (Cho et al., 2006)

There have been recent developments in the field of green nanotechnology with a focus on the growing importance of natural flavonoid compounds such as Morin hydrate for synthesising nanoparticles and for use in biomedical engineering. Researchers are studying how Morin hydrate affects the size, shape, stability, surface chemistry and therapeutic activity of nanoparticles. The results of many studies indicate that nanoparticles synthesised through Morin-mediated methods have superior physicochemical properties and improved biological performance. Morin hydrate can serve multiple functions at once; it acts as a reducing agent, stabilising agent, and bioactive coating material for nanoparticles, which is a major advantage over traditional methods of nanoparticle synthesis. Because Morin has multiple functions, it simplifies the manufacturing process of nanoparticles and increases the safety and effectiveness of the products produced. Additionally, Morin-based manufactured nanomaterials have shown great potential in the areas of drug delivery, cancer treatment, antimicrobial treatment, antioxidant treatment and diagnostic imaging. With the continued interest in sustainable and biocompatible nanotechnology, it is likely that Morin hydrate will become increasingly important in developing next-generation nanomaterials. Large-scale synthesis,

mechanisms of action, and clinical studies are future directions of research that will help to establish Morin hydrate's ability to make a positive contribution to the pharmaceutical and biomedical fields. Consequently, Morin hydrate is an excellent natural resource to assist in environmentally friendly nanoparticle manufacturing and to improve nanotechnology-based healthcare solutions. (Cushnie& Lamb, 2011)

Zinc oxide (ZnO) nanoparticles

Naturally occurring flavonoid Morin hydrate has been the focus of significant nanotechnology interest due to its various chemical and biological benefits. It is at home in various members of the Moraceae family, and it can also be found in various medicinal plants which provide both antioxidant and therapeutic qualities. Each of its multiple aromatic ring-bound hydroxyl groups give it significant reducing abilities. The hydroxyl groups in Morin hydrate donate electrons to metal ions, which change them into elemental or metallic oxide nanoparticles. These unique qualities make Morin hydrate a viable reducing reagent for producing green nanoparticles. Unlike some of the other standard reducing agents, Morin hydrate provides a safer and more sustainable alternative, since many standard reducing agents are toxic and/or environmentally damaging. Its naturally occurring nature and low toxicity make it a highly appealing starting material for biomedical applications where biocompatibility is a central consideration. In addition to reducing metal ions, it will also have hydrogen bonding and chelation interactions with the surfaces of newly formed nanoparticles, which control nanoparticle growth and prevent excessive aggregation during synthesis. (Sirelkhatim et al., 2015)

Morin hydrate has a polyphenolic structure that includes numerous hydroxyl groups that can act as electron donors and therefore participate in redox

reactions. During the nanoparticles' synthesis, morin hydrate will reduce various metal (Zn, Fe, Ag, Au) ions through the transfer of electrons from morin to produce nanoscale particles of metal while being oxidized themselves as a result of the electron donation. Due to this reduction process, synthetic reducing agents that may leave behind toxic residuals are not required as part of the synthesis process. The efficiency with which morin hydrate can be used as a reducing agent is influenced by a multitude of factors including, but not limited to, the pH, temperature, and concentration of the metal precursor being utilized as well as the identity of the metal precursor. Research suggests that the position of hydroxyl groups in the morin structure provides optimal conditions for enhanced electron donation, which leads to more efficient nanoparticle formation. Additionally, due to the antioxidant properties found in morin, the nucleation and growth of nanoparticles can be better controlled yielding nanoparticles with the desired physicochemical properties. The use of morin hydrate in nanoparticle synthesis aligns with the growing trend towards using environmentally sustainable approaches by utilizing naturally occurring materials. This will not only reduce environmental impact but also produce high-quality products and allow for efficient synthesis of nanomaterials. Therefore, morin hydrate is a viable natural alternative to traditional chemical reducing agents used in the fabrication of nanomaterials.(Agarwal et al., 2017)

Morin hydrate has two principal functions in nanoparticle synthesis as a strong reducing agent and as a capping agent. As soon as nanoparticles form, they have a very high energy state due to the amount of energy they have accumulated from the process of formation, so they want to reduce their energy levels by aggregating together. The

aggregation of nanoparticles can negatively influence their size distribution, biological activity, and long-term stability. Morin hydrate aids in preventing this aggregation by adsorbing to the surface of the newly formed nanoparticles, providing an additional layer of protection to individual particles. Therefore; morin hydrate provides both steric and electrostatic stabilization to the nanoparticles. This means that morin hydrate minimizes the interactions between different nanoparticles and keeps the nanoparticles in a stable colloidal suspension. The hydroxyl and carbonyl groups present in morin hydrate have an ability to form strong interactions with metallic and metal oxide surfaces. Hence, by providing complete surface coverage on the nanoparticles, morin hydrate helps generate very narrow size distributions of nanoparticles, improve the ease of dispersibility of the nanoparticles, and prolong the stability of nanoparticles in physiological solutions. The ability of morin hydrate to be both a reducing and stabilizing agent therefore simplifies the synthesis of nanoparticles and reduces the number of additional chemicals that would otherwise be necessary as additives. The multifunctional nature of morin hydrate represents a significant contribution towards the creation of safer, more efficient, and more environmentally friendly methods of producing nanoparticles. (Wang et al., 2019)

The use of morin hydrate on surface of nanoparticles can greatly improve their therapeutic and biological properties. Morin has a large number of beneficial properties itself; these include extremely strong anti-oxidative, anti-inflammatory, antimicrobial and anticancer properties and the addition of morin onto nanoparticles will probably be useful either enhancing or maintaining those properties. Morin that is attached to the surface of nanoparticles can scavenge reactive oxygen species

and help to protect biological tissue from oxidative damage. The antioxidant properties of morin are especially important in biomedicine due to oxidative damage's contribution to the progression of diseases. In addition, morin-coated nanoparticles typically have much better interactions with biological membranes, aiding cellular uptake and increasing the effectiveness of their therapeutic effects. Studies have also shown that nanoparticles that have been functionalized with flavonoids (such as morin) have demonstrated significantly stronger antimicrobial propensities and greater cytotoxicity towards cancer cells when compared to unfunctionalized nanoparticles. The presence of morin hydrate on the surface of the nanoparticle also helps to maximize biocompatibility by decreasing unfavorable interactions with normal cells and tissues. Accordingly, morin hydrate appears to be an ideal candidate for incorporation into multifunctional nanotherapeutics. Combining nanoparticle technology with naturally-derived bioactive substances represents a strong strategy to improve treatment outcomes while minimizing potential side effects. Therefore, morin hydrate has become an increasingly important ingredient in the design and development of cutting-edge nanomedicine systems for future application purposes. (Rasmussen et al., 2010)

There have been recent developments in the field of green nanotechnology with a focus on the growing importance of natural flavonoid compounds such as Morin hydrate for synthesising nanoparticles and for use in biomedical engineering. Researchers are studying how Morin hydrate affects the size, shape, stability, surface chemistry and therapeutic activity of nanoparticles. The results of many studies indicate that nanoparticles synthesised through Morin-mediated methods have superior physicochemical properties

and improved biological performance. Morin hydrate can serve multiple functions at once; it acts as a reducing agent, stabilising agent, and bioactive coating material for nanoparticles, which is a major advantage over traditional methods of nanoparticle synthesis. Because Morin has multiple functions, it simplifies the manufacturing process of nanoparticles and increases the safety and effectiveness of the products produced. Additionally, Morin-based manufactured nanomaterials have shown great potential in the areas of drug delivery, cancer treatment, antimicrobial treatment, antioxidant treatment and diagnostic imaging. With the continued interest in sustainable and biocompatible nanotechnology, it is likely that Morin hydrate will become increasingly important in developing next-generation nanomaterials. Large-scale synthesis, mechanisms of action, and clinical studies are future directions of research that will help to establish Morin hydrate's ability to make a positive contribution to the pharmaceutical and biomedical fields. Consequently, Morin hydrate is an excellent natural resource to assist in environmentally friendly nanoparticle manufacturing and to improve nanotechnology-based healthcare solutions. (Ahamed et al., 2010)

Iron oxide (Fe_3O_4) nanoparticles

Magnetite nanoparticles (Fe_3O_4) are some of the most thoroughly researched magnetic nanomaterials owing to their intriguing physical, chemical, and biomedical characteristics. These nanoparticles possess superparamagnetism at the nanoscale, allowing them to respond very quickly to external magnetic fields while exhibiting no residual magnetism (residual magnetism). This feature makes them highly useful in many biomedical applications such as MRI, targeted drug delivery, hyperthermia treatment, biosensing, and tissue engineering. Fe_3O_4 nanoparticles also have

increased surface area, increased reactivity, and increased interaction with biological systems owing to their small size, which all make them suitable for use as diagnostic and therapeutic agents. Additionally, iron is one of the essential elements in the human body and thus helps to explain the relatively high biocompatibility of iron oxide nanoparticles when they are used in a controlled manner. There are many methods of synthesizing iron oxide nanoparticles; however, the "green synthesis" method is receiving a lot of interest due to its environmentally friendly and low toxicity. Iron oxide nanoparticles synthesized using green methods may have enhanced stability and improved functional properties due to coating with natural phytochemicals. Iron oxide nanoparticles have been the subject of considerable interest in nanomedicine as a way to create safe, efficacious, and multifunctional therapeutic systems. (Gupta et al., 2005)

Fe_3O_4 nanoparticles, with their superparamagnetic properties, have become one of the most important applications in the biomedical field, particularly as MRI contrast agents. The superparamagnetic properties are used to enhance contrast between different types of tissues, meaning that they improve the accuracy of imaging and therefore the accuracy of diagnosis from MRI or magnetic resonance spectroscopy studies. Compared to current standard magnetic resonance contrast agents, iron oxide nanoparticles are also safer to use, and have fewer toxic effects, allowing them to be used in clinical applications. Moreover, Fe_3O_4 nanoparticles can be functionalized with various biomolecules, including drugs, antibodies, or ligands, such that the nanoparticles can be directed to a specific site for drug delivery or targeted imaging. By doing so, Fe_3O_4 nanoparticles can also be classified as theranostic agents, meaning that they can provide diagnostic and therapeutic

features in one product. In drug delivery applications, iron oxide nanoparticles can be guided to specific target sites via external magnetic fields, thereby reducing the overall side effects of drug therapy and improving the success of treatments related to drug therapies. Furthermore, due to their ability to generate localized heat in the presence of an alternating magnetic field, Fe₃O₄ nanoparticles can also be used for hyperthermia cancer treatments, where the raised temperature is used to selectively kill cancer cells. These properties demonstrate the versatility of Fe₃O₄ nanoparticles as current and future biomedical engineering and precision medicine devices. (Laurent et al., 2008)

Biocompatibility and safety must be key considerations when developing nanoparticles for use in biomedicine. The human body contains iron (Fe) naturally, contributing to the transport of oxygen and metabolic processes within the body. When nanoparticles made up of Fe₃O₄ have been designed appropriately, they can potentially metabolize into and/or become incorporated into normal pathways for iron storage in the body and thus alleviate many of the long-term toxicity concerns associated with using them in humans and animals. However, the biological activity associated with the use of iron oxide nanoparticles will depend on several different factors including particle size, surface coating, dosage, and the amount of time exposed to the nanoparticle. In addition, uncoated nanoparticles or nanoparticles that have been poorly stabilized may produce oxidative stress and an inflammatory response due to the generation of reactive oxygen species (ROS). It is common to use surface modification techniques to modify the surface of iron oxide nanoparticles using biocompatible polymers, proteins, or compounds derived from plants to reduce the level of toxicity associated with their use. Using a green synthesis technique will provide a

natural capping agent that can lower levels of aggregation and increase stability when using iron oxide nanoparticles in a biological environment. In addition to lowering levels of toxicity, surface modifications will enhance both the ability of cells to uptake nanoparticles and their circulation time in the blood system. Because of these reasons, controlling the surface chemistry of iron oxide nanoparticles is an important consideration to ensure their safe use in the biomedical market, especially for drug delivery systems and imaging. (Wu et al., 2015)

Iron oxide nanoparticles exhibit good antimicrobial and antioxidant properties when produced through green methods. Their antimicrobial properties are mainly due to their ability to create reactive oxygen species and disrupt the membrane of microbial cells. In addition, when the iron ions that are released from the iron oxide nanoparticles disrupt the metabolism of microorganisms as well as enzyme function, this can lead to the death of the microorganism. Furthermore, when they are coated with natural substances like flavonoids, their biological responses are greatly enhanced by synergistic effects. The use of phytochemical coatings increases the antimicrobial activity as well as the antioxidant function of iron oxide nanoparticles, thus reducing the amount of oxidative damage to biological systems. This produces several advantages for iron oxide nanoparticles that have been produced through green methods in biomedicine, where the major source of damage is related to oxidative processes. Additionally, iron oxide nanoparticles have catalytic abilities that enable them to be involved in redox processes, thus offering great potential for both environmental detoxification and degradation of pollutants. Lastly, the combination of biological activity and magnetic properties gives iron oxide nanoparticles multiple

uses as therapeutic agents and for environmental applications. Consequently, further studies continue to reveal new uses of iron oxide nanoparticles for both nanomedicine and biotechnology. (Mahdavi et al., 2013)

While iron oxide nanoparticles have numerous benefits associated with their usage, there is still a need to carefully investigate the long-term safety and impacts on our environment. They have been generally recognized as biocompatible; however, when nanoparticles accumulate within tissues in excess of an acceptable limit then they may develop potentially toxic properties due to oxidative stress. As a result of this concern, it is critical that dosage control, surface engineering, and proper functionalization occur prior to any potential use of these materials in applications. Recent advancements in green synthesis techniques have shown promise for improving the safety profile of iron oxide nanoparticles by employing fewer hazardous chemicals as their stabilizers along with more natural alternatives, thereby improving reproducibility and increasing environmental sustainability for nanoparticles throughout the entire fabrication process. Continued research is being conducted to optimize the conditions under which nanoparticle synthesis occurs to allow the user to better control the characteristics (size, shape and surface properties) of an iron oxide nanoparticle for specific biomedical uses. Standardized guidelines must be implemented in order to regulate the use of these nanoparticles and ensure that all toxicity assessments follow uniform criteria to ensure their safe transition from clinical studies into clinical applications. As a promising technology, the integration of iron oxide nanoparticles into innovative drug delivery systems, imaging modalities, and novel therapies for the treatment of cancer, provides evidence of the growing significance of iron oxide nanoparticles in

the rapidly evolving field of nanomedicine. Continued research and development of Fe₃O₄ Nanoparticles will establish their pivotal role in the future of precision medicine and environmentally friendly nanotechnology. (Yew et al., 2020)

Enhanced Stability and Biocompatibility

Nanoparticle stability and biocompatibility are two of the most significant elements contributing to the effectiveness of nanoparticles used in biomedical applications. Stability means the capacity of nanoparticles to keep their physical or chemical properties over an extended time without aggregating, sedimenting or degrading, while biocompatibility indicates a nanoparticle's ability to interact with the biological system without any negative or toxic effects. Aggregation typically occurs with nanoparticles that have unstable structures, which in turn reduces the surface area, modifies the tendency of nanoparticles to chemically react with each other through chemical bonding, and therefore lessens their ability to be effective therapeutics for treating diseases/patients. Similarly, poor biocompatibility can affect cell viability (cytotoxicity), induce inflammatory responses (inflammation), and modulate the immune response adversely, thereby restricting the clinical applications of nanoparticles. Consequently, in order for nanoparticles to be used successfully in drug delivery systems, imaging systems, cancer therapies, and antimicrobial therapies; they must possess both high levels of stability and biocompatible properties. The use of green synthesis practices involving various plants, flavonoids, and other naturally derived plant material substances have demonstrated excellent capabilities in enhancing these two characteristics. The green synthesis process involves using biological agents to serve as natural capping and

stabilizing agents to form a protective coat around nanoparticles, thus reducing their tendency to aggregate and enhancing their ability to disperse throughout the biological media in which they are used. In summary, nanoparticles synthesized using green synthesized methods exhibit a greater degree of physiological compatibility and reduced toxicity, making them a superior candidate for use in biomedical applications. (Mourdikoudis et al., 2018)

The surface chemistry, size distribution and conditions used to produce these nanoparticles determines their stability; however, nanoparticles created with smaller, consistent sizes tend to have greater stability than larger ones because smaller particles do not experience as much gravitational force to pull them to the bottom of a liquid. Additionally, because smaller nanoparticles are less likely to collide with each other and form larger aggregates than larger particles, their ability to resist aggregation tends to improve. Zeta potential (the charge associated with the surface of a particle) is another critical indicator for maintaining the stability of colloidal nanoparticles; therefore, highly charged surfaces will repel one another by means of electrostatic forces and inhibit the formation of aggregates. In addition, biological solutions are often composed of salts and proteins that change these electrostatic forces and contribute to the instability of nanoparticles; therefore, surface modifications are necessary to retain the stability of nanoparticles when they are used in a biological environment. The application of natural products for the green synthesis of nanoparticles produces organic coatings on the surface of metal or ceramic nanoparticles and provides additional steric stabilization of particles by preventing them from interacting with each other. The stabilization of nanoparticles can also be achieved by controlling the parameters during synthesis, including but not

limited to: pH, temperature and concentration. Successful stabilization of nanoparticles allows these materials to retain their physical and functional properties, providing predictable performance in biomedical applications. If nanoparticles do not maintain adequate stability, they will be ineffective at achieving an optimal therapeutic effect because they will lose structural integrity and functional properties before reaching their target site. Consequently, it is imperative that nanomaterials manufactured for medical and pharmaceutical applications meet the optimum conditions necessary for achieving long-term stability via adequate synthesis techniques and appropriate surface modifications. (Wang et al., 2016)

Biocompatibility, like stability, has a critical impact on the interactions between nanoparticles and cells, tissues and biological systems. When introduced into an organism, a biocompatible nanoparticle must not have a toxic effect, produce an immune response or induce oxidative stress. Some of the factors that influence biocompatibility include the particle size and shape, surface charge, coating materials, and dosage. Smaller nanoparticles often penetrate cells more easily, which may be beneficial to drug delivery; however, if not controlled properly may increase the potential for toxicity. Surface coatings derived from naturally occurring biomolecules result in a much greater level of biocompatibility because they reduce the amount of direct contact between the nanoparticle core and biological components. In addition to improving the biocompatibility of the nanoparticles by providing a barrier to protein adsorption, these coatings also reduce immune recognition and increase circulation time in the blood. Particles produced through “green” synthesis methods generally exhibit greater biocompatibility than those produced synthetically, since they lack toxic

reagents and are often coated with natural phytochemicals. These natural biomarkers also possess additional biological activity such as antioxidant and anti-inflammatory properties. Thus, both reducing toxicity and enhancing therapeutic interaction within biological systems enhances the biocompatibility of the nanoparticle. (Jeevanandam et al., 2018)

Nanoparticles in biomedicine are better able to achieve therapeutic value because of two critical features—better biocompatibility and enhanced stability. Stability ensures that all active species remain unaffected prior to the delivery of the nano-entity to the desired location (i.e., the site to which the drug has to be delivered), whereas the biocompatibility of a nano-entity ensures that it will interact safely with the body after being administered. The combined effect of these properties serves to improve the efficacy of drug delivery, reduce the incidence of adverse effects, and ultimately provide improved therapeutic outcomes. In the case of cancer treatment, the ability of stable and biocompatible nanoparticles to accumulate at an increased rate in tumor tissue (i.e., greater permeability or retention) allows for targeted drug delivery from the nanoparticle to the tumor. In antimicrobial applications, stable and biocompatible nanoparticles effectively bind to microorganisms while causing no harm to healthy surrounding tissues. In diagnostic imaging, stable nanoparticles improve the reliability of contrast enhancement by providing predictable and confident enhancement of the structure of the investigated tissue or organ when imaged. The incorporation of chemically derived natural stabilizing materials during the synthesis of nanoparticles has increased these benefits further by creating nanoparticles with multifunctional surfaces that contain both stability and biological activity. The combination of these characteristics

makes nanoparticles particularly attractive candidates for use in innovative nanomedicine systems where precise control over performance within complicated environments is necessary. Thus, it is essential to provide both stability and biocompatibility in developing safe and effective nanoparticle therapeutics for future clinical applications. (Yu et al., 2019)

In recent years, advances in nanotechnology have been primarily focused on developing a sustainable, safe, long-term stable nanoparticle product via both greener synthesizing methods and surface engineering techniques. Many researchers have begun to utilize plant extract, protein, polysaccharide, and flavonoid materials to stabilize and make nanoparticles more compatible with biological systems. Not only do these naturally derived materials prevent nanoparticles from agglomerating, they also help to disperse nanoparticles within physiological fluids, both critical for intravenous and oral delivery of drugs. Surface functionalization with biocompatible polymers, like polyethylene glycol (PEG), is one of the most common methods utilized to enhance the overall nanoparticle stability and to help prevent immune system recognition. Therefore, these surface modifications help to extend circulation time and improve targeting capability. Additionally, advances in characterization techniques have allowed researchers to better understand how nanoparticles behave while within a biological environment, leading researchers to optimize their design for certain applications. Nevertheless, challenges in creating a consistent method for large scale manufacture and stable in vivo storage of these nanoparticles still exist. Further research continues to refine methods that will assure both reproducibility and safety across various nanoparticle systems. In conclusion, continued integration of green chemistry principles into the

field of nanotechnology is an essential aspect of creating stable and biocompatible nanomaterials for use in biomedical and pharmaceutical applications. (Kumar et al., 2020)

Antioxidant Activity and Antimicrobial Activity

The antioxidant activity of materials is one of the key biological functions that helps all living systems to combat oxidative stress caused by reactive oxygen species (ROS) generated in biological systems (an imbalance of ROS and the ability of the organism to neutralize them). An excessive amount of ROS can damage overall cellular structures (lipids, proteins, and DNA) in an organism which, in turn, leads to many different diseases or conditions (e.g., cancer, diabetes, cardiovascular diseases, and neurodegenerative disorders). Nanomaterials, particularly when made using green chemical processes, can provide effective antioxidant potential based on their surface reactivity and the availability of bioactive materials. In particular, metal oxide nanoparticles (e.g., zinc oxide and iron oxide) may also produce and/or eliminate ROS based on their surface chemistry and environmental conditions. Furthermore, stabilizing these nanoparticles with natural substances (e.g., flavonoids) can improve their antioxidant potential by creating a synergistic effect. As a result, these natural coatings also contribute to the ability of these nanoparticles to scavenge free radicals, thereby enhancing the overall effectiveness of these nanoparticles in biological systems. There are several common methods for measuring the antioxidant activity of nanoparticles such as DPPH, ABTS, and FRAP assays. Because of the presence of plant-derived molecules that remain on the surface of nanoparticles produced using green synthesis methods, these nanoparticles have relatively better

antioxidant efficiency than do equivalent-conventional synthesized nanoparticles and therefore are ideally suited for use in medical applications where oxidative damage must be controlled. (Zhang et al., 2015)

The antioxidant properties of nanoparticles involve several mechanisms, such as directly neutralizing free radicals, reducing the activity of oxidative enzymes, and boosting the cellular defense systems against oxidative stress. Smaller nanoparticles with larger surface areas tend to demonstrate greater antioxidant effectiveness because they interact more with reactive species. Enhancements occur when phytochemicals are added to their surfaces, improving their capacity to combat free radicals. Plant extracts high in flavonoids and phenolic compounds have potent electron-donating capabilities that aid in stabilizing reactive oxygen species. During the synthesis of nanoparticles, these components can both reduce metal ions and adhere to the nanoparticle exterior, thereby increasing their antioxidant abilities. Moreover, metal oxide nanoparticles may influence intracellular signaling pathways associated with oxidative stress response, offering additional protective effects at the cellular level. This combined action of nanoparticles along with natural substances makes green-synthesized nanomaterials particularly effective for addressing diseases linked to oxidative stress. Such antioxidant functions are crucial in cancer treatment because maintaining oxidative balance is vital for regulating tumor growth and programmed cell death (apoptosis). Hence, green nanoparticles present a promising avenue for developing cutting-edge antioxidant therapies within contemporary medicine. (Li et al., 2017)

Nanoparticles' ability to kill microbes has attracted large amounts of interest because of the growing problem with-resistant microorganisms. In the

world today there has been an increased need for alternative therapies. Antimicrobial properties can be found in metal oxide nanoparticles like iron (Fe_3O_4) and Zinc (ZnO) (bacteria, fungi and viruses). Antimicrobial mechanisms involve several different pathways. These pathways include generating reactive oxygen species (ROS), disruption of the cell membranes, leakage of the intracellular contents, and interfering with essential metabolic processes. ZnO nanoparticles produce ROS like hydrogen peroxide which is usually generated through oxidative pathways and therefore cause oxidation damage to the microorganisms living in this toxic environment. Nanoparticles also possess antimicrobial activity (e.g. FeO) however by modifying the nanoparticles with bioactive agents they are more effective than when they are not modified. Because of the small size of nanoparticles they have been shown to have a stronger interaction between nanoparticles and the external surface of microorganisms and the damage done interacts at the structural level as well. Therefore, positively charged nanoparticles can adhere to the negatively charged bacterial cell wall which results in the alteration of the structure of the bacteria causing bacterial cell death. Using green synthesis methods to produce these polymers can have additional benefits on enhancing the antimicrobial activity if the phytochemicals can act synergistically with the metal ions on the particle surface. This interaction increases the efficiency of the antimicrobial properties while decreasing the toxicity to human/animal cells. Therefore it is reasonable to assume that these nanoparticles may provide a new alternative to conventional antibiotics for use against resistant microorganisms. (Sondi&Salopek-Sondi, 2004)

Nanoparticles have a variety of antimicrobial mechanisms that depend on several physicochemical properties, including size, shape,

surface charge, and concentration. Smaller nanoparticles generally provide greater antimicrobial effectiveness due to increased surface area, allowing for better penetration into microbial cells. Additionally, surface functionalization with plant extracts enhances the interaction between nanoparticles and microorganisms and improves the overall antimicrobial efficacy of nanoparticles. Among many other antimicrobial mechanisms, nanoparticles produce reactive oxygen species (ROS) that induce oxidative stress within microbial cells, damaging proteins, lipids, and DNA. The release of metal ions from nanoparticles also contributes to the antimicrobial activity of nanoparticles by disrupting enzymatic systems and metabolic pathways. Green-synthesized nanoparticles exhibit reduced cytotoxicity toward human cells, while still retaining strong antimicrobial properties. Therefore, the selective toxicity of green-synthesized nanoparticles makes them ideal candidates for use in biomedical applications, including wound healing, medical device coatings, and infection control. Furthermore, nanoparticles are also used in combination with antibiotics to enhance their antimicrobial effect and to overcome the resistance mechanisms of bacteria. Using this synergistic approach is essential for combating types of bacterial strains that are resistant to multiple drugs. Research is ongoing to investigate how to optimise the properties of nanoparticles to develop their maximum antimicrobial effect while also maintaining human safety and compatibility with the environment.(Prabhu&Poulose, 2012)

Recent developments in nanotechnology have enhanced our comprehension of the characteristics and applications of nanoparticles and their antioxidant and antimicrobial properties. Researchers are now using greener methods to produce these nanomaterials so they remain

effective as well as safer for use. The addition of natural compounds, including flavonoids, polyphenols, and extracts from plants, significantly enhances the overall antioxidant and antimicrobial effects of nanoparticles. These natural biomolecules serve as reducing agents while synthesizing the nanoparticles, but they also remain chemically bonded to the surface of the nanoparticle; thus, they provide an additional way to biologically function in vivo. By utilizing advanced characterization techniques, researchers have gained insights into how nanoparticle structure and biological activity are related. Research has shown that optimized size, shape, and surface chemistry of nanoparticles can greatly enhance their therapeutic effectiveness. Antioxidant nanoparticles' role in reducing oxidative stress-induced cellular damage is well-documented, while antimicrobial nanoparticles' use in controlling infection and microbial growth is becoming more widely accepted. The combination of these two functionalities within one nanomaterial suggests tremendous potential for multifunctional therapeutic usage; however, various issues such as long-term safety, stability, and large-scale production still present challenges for researchers exploring ways to provide beneficial health care products over the long term. Ongoing research will help researchers understand the mechanisms by which these nanoparticles function as well as optimize their clinical applications. Overall, antioxidant and antimicrobial nanomaterials demonstrate significant promise for advancement in sustainable nanomedicine and innovation in health care. (Rajiv et al., 2013)

Conclusion

The study demonstrates the importance of green synthesis methods to produce biocompatible, stable and therapeutically effective nanoparticles from natural compounds like Morin hydrate. Green

nanotechnology produces a sustainable and environmentally friendly method to create metal-containing nanoscale materials as it does not use toxic reagents and minimizes environmental hazards associated with standard physical or chemical processes. Biomolecules derived from plants help reduce metal ions into nanoparticles and result in more stable and effective nanoparticles through their improved biological activity and dispersion characteristics. Among the number of types of nanoparticles evaluated in this study, zinc oxide (ZnO) exhibited potent antimicrobial and anticancer activities due to the ability of ZnO nanoparticles to produce reactive oxygen species that can disrupt microbial and cancer cell function. Conversely, the iron oxide (Fe₃O₄) nanoparticles exhibited excellent magnetic properties and biocompatibility and show significant promise for application in drug delivery, imaging modalities, and hyperthermia. The stabilization of both nanoparticle systems with Morin hydrate provided additional antioxidant activity, enhanced surface stability, and increased therapeutic efficacy through synergistic interactions. Results of comparative evaluation demonstrate that each nanoparticle has advantages based on use in specific biomedical applications.

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