Zinc Oxide Nanoparticles and Their Physiochemical Properties

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Zinc oxide nanomaterials have been the cynosure of this decade because of their immense potential in different biomedical applications. It includes their usage in the prognosis and treatment of different infectious and cellular diseases, owing to their peculiar physiochemical properties such as variable shape, size, and surface charge etc. Increasing demand and usage of the ZnO nanomaterials raise concerns about their cellular and molecular toxicity and their biocompatibility with human cells.

Keywords: ZnO nanoparticles ; biocompatibility ; cancer prognosis

1. Introduction

Cancer is a devastating disease affecting millions of people worldwide which has necessitated the exploration of novel and effective therapeutic approaches [1]. Traditional treatments, such as chemotherapy and radiation therapy, often encounter limitations such as drug resistance and toxicity to healthy tissues [2]. Therefore, there is a pressing need to develop innovative cancer therapies that can overcome these challenges. In recent years, nanoparticles, specifically zinc oxide nanoparticles (ZnO NPs), have emerged as a promising area of research in cancer treatment [3]. ZnO NPs possess unique characteristics that make them highly suitable for cancer therapy [4]. Their high surface area-to-volume ratio enhances reactivity and improves drug delivery efficiency. Moreover, their small size enables functionalization for targeted delivery to cancer cells while sparing healthy cells from harm. Additionally, ZnO NPs exhibit photocatalytic properties, which can be harnessed for photodynamic therapy [4]. Studies have shown that ZnO NPs can inhibit the progression of cancer cells by inducing apoptosis, cell cycle arrest, and DNA damage [5]. Furthermore, they have the potential to enhance the efficacy of traditional cancer treatments, such as chemotherapy and radiation therapy, by increasing drug uptake and improving the delivery of therapeutic agents to cancer cells [5]. Although ZnO NPs offer significant promise in cancer therapy, addressing potential risks and concerns is crucial for their clinical application. One major concern is the potential toxicity of ZnO NPs, which can vary depending on size, shape, and surface charge [6]. A comprehensive understanding of the interactions between ZnO NPs and cells or tissues is still lacking, necessitating further investigation to elucidate their biological effects. Another concern is the possibility of ZnO NPs accumulating in organs and tissues, which may lead to long-term health effects [7]. In light of these considerations, it is clear that ZnO NPs have shown great potential as cancer therapies, owing to their unique properties and ability to enhance the effectiveness of conventional treatments. However, addressing the identified risks and concerns and conducting further research to fully comprehend the biological effects of ZnO NPs are imperative for the development of safe and efficient methods for cancer therapy [8].

Moreover, ZnO NPs have demonstrated great potential in drug delivery applications, capitalizing on their distinctive physicochemical characteristics, such as a large surface area to volume ratio, biocompatibility, and photostability [9]. ZnO NPs can effectively carry various drugs, including anti-cancer agents, antibiotics, and anti-inflammatory drugs. Different strategies for drug delivery use ZnO NPs, such as surface loading of drugs onto the nanoparticles and encapsulating drugs within the NPs. These approaches have shown successful delivery of drugs such as doxorubicin, paclitaxel, curcumin, ibuprofen, and methotrexate [8][10].

Furthermore, functionalizing ZnO NPs with targeting ligands, such as antibodies, peptides, or aptamers, have been explored to enhance their specificity for particular cell or tissue types, thereby improving drug efficacy and minimizing side effects [11]. The ability of ZnO NPs to deliver drugs with enhanced targeting and controlled release has the potential to revolutionize drug delivery systems, improving the delivery of drugs and reducing their adverse effects [12]. However, further research is necessary to fully understand the safety and efficacy of these approaches [13]. In recent studies, zinc oxide quantum dots (ZnO QDs) have also shown promise as pH-responsive pore-blockers and drug delivery agents [14].

These studies have demonstrated the successful doxorubicin (DOX) delivery to cancer cells using ZnO QDs, resulting in efficient drug release in intracellular compartments and increased cytotoxicity [15]. Additionally, ZnO-functionalized upconverting nano theranostic agents have shown the potential for targeted drug delivery and real-time monitoring of treatment efficacy through their multi-modality imaging capabilities.

Utilizing ZnO NPs and their derivatives in cancer therapy and drug delivery holds significant promise. These nanoparticles offer unique properties that can enhance the effectiveness of traditional treatments and enable targeted drug delivery. However, it is crucial to address potential risks and concerns associated with their use and conduct further research to fully understand their biological effects and develop safe and efficient cancer therapy and drug delivery methods. In overcoming these challenges, ZnO NPs have the potential to revolutionize cancer treatment and improve patient outcomes [16][17].

2. Zinc Oxide Nanoparticles and Their Physiochemical Properties

Owing to the unique optical properties of ZnO NPs, they have been considered an important and distinctive tool for different biomedical and environmental applications. Some of these include the following.

2.1. Size and Shape

Zinc oxide nanoparticles (ZnO NPs) have garnered significant attention due to their distinctive properties associated with their size and shape. The physical and chemical characteristics of ZnO NPs are greatly influenced by their size, shape, and surface area. Specifically, the morphological features of ZnO NPs play a crucial role in determining their optical, electronic, and magnetic properties. For instance, spherical ZnO NPs exhibit a higher surface area-to-volume ratio compared to rod-shaped ones, resulting in enhanced reactivity and light absorption capabilities. Moreover, ZnO NPs possess an elevated surface area-to-volume ratio, rendering them highly reactive and effective in diverse applications such as catalysis, sensors, and biomedical applications. However, it is important to note that the size of ZnO NPs can also impact their toxicity and biological activity, underscoring the need to optimize the nanoparticles' size and structure for specific applications [18][19].

The characterization of ZnO NPs in different dimensions (1D, 2D, and 3D) has been categorized using various standard techniques. The details can be specified as the following.

2.2. Surface Area

The surface area of ZnO NPs is crucial in determining their properties and applications. They have a large surface-to-volume ratio, and so ZnO NPs have more surface atoms available for reactions, making them more reactive than their bulk counterparts [18]. This increased surface area can enhance their catalytic, photocatalytic, and sensing properties, making them attractive for various applications. The surface area of ZnO NPs also affects their strength and biocompatibility [20]. Large surface areas can increase the surface energy and reactivity of the nanoparticles, leading to accumulation and instability. On the other hand, smaller ZnO NPs with a large surface area can interact with biological molecules and cells more efficiently, making them useful in biomedical applications [21]. For example, a study investigated the impact of surface area on the efficacy of zinc oxide nanoparticles for treating lung cancer in mice. They prepared two types of nanoparticles: large-sized particles with a low surface area, and small-sized particles with a high surface area. The mice were divided into two groups, with each group receiving one type of nanoparticle treatment. Results showed that the group treated with small-sized nanoparticles, having a higher surface area, exhibited a greater reduction in tumor size compared to the group treated with large-sized nanoparticles. This suggests that surface area influences the therapeutic effectiveness of zinc oxide nanoparticles in lung cancer treatment [22]. Moreover, the surface area of ZnO NPs can be modified through various surface modification techniques, including surface functionalization and doping, which can alter their physicochemical properties and improve their performance in specific applications. Therefore, controlling and optimizing the surface area of ZnO NPs is crucial for designing and developing their applications in various fields.

2.3. Electrical and Optical Properties

Zinc oxide nanoparticles (ZnO NPs) possess unique optical and electrical properties that make them highly desirable for various applications. Regarding optical properties, ZnO NPs have a wide bandgap, allowing them to absorb ultraviolet (UV) light effectively. These characteristics benefit applications such as photocatalysis and photovoltaics, enabling efficient solar energy conversion into electricity [23]. The optical properties of ZnO NPs can be altered by adjusting their size and form, leading to a blue shift in the absorption edge known as quantum confinement [24]. Additionally, certain sizes and shapes of ZnO NPs exhibit the surface plasmon resonance (SPR) effect, which results in strong absorption and scattering of light in the visible and near-infrared regions. This makes ZnO NPs useful in biosensing and imaging applications. The electrical properties of ZnO NPs are also important. They are semiconducting materials with a wide bandgap, capable of efficiently absorbing and emitting UV light [25]. Doping ZnO NPs with impurities can further modify their electrical properties, enabling n-type or p-type conductivity and facilitating their use in electronic devices such as transistors, LEDs, and solar cells. The size, shape, and surface area of ZnO NPs also influence their electrical characteristics, with nanorods and nanowires displaying anisotropic properties and small NPs exhibiting size-dependent electrical behavior. Through manipulating the dimension, form, and surface properties of ZnO NPs, their optical and electrical characteristics can be fine-tuned to suit various applications in fields such as photocatalysis, photovoltaics, and optoelectronics [26].

2.4. Thermal Stability

The thermal properties of ZnO NPs are essential for their applications in various fields, including electronics, catalysis, and energy storage. ZnO NPs have a high melting point of approximately 1975 °C and a low thermal conductivity, making them good thermal insulators. The thermal conductivity of ZnO NPs will be enhanced by doping with elements such as aluminum, gallium, or indium, which can also modify their electronic and optical properties [27]. These doped ZnO NPs can be used in thermoelectric applications to convert heat energy into electrical energy. Furthermore, the thermal stability of ZnO NPs can be improved by surface modification techniques such as coating with a protective layer or functionalization with organic or inorganic molecules. These modifications can also enhance their dispersion and prevent accumulation, improving thermal conductivity and stability. In addition, ZnO NPs can be used as thermal energy storage materials due to their high specific heat capacity, which can store thermal energy efficiently. This property makes them useful in solar energy storage and waste heat recovery applications. In conclusion, the thermal properties of ZnO NPs are crucial for their applications in various fields, and their properties can be tailored by doping surface modification and size control.

2.5. Magnetic Properties

ZnO NPs are not magnetic in their pure form because they have no unpaired electrons in their crystal structure. However, the magnetic characteristics of ZnO NPs can be induced by doping with magnetic ions or by forming magnetic nanocomposites with other materials. Doping ZnO NPs with magnetic ions such as iron, cobalt, or nickel can introduce magnetic moments to the crystal structure, leading to magnetic properties. These magnetic ZnO NPs can be used in magnetic data storage, sensors, and biomedical applications. In addition, magnetic nanocomposites can be formed by incorporating ZnO NPs into magnetic materials such as iron oxide or cobalt oxide. These composites exhibit unique magnetic properties that can be tailored by controlling the nanoparticles' size, shape, and composition. Magnetic ZnO nanocomposites can be used in magnetic hyperthermia, drug delivery, and MRI [28]. Moreover, their shape and size can also influence the magnetic properties of ZnO NPs. For example, ZnO nanorods can exhibit anisotropic magnetic properties due to their elongated shape. Additionally, smaller ZnO NPs have a larger surface area-to-volume ratio, which can increase their magnetic moments and enhance their magnetic properties. The magnetic characteristics of ZnO NPs can be induced by doping, forming magnetic nanocomposites, and controlling their size and shape. These magnetic properties make ZnO NPs attractive for data storage, sensors, and biomedicine applications [27].

2.6. ROS Inducing Property

ZnO NPs have attracted significant attention as antibacterial agents due to their unique characteristics. ZnO NPs can prevent the growth of many bacteria, including Gram-positive and Gram-negative bacteria, making them an attractive alternative to conventional antibiotics. ZnO NPs' antibacterial characteristics are primarily attributed to their ability to generate ROS upon UV or visible light exposure. ROS can cause oxidative stress and damage bacterial cells, inhibiting bacterial growth and cell death [29][30]. Moreover, ZnO NPs can also interact with bacterial cell membranes, disrupting their structure and function. ZnO NPs can penetrate the cell membrane and interact with intracellular components, and inhibit bacterial growth [31].

Furthermore, the antibacterial properties of ZnO NPs can be enhanced by size and shape control, as smaller particles and particles with a higher surface area-to-volume ratio can exhibit more significant antibacterial activity. ZnO NPs exhibit solid antibacterial properties due to their ability to generate ROS and interact with bacterial cell membranes. Both Gram-positive and Gram-negative bacteria strains are susceptible to the ZnO NPs. ZnO nanoparticles have been demonstrated to be less effective against Gram-positive bacteria, according to the available research. Gram-negative bacteria have a modest advantage in resistance because of the unique structure of their cell walls [32]. Gram-negative bacteria, in contrast to Gram-positive bacteria, have an extra outer membrane that includes lipopolysaccharides (LPS). LPS has been shown to boost bacterial resistance, especially to antibiotics, by enhancing the barrier characteristics of the outer membrane [33]. The size and shape of ZnO NPs can also influence their antibacterial activity. Gram-positive bacteria such as *Bacillus* *subtilis* and *Staphylococcus aureus* as well as Gram-negative bacteria such as *Pseudomonas aeruginosa*, *Campylobacter jejuni*, and *Escherichia coli* have been used to investigate ZnO NPs' antibacterial activity [34]. Upon reducing the size of the ZnONP to the nano range the bacteriostatic effect was enhanced against *S. aureus*, *E. coli*, *P. aeruginosa*, and *Pseudomonas fluorescens* [35]. These properties make ZnO NPs attractive for various antibacterial applications, including wound healing, food packaging, and water purification [36]. Overall, the physical properties of ZnO NPs make them a promising material for several uses, including electronics, photonics, catalysis, and biomedical applications [37].

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