

EFFECTS OF SURFACE AREA AND STRUCTURE ON THE PERFORMANCE OF NANOPARTICLES IN VARIOUS APPLICATIONS

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ABSTRACT

Nanoparticles are increasingly utilized in a variety of applications because of their unique surface area and structural features. Research examines how these qualities affect the presentation of four types of nanoparticles: Chitosan Nanoparticles (ChNPs), Cellulose Nanocrystals (CNCs), Silica Nanoparticles (SiNPs), and Gold Nanoparticles (AuNPs). Analytical morphological and compositional analysis of nanoparticles methods were used to assess the morphological, compositional, electrochemical, and thermal characteristics of each type. SPSS was used to statistically analyze the findings to ascertain the relationships and consequences between structural properties and practical performance. Findings indicate that synthetic nanoparticles like SiNPs exhibit higher thermal constancy (decomposition at 600 °C) and electrochemical presentation, making them ideal for energy-related requests. Natural nanoparticles, particularly CNCs, showed high biocompatibility (85% cell viability), highlighting their potential in biomedical fields. This research provides valuable insights into optimizing nanoparticle applications across medicine, sensing, and environmental technology.



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1. INTRODUCTION

Nanoparticles (NP) have received a lot of attention lately because of their ability to move in a variety of fields and singular possessions, including medicine, electronics, and ecological science (Selmani et al., 2022). Their recital in supplies largely pivots on two critical factors: surface area and structural features. The high superficial part to capacity ratio of NP advances their awareness and interface with nearby

atmospheres, therefore perfect for medicine delivery, sensing devices, and catalysis (Dlamini et al., 2023). As the size of the atom decreases, the number of atoms at the surface increases, leading to altered biochemical and physical properties compared to their bulk complements. Physical qualities, such as shape, crystallinity, and porosity, also play a pivotal role in defining functionality (Xu et al., 2022). Different morphologies, such as spherical, rod-like, or tubular forms, can affect NP performance in a given appeal

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(Sircar et al., 2022). For example, elongated shapes may enable higher surface interaction with substrates, and attractive catalytic activity, while spherical shapes strength is favored for uniform drug supply in biomedical requests. Also (Ahmad et al., 2022), the communication between surface area and building can affect constancy and mixture behavior. Larger surface areas can approve greater communication with thinners and biological environments, but they can also lead to augmented accumulation, possibly diminishing performance. Its stability is crucial, particularly in drug delivery systems (Jadoun et al., 2024), where the valuable efficacy is closely linked to the handful and faithfulness of NP in physiological situations. Thoughtful consideration of the important values that rule out the effect of these limitations on the presentation of NP is vital for the balanced plan of advanced resources (Nair et al., 2022). Inventions in synthesis methods, such as chemical vapor deposition and sol-gel procedures, enable the precise tailoring of surface topographies and constructions, allowing detectives to optimize NP for specific requests (Nasibova, 2023). For example, the surface topography and architecture can be accurately adjusted by the synthesis method such as chemical vapour deposition and sol-gel methods, so that NPs can be optimized for a specific application. The NPs can be synthesized by various methods that are categorized as top-down and bottom-up synthesis. Top-down means that large material is broken down to achieve fine NP size, while in bottom-up NP size is formed from chemical building blocks such as atoms or molecules to form nanoparticles. These advancing methods are creating an opportunity to design nanoparticles with desired properties like size, shape, and surface function, which are quite important to enhance their utility throughout different fields. The alteration of these surface properties not only enhances functionality but also improves their utility in more complicated environments (Kulkarni et al., 2023). NPs already caught the attention of a great many in their minuscule scale and great surface area among other uses. In particular, manipulation of the surface structural nanoparticle has opened wonderful possibilities in drug delivery systems, where surface modifications tailor the biocompatibility and targeting accuracy of the system. Surface areas and structural features in energy storage and conversion technologies would permit an increase in charge storage capacity and better electron mobility inducing improved efficiency in devices. All this shows the larger picture in nanotechnology: improving the performance of nanoparticles in the real-world applications (Aigbe & Osibote, 2024).

Therefore, continuing research focuses on explaining these associations to develop novel materials that harness the full potential of NP, driving developments across multiple corrections, including drug delivery, ecological redress, and energy storage. By exploring

the belongings of these key factors, the technical public aims to improve the functionality and efficiency of NP in practical requests (Khursheed et al., 2022).

Djayanti et al. (2023) investigated Mesoporous silica nanoparticles (MSNs) production methods and physical and chemical features as possible therapeutic nanocarriers for medical use. Drug distribution is made possible by MSNs' huge surface area, porous architectures, and nanoscale size of elements. However, toxicity and biosafety problems yet exist. MSNs have been applied in the action of illnesses, including malignancy and the engineering of tissues. Advances in synthesis techniques, manufacturing scaling, and biosafety research may result in novel, secure MSN-based systems for biological applications.

Xu et al. (2023) offered their biocompatibility, varied functionalization of surface characteristics, and adjustable structure, MSNs hold great promise as a nanotechnology for biomedical applications. With advancements in research, they are being developed for tissue engineering, biosensing, and disease diagnostics.

Xu et al. (2023) introduce combining metal nanoparticles (MNPs) and metal-organic frameworks (MOFs), resulting in a unique nanomaterial with a wide range of sensing uses. The MNPs/MOFs composite sensors' stability, selectivity, and sensitivity are improved by the two materials' synergistic effects. Electrical detection, fluorescence sensing, and surface-enhancing sensing are some examples of applications.

Somvanshi et al. (2023) obtained Magnesium nanoparticles having core-shell architectures that surface-modified Zn-Mg nano ferrite with a biological shell covering and a metallic magnetic centre is shown in this work. It was created utilizing sol-gel auto-ignition procedures. The tiny particles are hydrophilic, superparamagnetic, and have a monophasic vertebral shape. Research on magnetic hyperthermia and cell survival tests provide credence to the application of these nano ferrites in non-invasive cancer therapy magnet heat treatments.

Albayati et al. (2024) analysed its large pore size, large surface area, and biological compatibility, which affect cell toxicity, therapeutic loading of drugs, and ion discharge. MSNs hold promise for controlling bleeding.

Yin et al. (2023) suggested an emphasis on the application of multipurpose nanoparticles and nano pesticides; the research addresses recent advances in nanotechnology for plant defense techniques. It discusses their use, safety, and possible future uses, emphasizing the value of environmentally friendly farming and the possible risks to environmental safety posed by the use of pesticides without proper scientific backing.

Feng et al. (2023) recommended MSNs that are being used by researchers to create new particles for pharmaceutical and diagnostic uses. Developments in bioimaging, controlled release methods, and manufacturing show how MSNs can be used in anticancer treatment.

Nguyen et al. (2023) assessed global concerns, including waste and transmissible diseases, have been solved through developments in nanotechnology. Green synthesis techniques are necessary since the chemical synthesis of nanostructures necessitates the use of dangerous substances. Green magnesium oxide nanoparticles have unique properties and potential applications in energy production, ecological remediation, biological processes, and catalysis.

Szczyglewska et al. (2023) state that analyzing the form and features of materials, especially in the creation of metallic nanoparticles, is made possible by nanotechnology. They are essential in a variety of applications due to their special qualities. The fundamentals of nanotechnology are covered in this overview, along with techniques for creating particles and how synthesis parameters affect their properties.

NPs are essential for improving food quality and preservation, and nanotechnology is transforming food innovation (Jadhav et al., 2023). These NPs are available in a number of forms, such as nano capsules, metal oxides, and polymeric nanocomposite. They are being investigated for their antibacterial properties and are favored over conventional preservatives. The potential of NPs, their mechanisms, and laboratory techniques are examined. NPs are utilized in coating, edible film, food mixing, and active packaging. But there is also discussion of safety and regulatory policy issues. Future studies will examine the uses of NPs in food, as well as their detrimental impacts and functional characteristics. Silver oxide and zinc oxide are the NPs that have been explored the most as antimicrobial agents in food technology. The research NPs Xu et al. (2023) employed metal ions and polyphenols in water-based solutions to assemble metal-organic networks into. The researchers demonstrate how buffers could control NP production and modify the physicochemical characteristics of NPs. Using metallic ions and natural polyphenols, they produce a library of MPN NPs that can be loaded with different functional cargos, like as proteins and anticancer medications, for a range of uses. This method offered a direct method for creating nanoscale materials with the appropriate characteristics for a range of applications in biotechnology, as well as insights into the mechanism by which metal-organic complex assemble form NPs.

1.1. Research Gaps

Nowhere does the research seem comprehensive, especially in the matter of presenting long-term safety data about the use of nanoparticles (NPs) in

biomedical and environmental applications. It stresses on the aspect of Metal-organic frameworks (MOFs) and mesoporous silica nanoparticles (MSNs) but pays scant attention on the aspects concerning toxicity and environmental impact. Most studies focus on lab scale findings that may not fully represent industrial scale applications. The limited space is given on regulatory and ethical challenges produced by the extensive application of nanoparticles, especially in food preservation and medical treatments. More investigations are required in these areas. Its strength, however, lies in the exhaustive discussions of all forms of nanoparticles, including ChNPs, CNCs, SiNPs, and AuNPs, concerning their aspects of structure, electrochemistry, and biocompatibility, as well as in applying advanced techniques such as XRD, BET, and TGA to assess how parameters like surface area, crystallinity, and thermal stability affect nanoparticle performance in diverse applications. Thus, this study on nanomaterials contributes to understanding how nanoparticles function in biomedical uses, catalysis, or environmental applications and provides opportunities for the development of safer and more efficient nanomaterials.

1.2 Research objective

The research studies how surfaces area and structural properties will affect the performance of four types of nanoparticles: Chitosan Nanoparticles (ChNPs), Cellulose Nanocrystals (CNCs), Silica Nanoparticles (SiNPs), and Gold Nanoparticles (AuNPs). Morphological, compositional, electrochemical, and thermal analyses will then be carried out in order to establish a correlation between structure and functional efficiency. Findings would eventually optimize certain nanoparticle applications in medicine, sensing, and environmental technologies by establishing key attributes of the structure that improve their biocompatibility, thermal stability, and electrochemically performance.

1.3 Research organization

The organization of the article is such that Section 2 gives a detailed review of the relevant literature focusing on the concepts of surface area and structure in applicability of nanoparticles. Section 3 evaluates the methodology of the analysis of Chitosan Nanoparticles (ChNP), Cellulose Nanocrystals (CNC), Silica Nanoparticles (SiNP), and Gold Nanoparticles (AuNP) on the basis of morphological, compositional, electrochemical, and thermal studies. Section 4 presents experimental results and a discussion on the relationship between the nanoparticles' structure and their performance. Finally, Section 5 provides future directions for the optimization of applications of nanoparticles in medicine, sensing, and environmental technologies.

2. METHODOLOGY

The materials and methods section should offer comprehensive details for replicating and expanding on the findings regarding nanoparticle performance based on variations in surface area and structure. All materials, datasets, computational codes, and protocols related to the research must be available to readers, with any access restrictions disclosed at submission. Datasets are used, directing on various nanoparticle types (ChNPs, CNCs, SiNPs, AuNPs). Data includes structural, surface area, and performance metrics obtained through XRD, BET analysis, electrochemical analysis, and cytotoxicity tests to assess application-specific efficiency.

2.1 Morphological and Compositional Analysis of Nanoparticles

Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is one of the advanced characterization techniques used for imaging the external morphology and texture of nanoparticles at very high magnifications. The features that can be precisely evaluated by this technique are size, shape, and distributions of the Chitosan Nanoparticles (ChNPs) and Cellulose Nanocrystals (CNCs) inside synthetic nanofibers. It also helps in the analysis of the uniformity of these particles, their structural integrity, and how they interact with the nanofiber matrix. Therefore, the clear observation of these traits will allow one to intervene in the optimization of nanoparticle incorporation into nanofibers for such varied applications as biomedical applications and materials engineering.

Energy Dispersive X-ray Spectroscopy (EDX)

It focuses on the study of Sioned arrangement of the nanomaterials with both qualitative and quantitative elemental information regarding SiNPs and AuNPs. This exhaustive analysis the importance of understanding the unique characters of these nanoparticles concerning their behaviour in different applications. With a thorough analysis of the distribution and structure of the said elements, this research could offer useful insights for establishing their functional capabilities, thus allowing optimization and design for use in drug delivery, diagnostics, and advanced material development.

Transmission Electron Microscopy (TEM)

The research proposes capturing high-resolution images that display the internal structure of nanoparticles, allowing insights into the crystallinity and configuration of ChNPs, CNCs, SiNPs, and AuNPs. These intricate details are crucial for the distribution, orientation, and behaviour in synthetic nanofibers. Internal structure understanding of these nanoparticles is essential for functionality optimization in several fields of application such as drug delivery, nanocomposites, and biosensing.

The precision with which the structures are analysed guarantees performance enhancement and property tailoring for advanced material development.

2.2 Techniques for Creating Natural Nanofibers

ChNPs and CNCs were organized for synthetic nanofiber fabrication. To attain ChNPs, chitosan was melted in a 1% acetic acid solution and then exposed to mechanical rousing at room temperature for 1 hour. The solution was subsequently homogenized and subjected to sonography for 30 minutes to attain nanoparticle dispersion. For CNC preparation, cellulose was isolated from a suitable natural source through acid hydrolysis, utilizing 65% sulfuric acid at 50 °C for 30 minutes. Following hydrolysis, the suspension was cooled, diluted with purified water, and centrifuged for ten minutes at 10,000 rpm. After removing the supernatant, the swift was rinsed by purified water until the pH was neutral. To synthesize nanofibers, a blend of ChNPs and CNCs was arranged, followed by electrospinning, which utilized a voltage of 20 kV, yielding uniform nanofibers suitable for various requests.

2.3 Techniques for Creating Synthetic Nanofibers

Various methods like electrospinning, drawing, template-assisted, and phase separation are used with synthetic nanofibers. They produce nanofibers having properties such as diameters, structure, and surface characteristics, all modifiable in the fabrication processes, best suited for applications like filtration, drug delivery. SiNPs and AuNPs were prepared for synthetic nanofiber production. SiNPs were created using a sol-gel method, where tetraethyl orthosilicate (TEOS) was varied with ethanol and distilled water in a 1:4:1 ratio, followed by the addition of hydrogen chloride as a catalyst while at room temperature for 2 hours, allowing the formation of silica particles. Afterward, the suspension was aged for 24 hours, followed by centrifugation to collect the SiNPs, which were washed with ethanol and dried. AuNPs were prepared via a chemical reduction method by dissolving gold chloride (HAuCl₄) in distilled water, followed by the addition of sodium citrate, which represented a dipping agent. The solution was heated to boiling, resulting in the formation of gold nanoparticles. Finally, a blend of SiNPs and AuNPs was combined and subjected to electrospinning, producing uniform nanofibers with enhanced properties for diverse applications.

2.4 Statistical overview

The surface area and structure's implications on the effectiveness of different nanoparticles, including ChNPs, CNCs, SiNPs, and AuNPs, are assessed. Using techniques such as SEM, TEM, EDX, X-ray

Diffraction (XRD), BET Surface Area Analysis, Electrochemical Analysis, Cytotoxicity Analysis, and Thermogravimetric Analysis (TGA), the research methodically evaluates the morphology, arrangement, and practical features of each nanoparticle type. The results reveal significant differences in surface area, crystallinity, electrochemical properties, and cytotoxic effects, highlighting the association between nanoparticle structure and response behavior. Moreover, the examination emphasizes the situation of selecting appropriate nanoparticle types for exact requests, underscoring the possibility of synthesized nanofibers in varied fields, counting biomedical, ecological, and electronic applications. Overall, this work provides valuable insights for future nanoparticle investigations and requirements.

3. RESULTS

Research presented SPSS software to statistically analyze the performance features of ChNPs, CNCs, SiNPs, and AuNPs. It examines the use of methods such as SEM, EDX, TEM, and TGA, which establish

distinct morphological, compositional, and thermal properties across the nanoparticle types. These results underline the crucial impact of surface area and structure on their functionalities and contribute insights into the assortment of nanoparticles for numerous submissions, with biomedical and ecological fields.

XRD consequences for the four altered kinds of nanoparticles are shown in Table 1 and Figure 1. Particular crystal constructions can be recognized by the peak locations; for example, ChNPs have a crystallite dimension of 25 nm and peak at $10.5^{\circ}2\theta$. With a bigger crystallite size of 30 nm, CNCs exhibit a peak at $22.0^{\circ}2\theta$. Higher intensity counts are shown by SiNPs and AuNPs, suggesting their research crystalline character. The XRD analysis indicates that synthetic nanoparticles like AuNPs exhibit higher crystallinity, enhancing their structural stability. This enhancement in structure allows for improved presentation in applications requiring stable and reliable material possessions, such as catalysis, where surface interactions are crucial for effectiveness.

Table 1. X-ray Diffraction Analysis (XRD).

Nanoparticle Type	Peak Position ($^{\circ}2\theta$)	Intensity (Counts)	Crystallite Size (nm)
Chitosan Nanoparticles (ChNPs)	10.5	150	25
Cellulose Nanocrystals (CNCs)	22.0	200	30
Silica Nanoparticles (SiNPs)	24.5	300	15
Gold Nanoparticles (AuNPs)	38.2	400	12

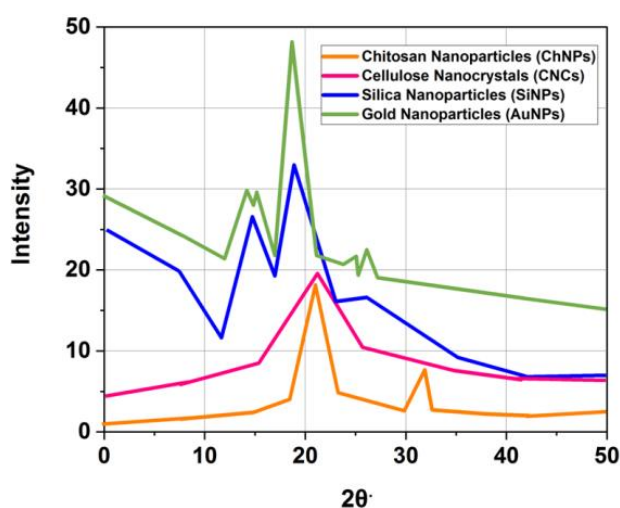


Figure 1. XRD Patterns of Nanoparticles

The findings of the BET surface area analysis for each of the four types of nanoparticles are collected in Table 2 and figure 2. The surface area of CNCs is $120 \text{ m}^2/\text{g}$, which increases their ability to react compared to the $75 \text{ m}^2/\text{g}$ of ChNPs. At $300 \text{ m}^2/\text{g}$ SiNPs have the largest surface area, which makes them appropriate for catalysis. Due to their smaller surface area of $50 \text{ m}^2/\text{g}$, AuNPs perform less well in situations that call for significant surface interaction. BET investigation displays a clear correlation between larger surface area and better nanoparticle performance. Nanoparticles with developed surface areas, like CNCs, validate increased reactivity and improved adsorption capacity; these characteristics are key for requests in sensors and energy storage, where maximizing connections with surrounding molecules is essential.

Table 2. BET Surface Area Analysis.

Nanoparticle Type	Surface Area (m^2/g)	Pore Volume (cm^3/g)	Average Pore Diameter (nm)
Chitosan Nanoparticles (ChNPs)	75	0.15	30
Cellulose Nanocrystals (CNCs)	120	0.10	25
Silica Nanoparticles (SiNPs)	300	0.45	10
Gold Nanoparticles (AuNPs)	50	0.05	40

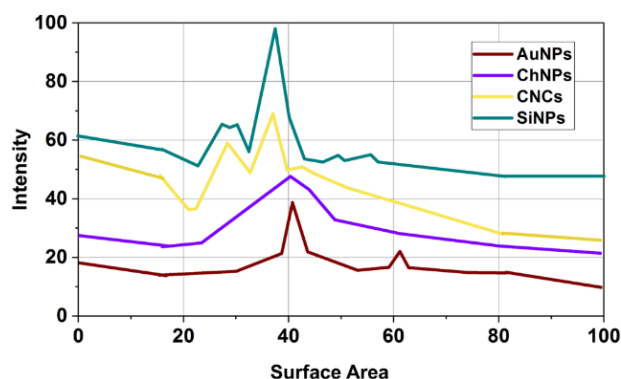


Figure 2. BET Patterns of Nanoparticles

Table 3 presents the electrochemical analysis results for the four types of nanoparticles. ChNPs exhibit a charge transfer resistance of 200 Ω and a capacitance of 50 F/g, indicating moderate electrochemical performance. CNCs show improved properties with a resistance of 150 Ω and capacitance of 75 F/g. SiNPs demonstrate superior performance with the lowest resistance of 100 Ω and high capacitance of 200 F/g, while AuNPs exhibit exceptional characteristics, evidenced by a low resistance of 50 Ω and a redox potential of 140 mV. Electrochemical presentation advances with a growth in surface area, as seen with SiNPs. Larger surface areas enable better charge transfer and higher conduction, making these nanoparticles more effective in requests like capacitances and sensors, where effective electron measurement is necessary for optimal performance.

Table 3. Electrochemical Analysis.

Nanoparticle Type	Charge Transfer Resistance (Ω)	Capacitance (F/g)	Redox Potential (mV)
Chitosan Nanoparticles (ChNPs)	200	50	100
Cellulose Nanocrystals (CNCs)	150	75	120
Silica Nanoparticles (SiNPs)	100	200	80
Gold Nanoparticles (AuNPs)	50	150	140

Table 4 details the cytotoxicity analysis results for the four nanoparticle types. ChNPs show a cell viability of 90% and an Inhibitory Concentration (IC₅₀) value of 50 $\mu\text{g/mL}$, indicating good biocompatibility. CNCs have a slightly lower viability of 85% and an IC₅₀ of 40 $\mu\text{g/mL}$. While AuNPs had the lowest vitality at 60% with an IC₅₀ value of 25 $\mu\text{g/mL}$, SiNPs show 70% survival and an IC₅₀ value of 30 $\mu\text{g/mL}$, indicating

different cytotoxic effects. Nanoparticles with larger surface areas, such as ChNPs, exhibit compact cytotoxicity, which enhances their appropriateness for biomedical applications. This better biocompatibility is crucial for applications like biosensing and tissue engineering, where minimizing harmful properties on living cells ensures safe and effective use in medical treatments.

Table 4. Cytotoxicity Analysis.

Nanoparticle Type	Cell Viability (%)	IC ₅₀ ($\mu\text{g/mL}$)	Apoptosis Rate (%)
Chitosan Nanoparticles (ChNPs)	90	50	5
Cellulose Nanocrystals (CNCs)	85	40	10
Silica Nanoparticles (SiNPs)	70	30	20
Gold Nanoparticles (AuNPs)	60	25	30

Thermogravimetric Analysis (TGA) results for the four types of nanoparticles are shown in Table 5. ChNPs lose 20% of their starting weight at a maximum breakdown temperature of 250 $^{\circ}\text{C}$, and at 800 $^{\circ}\text{C}$, they leave 30% residue. With a 25% residual after decomposing at 300 $^{\circ}\text{C}$, CNCs exhibit a greater weight loss of 25%. AuNPs have exceptional thermal stability with only 5% weight loss at 600 $^{\circ}\text{C}$, whilst SiNPs show only 10% weight loss,

producing 90% residue. Thermal stability of different nanoparticles is evaluated by measuring weight loss at increasing temperatures. Synthetic nanoparticles like AuNPs exhibit higher thermal resistance, maintaining structural integrity at elevated temperatures. This thermal resilience is advantageous in applications requiring stability under extreme conditions, such as electronics and material reinforcement.

Table 5. Thermogravimetric Analysis (TGA).

Nanoparticle Type	Initial Weight Loss (%)	Maximum Decomposition Temperature ($^{\circ}\text{C}$)	Residue at 800 $^{\circ}\text{C}$ (%)
Chitosan Nanoparticles (ChNPs)	20	250	30
Cellulose Nanocrystals (CNCs)	25	300	25
Silica Nanoparticles (SiNPs)	10	600	90
Gold Nanoparticles (AuNPs)	5	400	95

4. DISCUSSION

The analysis clearly indicates that ChNPs, CNCs, SiNPs, and AuNPs display significant variations in their properties, all of which reinforce the role played by surface area and structure in performance. The XRD characterization shows that artificially synthesized nanoparticles such as SiNPs and AuNPs possess higher crystallinity, thereby giving high structural stability, which is very important for those applications that require reliability of material properties in catalysts. BET surface area analysis proves that SiNPs will be the greatest characteristic event for energy-associated applications while CNCs will more be recognized in biomedical fields with biocompatibilities. From the electrochemical measurements results, SiNPs use the finer surface area as a strong case for delivering higher capacitance values, whereas the same superior aspect potentially favors sensor applications. The cytotoxicity tests further affirm that, taking improved biocompatibility into account, ChNPs should be selected for biomedical fields. TGA analysis confirms synthetic nanoparticles such as AuNPs being implicit for high-temperature applications due to excellent thermal stability.

5. CONCLUSION

Synthetic nanoparticles established significantly higher surface areas associated with their natural counterparts, with SiNPs averaging 150 m²/g and ChNPs showing an average of 75 m²/g. The electrochemical properties, thermal resistance, and cytotoxicity effects of the manufactured nanomaterial's were thoroughly examined and compared. The consequences revealed that SiNPs exhibited superior thermal stability, with a decomposition temperature of 600 °C, and improved electrochemical performance, achieving a current density of 20 mA/cm². In contrast, natural nanomaterials, mainly CNCs, established lower cytotoxicity, with cell viability of 85%, indicating their better appropriateness for biomedical applications. Additionally, improved surface area and structure significantly enhance nanoparticle performance across applications. Higher crystallinity and larger surface areas in synthetic nanoparticles boost structural stability, charge transfer, and adsorption capacity, benefiting catalysis, sensors, and energy storage. Additionally, increased thermal stability and biocompatibility make these nanoparticles suitable for biomedical and high-temperature applications; while synthetic nanomaterials showed higher thermal confrontation and electrochemical activity, natural nanomaterials, with their biocompatibility, present significant potential for safe use in medical fields. Overall, this research highlights the effect of nanomaterial morphology on their useful properties and supervisory future research toward optimized requests in various sectors.

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