

EXPLORING THE INTERRELATIONSHIP BETWEEN NANOPARTICLE PROPERTIES AND THEIR TOXICOLOGICAL EFFECTS

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ABSTRACT

The exploration of nanoparticle properties and their toxicological effects is crucial for advancing nanotechnology applications while ensuring environmental safety. Research investigates the interrelationship between the characteristics of nanoparticles, which include size, zeta potential, surface charge, and shape. A mixed-methods approach was employed, utilizing correlation analysis to identify significant relationships among the properties revealing strong to moderate correlations. Regression analysis established predictive relationships, which reveal that nanoparticle characteristics significantly influence toxicological outcomes. Additionally, t-tests were conducted to compare means across various conditions, demonstrating statistically significant differences in toxicity related to specific nanoparticle attributes. Thematic analysis of qualitative data highlighted key themes, such as the role of particle size in toxicity, the influence of surface charge on biological interactions, and the implications of shape on cellular responses. The findings emphasize the importance of understanding nanoparticle properties for developing safer nanomaterials and formulating informed regulatory policies. This research not only enhances knowledge in the field of nanotoxicology but also contributes to the responsible application of nanotechnology in various industries, ultimately promoting public health and environmental sustainability.



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1. INTRODUCTION

The unique features of nanoparticles (NPs) receive significant attention because they establish valuable applications across electronics, medicine and environmental remediation. Nanoparticles display greater surface area and reactivity and sizing-controllable

optical and magnetic properties which exceed bulk properties at nanometric dimensional levels.

However, their increased use has raised concerns about potential toxicological effects on hominoid strength and the abiotic environment (Khan & Hossain 2022). For instance, their size and magnitude can interact with biological systems,

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possibly making them poisonous to cells due to inflammation, oxidative stress, and cell damage (Nikzamir et al., 2021). However, the development of safer nanomaterials requires a fundamental understanding of the relationship between the properties (size, shape, surface charge, and surface chemistry) of NPs to their toxicological impact (Bilardo et al., 2022). As shown in Figure 1, NPs present in the human body have toxic effects.

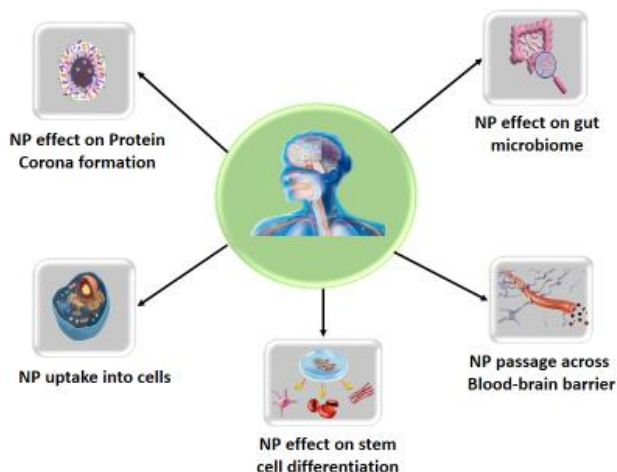


Figure 1. Schematic representation of toxic effects of NPs in the human body

The toxicological profile of NPs is often influenced by a strong dependency on their physiological characteristics, which include factors such as cellular uptake, biodistribution, and aggregation behavior of NPs (Garcés et al., 2021). The complexity of NPs presents a formidable challenge for researchers as well as regulatory bodies and points to the necessity of understanding changes in NP attributes to determine their potential hazard (Isibor et al., 2024). For instance, such information would inform the synthesis of NPs with low risks, and there would be an avenue to safe usage in many industries with minimal damage to ecosystems (Zhang et al., 2022). NPs present distinct physical qualities and chemical characteristics that powerfully affect their way of interacting with biological structures. The biodistribution and cellular uptake of NPs together with their toxicological effects depend on two key factors – their small size and varied morphology and surface charge and chemical composition. Knowledge about the relationships between nanotechnology attributes and biological system responses forms the basis for safe nanotechnology application. Various physicochemical properties of NPs lead to distinct toxicological effects that affect cell functions and inflammation and the general compatibility with biological environments. This research examines the effects of NP characteristics on cell reactions, the distribution of materials and their toxicological effects to improve nanomedicine risk assessment practices. The analysis of these interrelated factors between nanomaterials enables researchers to create secure and high-

performing therapeutic nanomaterials. Advancements in nanotechnology will help identify essential parameters of NP toxicity to build regulatory standards and optimize industrial as well as biomedical applications while maintaining safety in real-life implementations.

The NP characteristics and their toxicological effects come with multiple limitations. Variability in the synthesis of nanoparticles, their aggregation, and stability- thus complicating reproducibility-Differences in the routes of exposure, doses used, and biological models which do not allow for proper generalization and comparisons. Standardized protocols for testing do not exist, resulting in inconsistent assessment of toxicity. The complexities of biological interactions and long-term effects are still poorly understood. Besides, ethical concerns and regulatory gaps would also restrict a comprehensive evaluation. There is a call for reliable universal guidelines would be built to assess the toxicity of nanoparticles evaluated considering various environments and applications. The aim is to investigate unravel the relationship between the characteristics of nanoparticles, including size, zeta potential, surface charge, and shape, to see how they affect toxicological effects in biological interactions.

Egbuna et al. (2021) reviewed the toxic effects of NPs, the factors responsible for contributing to their toxicity, and the methods, by which the toxicity occurred. The results showed that size, shape, aspect ratio, surface coating, crystallinity, separation, accumulation, and surface area significantly contributed to NPs in their hazardous effect. Abbasi et al., (2023) suggested that NPs presented a wide variety of toxic mechanisms. The research assessed several factors that were reported to influence the behaviors and toxicities of NPs. The effects of several physiochemical characteristics were examined, which included a thorough analysis of the size, shape, structure, aggregation state, surface charge, and chemical form of NPs.

In their discussion of nanotoxicity mechanisms, Yang et al., (2021) covered the production of reactive oxygen species, the disintegration of NPs, the alteration of cell signaling pathways, and the development of protein corona. Some possible strategies to improve the understanding of NP toxicity were identified by the analysis. Such enhanced understanding could result in mitigating techniques that permit the safe use of NPs in humans. According to Attarilar et al., (2020), the NPs' interaction with the biological environment interrupted cells' normal processes and led to health problems. The research focused on metal as well as metal oxide NPs and demonstrated the parameters that affect NP toxicity. The research was successful in reducing the negative effects of NPs, particularly those that occur in biological therapy.

With NP safety, Zielińska et al., (2020) studied the ecotoxicology and toxicology of NPs for both humans and environmental health. The report also consisted of some of the major methods to fabricate and characterize polymeric NPs. Several synthesis techniques for NPs and their functionalization through covalent or non-covalent connections were discussed by (Saleh, 2020). The chemical and physical properties of NPs were presented in the research along with the techniques used to characterize them. The findings revealed that research on nanotoxicity was increasing at a rapid rate.

In their research, Najahi-Missaoui et al. (2020) examined the harmful impacts of NPs and how they interact with human cells. The research found several strategies to reduce and avoid NP toxicity for the advancement of safer nanotechnology. The findings demonstrated that stabilized metal oxide NPs were less hazardous when compared to unmodified NPs. Joudeh & Linke (2022) investigated the physicochemical properties of NPs. The research described various characteristics that were used in determining NPs. The difference between NPs and micro or bulk materials was also demonstrated. The results illustrated the physicochemical properties of several NP classes. Baranowska-Wójcik et al., (2020) examined the potential toxicity of inorganic nanoparticles to human health and also evaluated possible effects of NP exposure to living things. Results from their research revealed that constant low dose exposure to trace amounts of NPs might be affecting the heart, brain, and other internal organs. This paper further attempts to discuss about the different nature of nanoparticles that would affect their toxicological action on biological systems and environmental health.

The traditional synthesis methods for zinc oxide nanoparticles (ZnO-NPs) were associated with toxicity, while the alternative green synthesis approaches were eco-friendly. It discussed the biomedical applications of green synthesized ZnO-NPs their superior compatibility with biological systems and therapeutic potentials examined by Islam et al. (2022). The findings suggested that green synthesized ZnO-NPs far surpassed the traditionally synthesized ones in terms of antibacterial, anticancer, wound healing, and biosensor properties and exhibited lower levels of toxicity, thereby posing relatively little threats to the use in biomedical objectives. Sharma et al. (2021) determined the toxicological effects of metal, lipids, and protein-based nanoparticles all of which were commonly utilized in medication delivery. It intended to highlight their benefits, potential risks, and the necessity of nanotoxicology before clinical applications. It found that metal nanoparticles induce oxidative stress and may infiltrate the nucleus, while protein nanoparticles could cause hepatotoxicity and nephrotoxicity. It underscores the urgent need for further toxicity to address regulatory concerns and enhanced nano carrier safety.

The NP applications in health, particularly in medical diagnosis and therapy, while addressing the toxicological effects on various biological systems. It explored the underlying mechanisms of NP toxicity and evaluates classical and emerging models used in toxicity assessment were explored by Xuan et al., (2023). The highlights significant toxic effects of NPs on respiratory, nervous, endocrine, immune, and reproductive systems, along with carcinogenic potential. It identified accumulation, mitochondrial damage, inflammation, apoptosis, and epigenetic regulation as key mechanisms of toxicity. Liu et al. (2022) suggested the impact of key toxicity-associated properties of manufactured nanomaterials on their cellular uptake, trafficking, and toxicity mechanisms. Additionally, it examined advanced analytical methods, current regulatory frameworks, and challenges in nanotoxicology to enhance the safety evaluation of nanomaterials. It find that nanoparticle size, shape, surface properties, and corona formation significantly influence toxicity. Regulatory challenges persist, highlighting the need for standardized assessment methods to ensure nanomaterial safety.

1.1 Problem statement

NPs' distinct physicochemical characteristics have led to their growing application in consumer goods, industry, and medicine. Concerns regarding their possible toxicological impacts on the environment and human health, however, have not been addressed. It is unclear how the biological interactions of nanoparticles (NPs) relate to their size, design, surface charge, and composition. This knowledge gap hinders the development of safer nanomaterials. Understanding how these properties influence toxicity is essential for risk assessment and regulatory guidelines. The correlation between NP characteristics and their toxicological effects to support the design of safer and more sustainable nanotechnologies.

The research is designed as follows: Part 2 describes the method, which includes data collection, research design, and statistical analysis. Part 3 provides the test results. Part 4 discusses the findings of the research and Part 5 concludes the research with some key insights, limitations, and future scope.

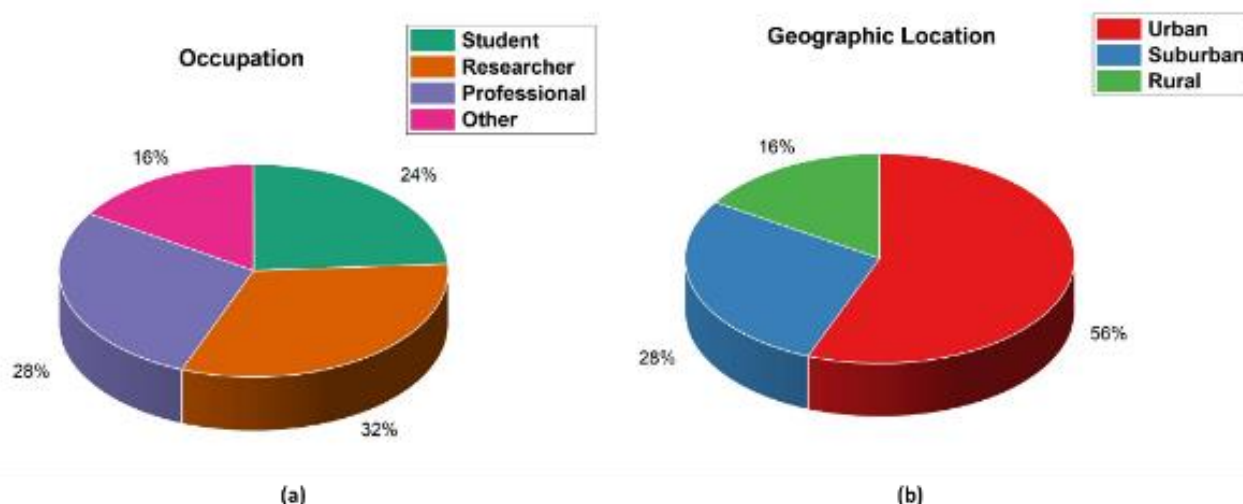
2. METHODOLOGY

2.1 Demographic Data

Demographic information for a research sample of 250 people is gathered. Geographical location, employment, age, gender, and previous exposure to financial literacy programs or knowledge platforms (NPs) are all included in the data were displayed in Table 1. It provides sample sizes and percentages about the types of backgrounds that have contributed to research on NP toxicity. The graphical illustration of the participants' occupation and geographic location is shown in Figure 2.

Table 1. Demographic Characteristics.

Demographic Variable	Category	Sample Size (n)	Percentage (%)
Gender	Male	120	48
	Female	130	52
Age Group	18 – 25	50	20
	26 – 35	70	28
	36 – 45	60	24
	46 – 55	40	16
	56 +	30	12
Occupation	Student	60	24
	Researcher	80	32
	Professional	70	28
	Other	40	16
Geographic Location	Urban	140	56
	Suburban	70	28
	Rural	40	16
Previous Exposure to NPs	Yes	90	36
	No	160	64


Figure 2. Graphical representation of (a) Occupation and (b) Geographic Location

2.2 Research Design

Research designs employ mixed-methods approaches to comprehensively explore the relationship between NP properties and their toxicological effects. Quantitative analysis will involve statistical techniques such as correlation analysis to examine the direction and strength of relationships between NP characteristics (e.g., size, shape, surface charge) and toxicity outcomes. Regression analysis will be utilized to predict toxicological responses based on NP properties, while t-tests will assess significant differences between groups to identify key influencing factors. These methods will provide empirical insights into measurable interrelations. On the qualitative front, thematic analysis will be conducted on data collected from expert interviews, case studies, or

literature to identify dominant themes regarding NP toxicity mechanisms. Thus, the approach will give detailed views on how the materials and physical properties of NP guide their interaction with biological systems. The combination of quantitative and qualitative aspects will provide a systemic view of how NP characteristics influence toxicity, thus supporting the understanding of the risk of exposure and the application of nano-technology in more sustainable ways.

2.3 Statistical Analysis

Statistical correlation analysis will be applied as a tool to analyse multivariate NP properties, like size, zeta potential, surface charge, shape and how those relate to their toxicological effects. By this statistical model,

one can quantify the influence of one property upon another and, therefore, reveal the core information regarding NP behaviour in live biological systems. Understanding such relationships is essential to anticipate the patterns of toxicity, adequately optimize design parameters for biomedical applications, and prevent possible hazards to human health. The determination of significant correlations provides mechanistic insight into how NP properties relate to their biological interactions and builds a platform for safer and more efficacious nanotechnology-based solutions.

3. RESULT

Utilizing the components in this section, assess the Regression Analysis, t-test, Correlation analysis, and Thematic Analysis.

3.1 Quantitative Test

Correlation Analysis

Correlation analysis is essential in understanding the interrelationship between NP properties and their toxicological effects. By statistically evaluating parameters such as composition, surface charge, size, and shape, it can identify patterns influencing biological interactions. Smaller-sized nanoparticles generally exhibit the greatest cellular uptake potential, and consequently, heightened toxicity. Surface modifications also impact reactivity and biocompatibility. Correlation analysis helps reveal dose-dependent effects, oxidative stress induction, and inflammatory responses, aiding in risk assessment. Identifying strong correlations between specific properties and toxicity mechanisms enhances nanoparticle safety by guiding rational design and regulatory strategies, ensuring their biomedical and industrial applications remain both effective and safe. Table 2 shows the correlation analysis performed on NP properties with their toxicological effects.

Table 2. Outcomes of Correlation Analysis.

Variables	Size (nm)	Zeta Potential (mV)	Surface Charge	Shape
Size (nm)	1.00	-	-	-
Zeta Potential (mV)	-0.65	1.00	-	-
Surface Charge	0.45	-0.30	1.00	-
Shape	-0.20	0.10	0.35	1.00

The diagonal values represent perfect correlations (1.00) for each variable interaction. There is a strong and negative correlation (-0.65) between Size (nm) and Zeta Potential (mV), which means that larger NPs tend to have lower zeta potential values and it could suggest that size affects the stabilization and dispersion of NPs in solutions, affecting reactivity and toxicity. There is a moderate positive correlation at 0.45 between Size (nm) and surface charge, indicating that the larger particles are associated with higher surface charges that may interact more intensely with biological systems. In contrast, the correlation of Zeta Potential (mV) with surface charge is weak and negative at -0.30, indicating that minimal alteration in zeta potential would affect the surface charge. Lastly, the correlation with the shape indicates that it is very weakly correlated with other variables. Overall, the findings demonstrate the interaction of NP properties.

Regression analysis

Regression analysis refers to a way of using one dependent variable to discover whether or not there is an association with one or more independent variables. For this research, regression analysis is employed to quantify the relationships of several NP properties (independent variables) to their toxicological effects (dependent variable). Table 3 presents the regression analysis results, which include the coefficients (β), standard errors (SE), correlation coefficients (R), coefficient of determination (R^2), adjusted R^2 , and p-values for each NP property used in this research. The result of the β value is depicted in Figure 3.

Table 3. Outcome of Regression Analysis.

Variables	Coefficient (β)	SE	R	R^2	Adjusted R^2	p-value
Size (nm)	0.45	0.10	0.78	0.61	0.59	<0.001
Zeta Potential (mV)	0.30	0.15	0.73	0.53	0.51	<0.001
Surface Charge	0.25	0.12	0.70	0.49	0.47	<0.001
Shape	0.35	0.18	0.72	0.52	0.50	<0.001

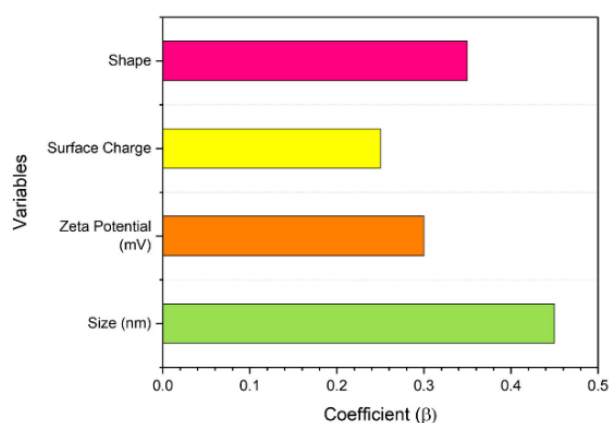


Figure 3. The outcome of the β value

For any independent variable, the value of β will inform how much the variable impacted the dependent variable. Generally, a greater positive coefficient value indicates a stronger effect of the NP size on toxicity. It could be stated that given the value of $\beta = 0.45$ for particle size, a one-unit increase in NP size might increase the toxicity by 0.45 units. The coefficients of zeta potential, surface charge, and shape are 0.30, 0.25, and 0.35, respectively, indicating that these characteristics also enhance toxicity but to a lesser extent than size.

SE values measure the variability associated with coefficient estimates and the lower values of SE represent

more precise estimates. R values represent the influence of the connection between independent and dependent variables. The R^2 values specify the amount of variability in the dependent variable that is described by independent variables, and for this analysis, 61% of the variability in toxicity can be attributed to size, 53% to zeta potential, 49% to surface charge, and 52% to shape. The adjusted R^2 values are also corrected for the total number of predictors in the model, and they provide additional support to the validity of the regression results that indicate that the NP properties produce a strong model. All p-values (<0.001), recommend a statistically significant relationship between each characteristic of the NP and its associated toxicological effect.

T-test

It is a statistical approach used to test whether the means of two groups have a substantial difference or not. It assesses whether the perceived differences are due to chance or reflect true variations in the populations. In this research, the t-test is applied for the comparison of the mean values of different NP properties like size, zeta potential, surface charge, and shape under different conditions. Table 4 summarizes the results obtained from the t-test on NPs properties in terms of M, SD, t-value, and p-value for each variable. The result of the t-value is represented in Figure 4.

Table 4. Results of t-test.

Variables	M	SD	t-value	p-value
Size (nm)	60.0	5.0	2.75	<0.001
Zeta Potential (mV)	50.0	3.5	3.10	<0.001
Surface Charge	90.0	4.5	2.20	<0.001
Shape	70.0	6.0	2.00	<0.001

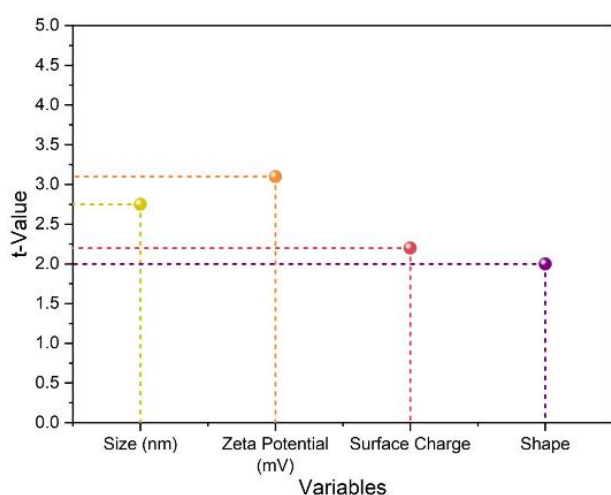


Figure 4. T-value outcome

The values of M represent an average measurement of each of the NP variables across the tested groups. For example, the size of the NPs is reported at the values of

$M = 60.0$ and $SD = 5.0$, which indicates that the distribution of the size of NPs is relatively small. Correspondingly, the zeta potential has the value of $M = 50.0$ and $SD = 3.5$. For surface charge, the value is at $M = 90.0$, and for shape, the value is at $M = 70.0$. The t-values are the proportion of the difference between the group means to the variability of the groups. Size has the value of $t = 2.75$, which indicates that the difference in toxicity is quite significant based on particle size. The p-values indicate the level of statistical significance of the outcomes, and the value of less than 0.001, at a very high level of significance. Overall, the t-test results gave very crucial information regarding variations in the toxicological profile of NP.

3.2 Qualitative test

Thematic analysis

It is a qualitative approach that examines, identifies, and reports on themes present in the data. This qualitative

method enables an in-depth exploration of participants' views on how particle size, surface charge, and shape contribute to toxicological outcomes.

Table 5 summarizes the outcomes of the thematic analysis, which presents the key themes identified about

the relative contributions of NP properties toward their toxicological effects. These themes have been grouped according to the relevance and significance reported by participants. Figure 5 depicts the mean (M) and standard deviation (SD) graph of thematic analysis.

Table 5. Thematic Analysis Outcomes.

Theme	Frequency (n)	M	SD	p-value
Impact of Particle Size on Toxicity (T1)	50	3.5	0.8	<0.01
Role of Surface Charge in Toxicity (T2)	30	2.8	0.7	<0.01
Relationship Between Charge and Toxicity (T3)	40	4.0	1.0	<0.01
Influence of Shape on Cytotoxicity (T4)	20	3.0	0.5	<0.01

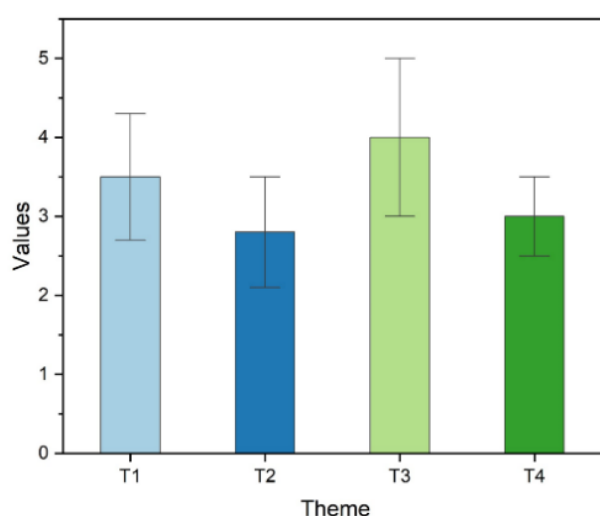


Figure 5. Mean (M) and standard deviation (SD) graph of thematic analysis

The first theme (T1) has the highest frequency of 50, which means that more participants agreed that particle size is the determining factor in having a high toxicity level. The mean value is at $M = 3.5$ ($SD = 0.8$). The statistical significance of the p-value (<0.01) is further affirmed to be very important when considering nanotoxicology. The second theme (T2) has a frequency of 30 with the perceived notion that there is a noticeable influence of surface charge on the interaction and toxicity of NPs. The value of $M = 2.8$ ($SD = 0.7$) is supported by a statistically significant p-value of less than 0.01. The third theme (T3) has a frequency of 40, which suggests that charge characteristic is a significant consideration while evaluating the toxicity of NP. Here, the mean value is at $M = 4.0$ ($SD = 1.0$), and participants strongly agree that charge correlates with toxicological outcomes and is further supported by a statistically significant p-value (<0.01). Finally, the theme T4 was reported to have a frequency of 20, which indicated that even though shape is believed to influence toxicity, it was seen as less significant of the three factors discussed in this research.

4. DISCUSSION

The effects of Np size, shape, zeta potential, and surface charge on biological interaction and toxicity are examined in the research. The results from quantitative tests highlight a significant correlation between the NP properties and their toxicological effects. The use of correlation analysis shows very strong correlations in size and toxicity such that smaller NPs would be expected to have more toxic potential because of a greater surface area and increased reactivity. Moderate correlations with zeta potential, surface charge, and shape suggest that the effects are not limited to these physical parameters but include further implications for NP interaction with biological systems. The outcomes of regression analysis indicate that size is the most important influencing factor of toxicity, then the surface charge, followed by the shape. T-tests confirm that the properties involved are highly significant, having low p-values for all the variables concerned, indicating that the concerned variables might play an important role in nanotoxicological studies. Further enrichment in understanding this relationship from the thematic analysis includes participants' perceptions play a crucial role in NP toxicity. It can be concluded that, although the general trends presented above are significant regarding the issues and understanding of nanoparticle (NP) characteristics, greater attention to these matters will enhance the design and subsequent application of nanomaterials, leading to improved safety and efficiency across various scientific fields, from medicine to environmental science. Concerns regarding the potential toxicological effects of nanoparticles are raised by their growing use in several industries. their composition, shape, size, and surface charge, as well as how these characteristics relate to biological systems. The understanding of such interdependencies is fundamental in predicting the toxicity of nanomaterials, ensuring their safe applications, and guiding regulatory policies for regulating the use of nanomaterials.

5. CONCLUSION

The significant influence of NP properties that include size, zeta potential, surface charge, and shape was examined in this research providing valuable insights and advancements in the field of nanotechnology. Clarifying for which these characteristics influence toxicological results appears to be critical for the promotion of safer and more effective nanomaterials in medicine and environmental science. The results showed significant correlations between the properties and the respective toxicity, and toxicology especially when viewed in terms of NP size. Together these properties explained a significant amount of the variance in toxicity as

supported by regression analysis. Because in reality, it is often hard to manipulate such NPs and test them in a controlled fashion, nevertheless, there are caveats to this analysis: that one specific group of NPs was used and under certain experimental conditions might not simulate actual conditions in real life. Qualitative data collected in this study reflect the views of participants, which are subjective and somewhat biased. Future work should shift the focus toward increased NP varieties and their behavior in complex biological environments. Advanced characterization techniques and participant pools in qualitative assessments would provide richer data. This research will be a basis for further investigations to minimize the risks related to NP exposure.

References:

- Abbasi, R., Shineh, G., Mobaraki, M., Doughty, S., &Tayebi, L. (2023). Structural parameters of nanoparticles Affecting their toxicity for biomedical applications: a review. *Journal of Nanoparticle Research*, 25(3), 43. <https://doi.org/10.1007/s11051-023-05690-w>
- Attarilar, S., Yang, J., Ebrahimi, M., Wang, Q., Liu, J., Tang, Y., & Yang, J. (2020). The toxicity phenomenon and the related occurrence in metal and metal oxide nanoparticles: a brief review from the biomedical perspective. *Frontiers in bioengineering and biotechnology*, 8, 822. <https://doi.org/10.3389/fbioe.2020.00822>
- Baranowska-Wójcik, E., Szwajgier, D., Oleszczuk, P., &Winiarska-Mieczan, A. (2020). Effects of titanium dioxide nanoparticles exposure on human health—a review. *Biological trace element research*, 193, 118-129.118-129. <https://doi.org/10.1007/s12011-019-01706-6>
- Bilardo, R., Traldi, F., Vdovchenko, A., & Resmini, M. (2022). Influence of surface chemistry and morphology of nanoparticles on protein corona formation. *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*, 14(4), e1788. <https://doi.org/10.1002/wnan.1788>
- Egbuna, C., Parmar, V. K., Jeevanandam, J., Ezzat, S. M., Patrick-Iwuanyanwu, K. C., Adetunji, C. O., &Ibeabuchi, C. G. (2021). Toxicity of nanoparticles in biomedical application: nanotoxicology. *Journal of Toxicology*, 2021(1), 9954443. <https://doi.org/10.1155/2021/9954443>
- Garcés, M., Cáceres, L., Chiappetta, D., Magnani, N., &Evelson, P. (2021). Current understanding of nanoparticle toxicity mechanisms and interactions with biological systems. *New Journal of Chemistry*, 45(32), 14328-14344. <https://doi.org/10.1039/D1NJ01415C>
- Isibor, P. O., Kayode-Edwards, I. I., Oyewole, O. A., Agbontaen, D. O., Onwaeze, O. O., Paul, E., &Chimbekujwo, K. I. (2024). Risk Assessment and Management in Nanotoxicology. In *Environmental Nanotoxicology: Combatting the Minute Contaminants* (pp. 267-293). Cham: Springer Nature Switzerland 2024. https://doi.org/10.1007/978-3-031-54154-4_13
- Islam, F., Shohag, S., Uddin, M. J., Islam, M. R., Nafady, M. H., Akter, A., ... &Cavalu, S. (2022). Exploring the journey of zinc oxide nanoparticles (ZnO-NPs) toward biomedical applications. *Materials*, 15(6), 2160.<https://doi.org/10.3390/ma15062160>.
- Joudeh, N., & Linke, D. (2022). Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists. *Journal of Nanobiotechnology*, 20(1), 262. <https://doi.org/10.1186/s12951-022-01477-8>
- Khan, S., & Hossain, M. K. (2022). Classification and properties of nanoparticles. In *Nanoparticle-based polymer composites* (pp. 15-54). Woodhead Publishing. <https://doi.org/10.1016/B978-0-12-824272-8.00009-9>
- Liu, Y., Zhu, S., Gu, Z., Chen, C., & Zhao, Y. (2022). Toxicity of manufactured nanomaterials. *Particuology*, 69, 31-48.<https://doi.org/10.1016/j.partic.2021.11.007>.
- Najahi-Missaoui, W., Arnold, R. D., & Cummings, B. S. (2020). Safe nanoparticles: are we there yet?. *International journal of molecular sciences*, 22(1), 385. <https://doi.org/10.3390/ijms22010385>
- Nikzamid, M., Akbarzadeh, A., & Panahi, Y. (2021). An overview on nanoparticles used in biomedicine and their cytotoxicity. *Journal of Drug Delivery Science and Technology*, 61, 102316.<https://doi.org/10.1016/j.jddst.2020.102316>
- Saleh, T. A. (2020). Nanomaterials: Classification, properties, and environmental toxicities. *Environmental Technology & Innovation*, 20, 101067. <https://doi.org/10.1016/j.eti.2020.101067>

- Sharma, S., Parveen, R., & Chatterji, B. P. (2021). Toxicology of nanoparticles in drug delivery. *Current pathobiology reports*, 1-12. <https://doi.org/10.1007/s40139-021-00227-z>.
- Xuan, L., Ju, Z., Skonieczna, M., Zhou, P. K., & Huang, R. (2023). Nanoparticles-induced potential toxicity on human health: applications, toxicity mechanisms, and evaluation models. *MedComm*, 4(4), e327. <https://doi.org/10.1002/mco2.327>.
- Yang, W., Wang, L., Mettenbrink, E. M., DeAngelis, P. L., & Wilhelm, S. (2021). Nanoparticle toxicology. *Annual Review of Pharmacology and Toxicology*, 61(1), 269-289. <https://doi.org/10.1146/annurev-pharmtox-032320-110338>
- Zhang, N., Xiong, G., & Liu, Z. (2022). Toxicity of metal-based nanoparticles: Challenges in the nano era. *Frontiers in Bioengineering and Biotechnology*, 10, 1001572. <https://doi.org/10.3389/fbioe.2022.1001572>
- Zielińska, A., Carreiró, F., Oliveira, A. M., Neves, A., Pires, B., Venkatesh, D. N., & Souto, E. B. (2020). Polymeric nanoparticles: production, characterization, toxicology and ecotoxicology. *Molecules*, 25(16), 3731. <https://doi.org/10.3390/molecules25163731>

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