

ASSESSMENT OF CYTOTOXIC AND INFLAMMATORY EFFECTS OF NANOPARTICLES IN INDUSTRIAL PROCESSES

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Received 15.03.2025

Revised 18.04.2025

Accepted 16.05.2025

Keywords:

*Nanoparticles, Cytotoxic,
Inflammatory Effects, Cell Culture*

ABSTRACT

The fast growth of nanotechnology has generated anticipates about the possible health dangers connected with workplace handling of nanoparticles in manufacturing operations. Chronic exposure to toxins can cause both abrupt cytotoxicity and persistent inflammation that can lead to various diseases. In this analysis, the cytotoxicity and inflammation reactions caused by widely used nanoparticles, such as Zinc oxide (ZnO), Titanium dioxide (TiO₂), calcium carbonate (CaCO₃), and Silver nitrate (AgNO₃), are assessed in an industrial environment. A Bone Marrow-Derived Macrophage (BMDM) was used to evaluate cell survival and inflammatory substance levels of cytokines. Transmission electron microscopy (TEM) image is implemented to visualize the size, shape, and structure of the cell to evaluate efficiently. The findings show that, whereas certain nanoparticles might cause inflammatory reactions, others influence oxidative stresses variously, emphasizing the necessity of nanoparticle-specific health and safety assessments. Nanoparticles containing TiO₂ and AgNO₃ elevated cytokines that promote inflammation, including IL-6 and TNF- α , by 48% and 55%, respectively. These results highlight the necessity for customized risk estimations and a variety of analytical techniques to fully comprehend the toxicity of nanoparticles, which helps to create safer procedures in companies using nanomaterials.



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1. INTRODUCTION

Nanoparticles are a material with dimensions less than 100 nanometres, when contrasted to their mass parallels; they display distinct chemical and physical characteristics. This material is commonly utilized in manufacturing processes, including medicines, electronic devices, and protective coatings, because of their

enhanced usefulness and reaction were examined by (Devasena et al., 2022). Due to their tiny size, they can enter biological structures, which raise questions regarding possible inflammation and damaging cell consequences. The subject of nanotechnology has advanced exponentially over the past 10 years, and several products incorporating nanoparticles are used in a range of uses, such as food research, beauty products, and

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medicines were examined by (Zhang et al., 2022) These materials have unique chemical, biological, and physical characteristics that set them apart from other similar bulk components or small molecules. Because of their special qualities, such as a large area and reaction, nanomaterials are employed extensively in manufacturing processes by (Cao et al., 2023). To ensure worker security and create laws, it is crucial to comprehend their cytotoxic and inflammatory impacts. Because of their size and large surface area, nanoparticles are widely used in many different sectors, such as therapeutic and diagnostic medical applications by (Zamanian et al., 2021). The ability of a nanoparticle to damage or kill cells by inducing oxidative damage, disrupting membranes, or interfering with biological functions is known as cytotoxicity. These particles are a major problem for industrial purposes because of their effects on the health of people and society. Studies have shown that the endurance and physical behaviour of silver nanoparticles change when biomolecules attach to them were assessed by (Eltaher & Wagih 2020). Nanoparticles can trigger inflammatory responses by activating the immune system and generating cytokines that promote inflammation, such as TNF- α and IL-6. Inflammatory chronic respiratory conditions or stiffness can result from prolonged exposure, especially in industrial environments. Understanding these effects is essential to lowering health risks and developing less harmful nanoparticles. Inflammation is the immune system's reaction to dangerous stimuli like bacteria, diseases, electromagnetic radiation, and toxic substances. The majority of inflammation occurs at the surface of the tissue by (Tlili et al., 2021). Because of their cytotoxic and inflammatory properties, workplace contact with nanoparticles during industrial operations including welding, coating, and manufacturing poses serious health hazards. Monitoring exposure levels and adhering to regulations are necessary to ensure worker safety and reduce unfavourable consequences by (Sharma et al., 2023). Because nanoparticles have special physicochemical features, toxicology and risk assessment explore the possible negative impacts of these particles on the environment and human health. Knowing the toxicity processes and exposure pathways becomes essential for developing safety criteria as their use in a variety of sectors grows. Thorough risk analyses support safer methods for producing and using nanoparticles and assist in informing regulatory choices by (Acharya, 2021). Yamini et al., (2023) suggested the relationships between beneficial microbes and nanoparticle pathways across the ecosystem. A modeling approach based on actual concentrations in the field can be able to validate ambient concentration forecasts. This work is to illustrate both the beneficial and detrimental effects of nanomaterials on ecosystems on both land and water, as well as the methods for reducing their harmful effects. Medici et al., (2021) demonstrated the fact that thousands of distinct nanoparticles have been discovered and produced, but comprehensive guidelines for limiting their exposure and assessing their possible toxicity were lacking. The

toxicity of nanoparticles has been linked to the discharge of highly sensitive metallic ions that can pass through cell membranes. To rationalize associated health risks and draw consideration to toxicology distresses associated with their progressively common practice, the source, biological toxicity and performance of several metal nanoparticles was addressed in the research. Cui et al., (2022) identified the possible influence of nanoparticle injection on upcoming CGS projects, the effect of silicon nanoparticles on the γ of CO₂ or decane system at high temperatures and pressures is investigated in detail in this paper. This has been accomplished by conducting several studies to ascertain how hydrophobic and hydrophilic nanoparticles of silicon affect the CO₂/oil systems. The model oil was used n-decane, and the oil phase was combined with varying concentrations of nanoparticles. The findings demonstrated that the pressure, temperature, and nanoparticle load in the oil phase were the key factors affecting CO₂/oil γ . The processes leading to both an increase and a reduction in nanofluid external strain were explained in the (Traciak & Żyła 2022), along with the reason, to a limited extent, the external strain value modifies as a rise in concentration of nanoparticle. The model was verified through experimental tests of the external strain of four different ethylene glycol-based nanofluids at a temperature of 298.15 K: titanium oxide (TiO₂), indium oxide (In₂O₃), zinc oxide (ZnO), and carbon nanotubes. The external strain values of the studied nanofluids and the suggested model accord fairly well. Svobodova-Sedlackova et al., (2022) proposed nitrate-based nanofluids and pure nitrate including Al₂O₃ and SiO₂ nanoparticles (1% wt) were subjected to ultraviolet-visible (UV-vis) spectroscopy and infra-red (IR). The obtained results verify the activity of the catalyst in nanoparticles by showing that they speed up the modification of nitrite breakdown under 500°C up to 4%. With reference to (baek et al., 2021), which evaluated the superior performance of the suggested model, a multiscale research of the effects of silicon carbide (SiC) aggregate formation on the physical capabilities of epoxy-based nanocomposites was carried out utilizing a continuous damage model. It was discovered that the phase transition zone's toughness and degradation characteristics should be different from those of the basic polymer to create nanocomposites of polymer with clustering in an appropriate way. Tlili et al., (2021) is analyzed the differences in the energy field and drive designations as well as the confined Nusselt number affected by the pertinent dimensionless variables. Ferrous particles with a spherical form were more efficient in transmitting energy than those with a tube or laminar structure. The outcomes were examined for three different forms of nanoparticles: linear, spherical, and cylindrical. The Deborah number and the unsteadiness parameter can be used to alter the Nusselt number. Jabir et al., (2021) demonstrated the biomedical uses of silver nanoparticle manufacturing using *Eriobotrya japonica* leaf extracted. According to the results, AgNPs could be a useful therapy for lowering allergy symptoms, avoiding bacterial infections, and decreasing sensitivity in the

coming years by boosting phagocytosis. Therefore, further research is needed to develop and improve nanoparticles to be utilized as immune-modulating agents, additives, and nano-drug delivery methods. The evaluation of cytotoxicity level and inflammatory impacts of nanoparticles in industrial applications on human cells. This analysis aims to find the physical characteristics of the nanoparticles that cause damage to cells and reactions of inflammation and also help to establish safety recommendations and legislative initiatives to safeguard workers from the health concerns linked with nanoparticle contact.

1.1 Contribution of the research

The contribution of the research is given below:

- Identifying Toxicity Characteristics: The analysis gives extensive data on cell death and immune responses related to various kinds of nanoparticles, assisting in the development of damaged cells that could be guided to safety precautions in industries.
- Hazard Assessment System: By linking nanoparticle properties to biological consequences, allowing for improved safety regulations and preventive methods for employees working with nanoparticles.
- Inflammatory analysis: To determine the inflammation in cells, the scintillator detectors are used and evaluate the lifespan of the cell in nanoparticles to protect the workers in the industry.

The rest of the analysis is divided into five various categories, such as introduction discussed in section 1, materials and methods demonstrated in section 2, results explained in section 3 and conclusion exposed in section 4.

2. METHODOLOGY

The statistics provide that various nanoparticles and their characteristics are explained and evaluated in detail by their concentration. Utilizing unique macrophage cells could be developed, treated, and executed in the mouse with an inducer. Cell viability is also examined using particular assays and data visualization through TEM images that can effectively show the structure of the compound, shape, and size. Lastly, cytotoxicity analysis and inflammatory impacts in cell culture are represented.

2.1 Development of cells and their treatment

For this analysis, Bone Marrow-Derived Macrophages (BMDM) executes according to regulatory standards and then retrieves the tibia and femur skeletons by utilizing L929 cell-conditioned media (LCCM) as an inducer. Utilizing a needle, carefully wash the bone platelets in sterile RPMI-1640 media supplemented with 10% fetal bovine serum (FBS) and 1% penicillin-streptomycin. Place the marrow mixture in a sterilized

container and filter it using a 70 µm cell separator to eliminate debris. After 5 minutes of centrifuging the filtrate at 300 g to pellet the cells, reinstate the pellet in the whole medium. Implant extracted cells from bone marrow at a density of 1×10^6 to 5×10^6 cells/mL in an incubator medium. Develop cells at 37°C with 5% CO₂ for 6-8 hours. Eliminate cells that are not adhesive by rinsing with phosphate-buffered saline (PBS). To stimulate specialization into macrophages, add 10-20 ng/mL of macrophage colony-stimulating factor (M-CSF) and cultivate for 5-7 days, refilling the growth medium every 2-3 days. After this time, the cells will have characteristic macrophage structures and could be employed for a variety of research purposes.

2.2 Evaluation of Cell Durability

Several assays could be utilized to determine the duration of the cultured cell in BMDM, the most frequently used method is called 3-(4,5-dimethyl thiazol-2-yl)-2, 5-diphenyltetrazolium bromide (MTT) assays is used in this analysis. Following treatments, the cells are cultured for three to four hours in 0.5 mg/mL MTT aqueous solutions, allowing the surviving cells to convert MTT to crystals of formazan. Following the removal of the medium-sized, the resulting formazan will dissolve in dimethyl sulfoxide (DMSO). Employing a device called a microplate reader, the density of light is determined at 570 nm, whereas an increased absorbance denotes better cells. As a substitute, other techniques, such as trypan blue isolation or the Cell Titer-Glo luminescence assays can be employed to validate outcomes, offering a thorough assessment of the impact of interventions on BMDM lifespan.

2.3 MTT Assay

In cell culture, to measure the lifespan and cytotoxic level of the cell, the colorimetric method named MTT test was utilized. By using the enzyme mitochondrial dehydrogenase, which converts a tetrazolium compound into intractable purple formazan crystals, it is possible to evaluate the metabolic processes of live cells. Following incubation, the resulting crystals become immersed in a soluble agent, such as DMSO or acidic isopropanol, and the spectrophotometer is used to detect their absorption at 570 nm. This assay helps to evaluate the toxicity level in the drug, proliferating cells, and treatment effects because the intensity of the color corresponds with the number of cells that survived.

2.4 Features of Nanoparticles

For the analysis, the utilized nanoparticles are Zinc oxide (ZnO), Titanium dioxide (TiO₂), Silver nitrate (AgNO₃), and calcium carbonate (CaCO₃). The concentration of the nanoparticles in diluted water from various industries could depend on the type of nanoparticles and their desired properties. It can range from lower to higher concentrations from 1 mg/mL to 100 mg/mL or more. While prescribing

medication a lower concentration is adequate to provide medical benefits and a higher concentration could be applied in several material composites or large compositions that attain more than 100mg/mL. By implementing electron microscopy such as Scanning Electron Microscopy (SEM) or Transmission Electron Microscopy (TEM) can be used to view the size of the nanoparticles. These techniques produce high-quality images and are recommended for defining complicating nanoparticle morphologies and aggregations. In this analysis, TEM is implemented to effectively look at the interior structure and microscopical level of the nanoparticles rather than SEM.

2.5 Visual assessment

TEM is frequently utilized to analyse the shape, size, and structure of crystals, and the chemical composition of the membrane in nanomaterials. The concentration of water diluted in nanoparticles should be 1 mg/mL; if it is higher, it enhances the accumulation, resulting in dispersion and decreased resilience. The sample could be prepared by diluting in water or ethanol, ensuring the particle size is less than 100nm and placed on the copper grid coated with carbon, which ranges from 5 to 10 μ L. Scintillator Detector of GatanOrius SC1000at 5 kV and distance between the pole piece at the bottom of the lens and the surface of the sample is 2 mm to 5mm.

2.6 Quantitative PCR (qPCR)

This technique is utilized to assess the amount of nucleic acids by implanting a current evaluation of the amplification process, which is a strong and perceptive method. To calculate the quantity of DNA or RNA developed in every cycle of PCR, fluorescent dyes or probes were employed. Substances used in qPCR are first transformed in reverse for RNA into complementary DNA (cDNA) if there is a requirement. The qPCR process is performed in a thermocycler fitted into a fluorescence recognition device, which allows brightness to be measured at every cycle. The fluorescence increases in proportion to the quantity of PCR items, allowing the base substance to be quantified. Analysing information often entails creating a conventional curve using known proportions of desired DNA to calculate its amount in unidentified specimens. Because of its excellent sensibility, particularity, and capacity to analyse numerous samples at once, qPCR is frequently employed in a variety of usages, involving analysis of gene expression, pathogen identification, genetic testing, and variation in gene assessment.

2.7 Analysis of cytotoxic level

The extracellular fluid that contains the discharged cytokines, is extracted after treatment and used to assess cytokines in the cultivation of cells. The enzyme-linked immunosorbent assay (ELISA) is a typical approach for measurement, which employs certain antigens to collect

and identify cytokines and provide a quantifiable signal proportionate to the cytokine concentration. As an alternate, multiplexed bead-based technique employs flow cytometry to detect many cytokines at once. Furthermore, the production of cytokines at either protein or mRNA levels could be measured using methods like Western blotting or PCR.

2.8 Effects of inflammation in cell culture

When nanoparticles come into contact with cells, they can activate biological processes like NF – κ B and mitogen-activated protein kinase (MAPK), which in turn can cause the creation of cytokines that promote inflammation, including TNF – α , IL – 6, and IL – 1. The lifespan of cells changes, oxygen depletion, and damage to cells could occur from this inflammatory reaction. The degree to which these effects are correlated with the properties of the nanoparticles, such as their capacity to combine with cellular membranes and elicit immunological responses underlines the necessity of carefully assessing the biological suitability and efficacy of nanoparticles in biomedical applications.

3. RESULT

The outcome of this analysis shows that the characteristics of the various nanoparticles with their cell culture provide the pH values, zeta potential values, and light scattering analysis. Evaluating the cytotoxicity level by its incubation period could effectively predict the result. Assessing the finding of various nanoparticles by its graphical representation and TEM image could be helpful to view the size and shape of the nanoparticles precisely. Finally, the inflammatory analysis test is taken by utilizing scintillator detectors to determine the cell viability in the cell culture medium. This analysis implemented SPSS 2.0 which was implanted.

3.1 Physical characteristics

Together with their compositions, pH values, dynamic light scattering (DLS) statistics, and other characteristics, Table 1 displays a variety of slurries that consist of diverse abrasive substances. TiO₂ makes up below 20% of the initial slurry, Ti-1, which has an agglomeration size of 35.40 nm, a pH of 8.5, and a zeta potential of 75.32 mV. Ti-2 has a pH of 7.2, a zeta potential of 45.60 mV, a lesser agglomeration size of 20.50 nm, and TiO₂ at less than 5%. Zinc oxide (ZnO) is under ten percent of Zn-1, which has an agglomeration size of 18.75 nm, a zeta potential of 95.00mV, and a pH of 6.8, and. With a zeta potential of 25.89mV, a pH of 5.5, and an agglomeration size of 28.90 nm, the Ag-1 slurry has less than one percent silver nitrate (AgNO₃). Finally, Ca-1 has an agglomeration size of 30.50 nm, a pH of 9.0, a zeta potential of 150.30 mV, and calcium carbonate (CaCO₃) at below 15%. The bulk of the content in each mix is made up of de-ionized water, with various proportions of unique additives included in every mixture.

Table 1. Features of slurries with size variation in nanometer (nm) including TEM outcome.

Mixture	Nanoparticles	Configuration	pH	DLS		Zeta Potential (mV)	TEM (nm)
				Accumulation Size (nm)	SD		
Ti-1	Titanium Dioxide (TiO ₂)	TiO ₂ < 20% Characteristics Compound< 5% Demineralized water> 75%	8.5	75.32	0.003	35.40	50.00
Ti-2	Titanium Dioxide (TiO ₂)	TiO ₂ < 5% Characteristics Compound< 10% Demineralized water> 85%	7.2	45.60	0.002	20.50	40.00
Zn-1	Zinc Oxide (ZnO)	ZnO< 10% Characteristics Compound< 4% Demineralized water> 86%	6.8	95.00	0.004	18.75	60.00
Ag-1	Silver Nitrate (AgNO ₃)	AgNO ₃ < 1% Characteristics Compound< 2% Demineralized water> 97%	5.5	25.89	0.001	28.90	30.00
Ca-1	Calcium Carbonate (CaCO ₃)	CaCO ₃ < 15% Characteristics Compound< 3% Demineralized water> 82%	9.0	150.30	0.005	30.50	70.00

3.2 The outcome of cytotoxicity level and lifespan of a cell

Table 2 represents the comparison of the cytotoxic impact of various nanoparticles, including TiO₂, ZnO, AgNO₃, and CaCO₃ with the incubation time of around 24 hours on several cell lines. The concentration of the nanoparticles varies from 1 to 100 µg/mL, percentage of cell viability, value of absorption, and cytotoxicity level were examined. The findings show that viability of the cell decreased to 45% at 100 µg/mL showing significant cytotoxicity, whereas TiO₂ at 10 µg/mL demonstrated a minimal cytotoxicity level with 85% cell viability. The

durability of ZnO at 10 µg/mL was 65% which denotes a low cytotoxicity level, but at 50 µg/mL (high cytotoxicity), it rose to 30%. The impact of AgNO₃ on breast cancer cells was remarkably different, with 70% viability at 1 µg/mL showing low cytotoxicity and only 20% vitality at 10 µg/mL with severe cytotoxicity. At 10 µg/mL with 90% viability, CaCO₃ exhibited mild cytotoxicity; however, at 100 µg/mL which contains 50% viability, it displayed significant toxicity. This information emphasizes the significance of nanoparticle concentration in evaluating the responses of cells by highlighting the varied degrees of cytotoxicity displayed by various nanoparticles across certain cell lines.

Table 2. Impact of Nanoparticle Concentration on Cytotoxicity and Cell Viability in Various Cell Lines.

Nanoparticle	Concentration (µg/mL)	Cell Line Used	Incubation Time (hrs)	Absorbance (nm)	Cell Viability (%)	Cytotoxicity Level
TiO ₂	10	A549 (Lung cells)	24	0.85	85%	Low
	100	A549	24	0.45	45%	Moderate
ZnO	10	HeLa (Cervical)	24	0.65	65%	Low
	50	HeLa	24	0.30	30%	High
AgNO ₃	1	MCF-7 (Breast)	24	0.70	70%	Low
	10	MCF-7	24	0.20	20%	High
CaCO ₃	10	L929 (Fibroblast)	24	0.90	90%	Low

3.3 Result of TiO₂ nanoparticles

Figure 1 shows that the hydrodynamic diameter of TiO₂ nanoparticles varied from 203 and 1.93 nm in liquid to 229.4 and 0.01 nm in cell medium for culture. The particle

size variation in PBS as TiO₂ of 356 and 0.29 nm showed no discernible pattern. This result shows that TiO₂ attains 363 and 0.59 nm which denotes a considerable rise in accumulation in media of cell culture lacking fetal bovine serum (FBS).

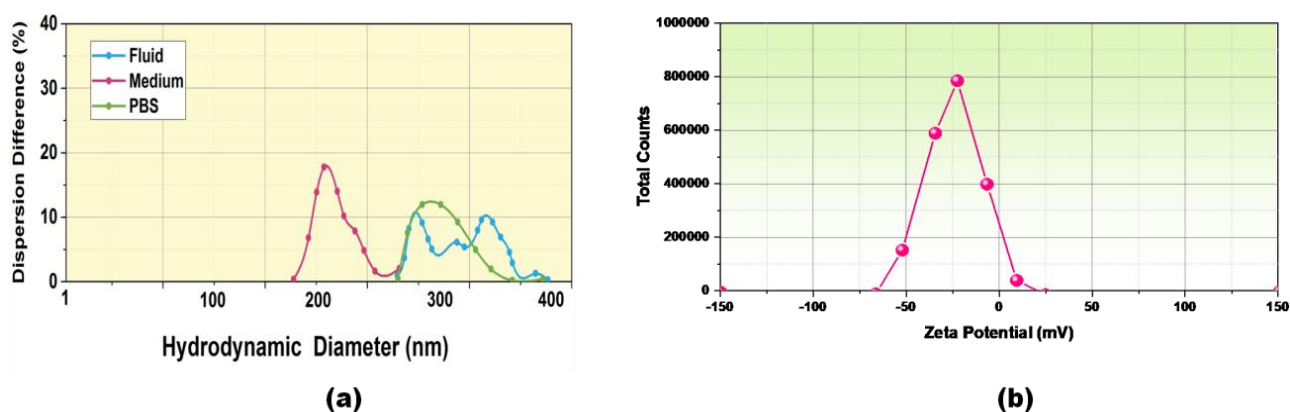


Figure 1. Nanoparticles: (a) Graphical representation of DLS of TiO_2 nanoparticles, (b) Zeta potential versus its total counts of TiO_2

3.4 Zinc Oxide nanoparticle outcome

ZnO nanoparticles were almost equally distributed in cell culture medium with 6.195 nm and liquid of 51.77 and 0.01 nm. The PBS of ZnO nanoparticles at 224.9

and 0.13 nm was less than that of other nanoparticles derived from the cell culture medium as shown in Figure 2. The ZnO nanoparticles achieve 362.9 and 1.93 nm revealing that without FBS it increases in size.

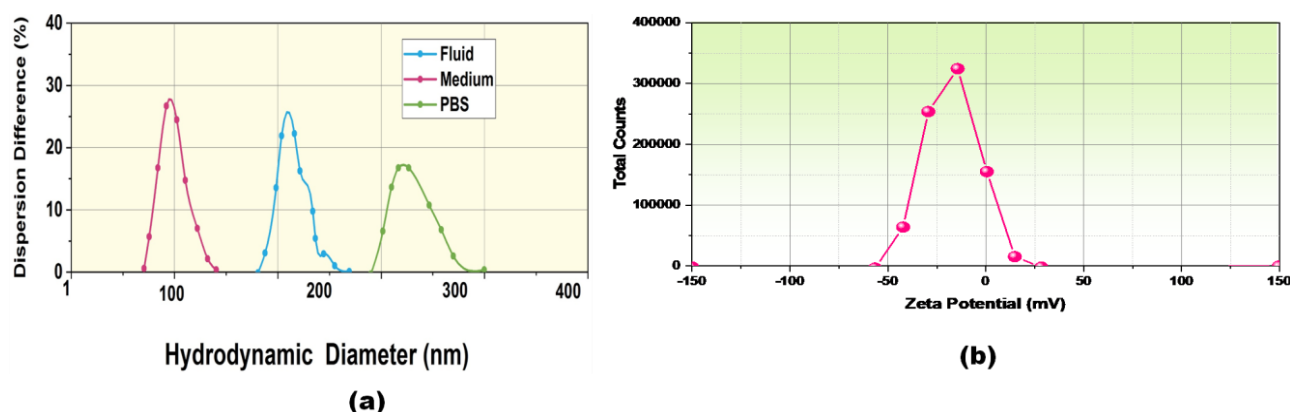


Figure 2. (a) DLS outcome for ZnO nanoparticles, (b) Graphical representation of Zeta potential of ZnO nanoparticles

3.5 DLS and Zeta potential findings of AgNO_3 nanoparticles

Additionally, AgNO_3 nanoparticles retained the same size distribution profiles in a cell culture, medium of 8.048 nm and liquid of 381.2 0.41 nm as shown in

Figure 3. While compared to medium silver nitrate generates a large aggregate size with 700.6 and 0.14 nm in PBS. Slurries based on AgNO_3 nanoparticles have the lowest diameters in the FBS-based cell culture medium, with 244.6 and 0.06 nm as a result.

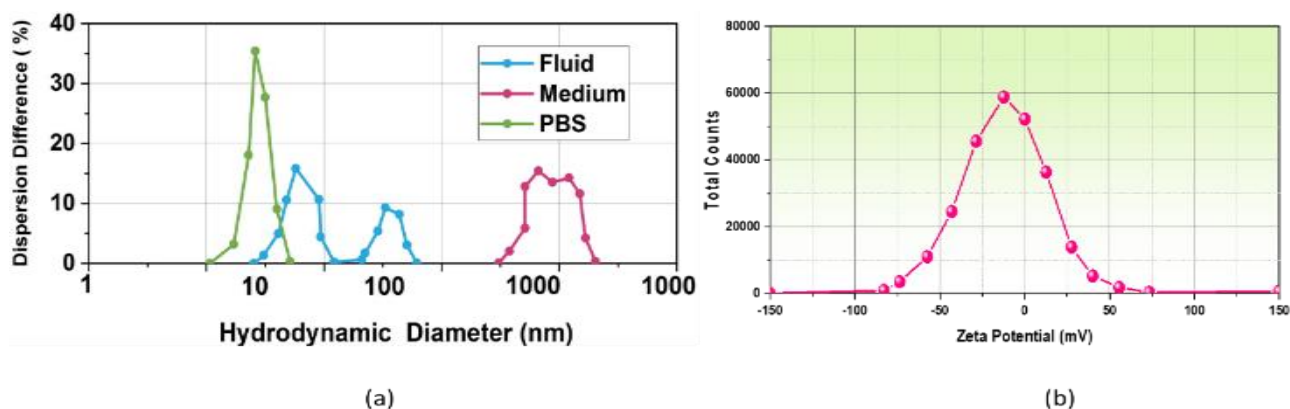


Figure 3. Nanoparticles: (a) Plot of DLS with hydrodynamic diameter and number of AgNO_3 nanoparticles, (b) Illustrating zeta potential and its counts of AgNO_3 nanoparticles

3.6 The outcome of CaCO_3 based on its number

The size distribution of CaCO_3 nanoparticles in liquid was 221.3 and 0.21 nm, and its cell culture medium was 6.123 nm and maintained. In contrast, silver nitrate

produces huge aggregate sizes of 750.4 and 0.12 nm in PBS as shown in Figure 4. The CaCO_3 nanoparticle-based slurries had the smallest diameters of 213.5 and 0.07 nm in the FBS-based cell culture medium.

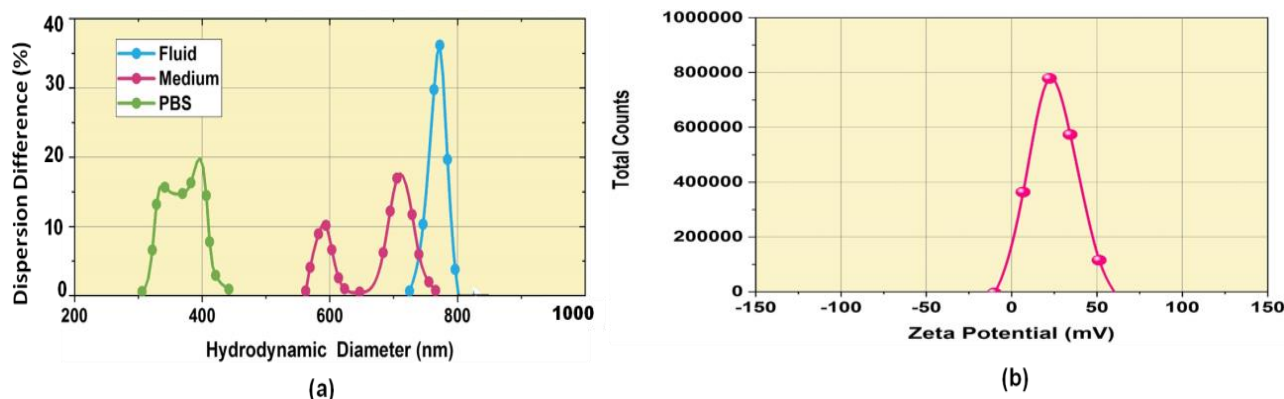


Figure 4. (a) Schematic view DLS in CaCO_3 nanoparticles (b) correlation of zeta potential and its aggregate measurements in CaCO_3 nanoparticles

3.7 Reaction of inflammation to nanoparticles

For analysing inflammation, Scintillator detectors play a vital role in oxidizing reactions for various nanoparticles such as ZnO , CaCO_3 , AgNO_3 , and TiO_2 . By using scintillation substances, which release light when they come into contact with ionized radiation, such detectors make it possible to quantify the electromagnetic radiation that nanoparticles release through inflammatory reactions accurately. This detector could determine the biological impact of these nanomaterials on inflammation in cells by examining their capacity to stimulate biological processes, such as $\text{NF} - \kappa\text{B}$ and mitogen-activated protein kinase (MAPK), according to the superior sensitivity and quick reaction period of scintillator detectors.

The generation of cytokines that promote inflammation, such as $\text{TNF} - \alpha$, $\text{IL} - 6$, and $\text{IL} - 1\beta$, could come from this process being triggered. It has a great deal about the inflammatory pathways that each nanoparticle triggers by tracking the signals that are released. This detector helps comprehend the security profiles of these particles and possible therapeutic uses in the public health and medicinal sectors.

4. CONCLUSION

The summary of this analysis shows that examining nanoparticles with their extremely tiny size is used for manufacturing purposes and to evaluate the cytotoxic level in the cells and inflammatory impact during cell culture. By using the MTT assay, the damage to living cells could be assessed by modifying the reagent to crystals due to its sensitivity. The drawback of this process is that depending on their size, shape, and surface chemistry, they could be impacted biologically. For evaluating inflammation in the cells, scintillator detectors can be used, because they provide short reaction times and highly sensible. When connected with ionized radiation, it can produce light, which permits energy resolution. The result of this analysis shows that TiO_2 attains 3623 and 0.59 nm, ZnO achieves 362.9 and 1.93 nm, AgNO_3 reaches 244.6 and 0.06 nm and CaCO_3 nanoparticles retain 213.5 and 0.07 nm which indicates an increase in agglomeration in cell culture medium. More research is needed to substantiate this assertion by modeling prolonged exposure and settings similar to persistent inflammation. Future scope is to contribute to the creation of specific ways to reduce the negative effects of nanoparticles, eventually influencing safety legislation and enhancing manufacturing procedures for employee wellness.

References:

- Acharya, N. (2021). Spectral simulation to investigate the effects of nanoparticle diameter and nanolayer on the ferrofluid flow over a slippery rotating disk in the presence of low oscillating magnetic field. *Heat Transfer*, 50(6), 5951-5981. <https://doi.org/10.1002/htj.22157>.
- Baek, K., Shin, H., & Cho, M. (2021). Multiscale modeling of mechanical behaviors of Nano-SiC/epoxy nanocomposites with modified interphase model: Effect of nanoparticle clustering. *Composites Science and Technology*, 203, 108572. <https://doi.org/10.1016/j.compscitech.2020.108572>.

- Cao, M., Li, Y., Song, X., Chen, Y., Sun, L., Shi, X., ... & Yuan, B. (2023). Carbon dots nanofluid: Reducing injection pressure in unconventional reservoir by regulating oil/water/rock interfacial properties. *Fuel*, 352, 129046. <https://doi.org/10.1016/j.fuel.2023.129046>.
- Cui, X., Zheng, L., Liu, Z., Cui, P., & Du, D. (2022). Determination of the minimum miscibility pressure of the CO₂/oil system based on quantification of the oil droplet volume reduction behavior. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 653, 130058. <https://doi.org/10.1016/j.colsurfa.2022.130058>.
- Devasena, T., Iffath, B., Renjith Kumar, R., Muninathan, N., Baskaran, K., Srinivasan, T., & John, S. T. (2022). Insights on the dynamics and toxicity of nanoparticles in environmental matrices. *Bioinorganic Chemistry and Applications*, 2022(1), 4348149. <https://doi.org/10.1155/2022/4348149>.
- Eltaher, M. A., & Wagih, A. (2020). Micromechanical modeling of damage in elasto-plastic nanocomposites using unit cell representative volume element and cohesive zone model. *Ceramics International*, 46(8), 10469-10480. <https://doi.org/10.1016/j.ceramint.2020.01.046>.
- Jabir, M. S., Hussien, A. A., Sulaiman, G. M., Yaseen, N. Y., Dewir, Y. H., Alwahibi, M. S., ... & Rizwana, H. (2021). Green synthesis of silver nanoparticles from *Eriobotrya japonica* extract: a promising approach against cancer cells proliferation, inflammation, allergic disorders and phagocytosis induction. *Artificial cells, nanomedicine, and biotechnology*, 49(1), 48-60. <https://doi.org/10.1080/21691401.2020.1867152>.
- Medici, S., Peana, M., Pelucelli, A., & Zoroddu, M. A. (2021, November). An updated overview on metal nanoparticles toxicity. In *Seminars in cancer biology* (Vol. 76, pp. 17-26). Academic Press. <https://doi.org/10.1016/j.semcancer.2021.06.020>.
- Sharma, K., Vijay, N., Bhardwaj, D., & Jindal, R. (2023). Flow of water conveying Fe₃O₄ and Mn–ZnFe₂O₄ nanoparticles over a rotating disk: significance of thermophoresis and Brownian motion. *Journal of Magnetism and Magnetic Materials*, 574, 170710. <https://doi.org/10.1016/j.jmmm.2023.170710>.
- Svobodova-Sedlackova, A., Huete-Hernández, S., Calderón, A., Barreneche, C., Gamallo, P., & Fernandez, A. I. (2022). Effect of Nanoparticles on the Thermal Stability and Reaction Kinetics in Ionic Nanofluids. *Nanomaterials*, 12(10), 1777. <https://doi.org/10.3390/nano12101777>.
- Tlili, I., Mustafa, M. T., Kumar, K. A., & Sandeep, N. (2020). Effect of asymmetrical heat rise/fall on the film flow of magnetohydrodynamic hybrid ferrofluid. *Scientific reports*, 10(1), 6677. <https://doi.org/10.1038/s41598-020-63708-y>.
- Tlili, I., Samrat, S. P., Sandeep, N., & Nabwey, H. A. (2021). Effect of nanoparticle shape on unsteady liquid film flow of MHD Oldroyd-B ferrofluid. *Ain Shams Engineering Journal*, 12(1), 935-941. <https://doi.org/10.1016/j.asej.2020.06.007>.
- Traciak, J., & Żyła, G. (2022). Effect of nanoparticles saturation on the surface tension of nanofluids. *Journal of Molecular Liquids*, 363, 119937. <https://doi.org/10.1016/j.molliq.2022.119937>.
- Yamini, V., Shanmugam, V., Rameshpathy, M., Venkatraman, G., Ramanathan, G., Garalleh, H. A., ... & Rajeswari, V. D. (2023). Environmental effects and interaction of nanoparticles on beneficial soil and aquatic microorganisms. *Environmental research*, 236, 116776. <https://doi.org/10.1016/j.envres.2023.116776>.
- Zamanian, M., Ashenai Ghasemi, F., & Mortezaei, M. (2021). Interphase characterization and modeling of tensile modulus in epoxy/silica nanocomposites. *Journal of Applied Polymer Science*, 138(5), 49755. <https://doi.org/10.1002/app.49755>.
- 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>

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