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e-ISSN 3105-4293
p-ISSN 3105-4285

# Journal of Nanotechnology and Innovative Materials

Vol 1, № 3, 2026

Baku - 2026

Western Caspian University

e-ISSN 3105-4293
p-ISSN 3105-4285

# Journal of Nanotechnology and Innovative Materials

## Vol 1, No 3, 2026

DOI:10.54414/VWTT8467

https://jnim.wcu.edu.az/

# Editor-in-Chief:

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https://doi.org/10.54414/DNOV3886

*Journal of Nanotechnology and Innovative Materials*

*Review Article*

# A Mini-Review on Nano-Enabled Energy Storage and Conversion Systems

**Gaurav Gupta**[1] **and Baseem Khan**[2]

[1]Department of Electrical Engineering, Faculty of Engineering & Technology, University of Lucknow, University Road, Babuganj, Hasanganj, Lucknow 226007, Uttar Pradesh, India
[2]Department of Electrical and Computer Engineering, Hawassa University, P.O. Box 05, Hawassa, Ethiopia

Received: 27.02.2026 Accepted: 06.03.2026 Published: 31.03.2026

https://doi.org/10.54414/VULL4304

## Abstract

It is well established that nanoscale design allows for the direct tuning of charge transfer, ion transport, catalytic activity, and interfacial stability as applied to electrochemical devices, making Nano-enabled energy conversion and storage systems an important frontier research area in support of electrification and decarbonization. This mini-review focuses primarily on nano-engineered materials and interfaces in key storage technologies, including lithium-ion batteries, sodium-ion batteries, solid-state batteries, and supercapacitors, while also discussing the broader implications of nanoscale design for electrochemical conversion platforms such as fuel cells, $CO_2$ reduction systems, and photoelectrochemical devices.

**Keywords:** energy conversion, nanocatalysts, lithium-ion batteries, fuel cells

## 1. Introduction

Nano-enabled energy technologies sit at the intersection of two bottlenecks that dominate modern electrification, i.e., interfacial losses and materials sustainability. The last decade's rapid scale-up of batteries for electric mobility and grid support has intensified both pressures, such as demand growth for automotive lithium-ion batteries has been steep, and critical-material supply chains remain concentrated, motivating chemistries and designs that reduce reliance on constrained elements while improving safety and performance [1], [2]. Nano-structuring addresses these constraints by changing the dominant physics and chemistry at device-relevant length scales. In electrochemical storage, nanoscale electrodes shorten diffusion lengths, increase electrochemically active surface area, and can accommodate strain, enabling higher rate capability and improved cycling, provided that the side effects of high surface area are mitigated through coatings, artificial interphases, and tailored electrolytes [3]. There are three broad themes in energy conversion with nano-catalysts like alloying, defect engineering, and single-atom, which expand active-site density and tune adsorption energetics. Nanoscale catalyst-layer architecture defines the mass transport, ionic conduction, and degradation pathways in a fuel cell electrode, so for fuel cells, the nanoarchitecture of electrodes is as important to performance as that of intrinsic catalyst activity [4]. Nanostructured catalysts and gas-diffusion electrodes (GDEs) seem to allow for industrially relevant current densities for $CO_2$ electroreduction, but with coupled stability problems that require a given device-level solution rather than just relying on catalyst design [5]. Then, for solar-to-fuel and photoelectrochemical (PEC) routes, these nanostructured photoelectrodes enhance light harvesting, charge separation, and catalytic turnover, whereas integrations of system-level assembly are becoming the key factor towards the realization of viable solar fuels [6], [7]. The overarching bottom line is that scale-up, reproducibility, and lifecycle impacts are constraints growing more acute; performance gains from nano-enabled innovations show every sign of being capped with scale-up, reproducibility, and lifecycle impacts. The most credible near-term pathway involves better-controlled interfaces at the minimally effective nanoscale via scalable processes, i.e., dry electrode fabrication, roll-to-roll coating, and selective atomic layer deposition, coupled with some consideration of safety, exposures, and sustainability [8], [9], [10], [11].

High energy storage, high power buffering, and efficient conversion of electrons to molecules and vice versa are structurally required for the indirect electrification of sectors difficult to electrify directly [1], [2]. For the energy transition in practice, the strategy must be a portfolio that includes lithium-ion and emerging battery chemistries for energy storage, supercapacitors and hybrid capacitors for high power transients, and electrochemical conversion platforms such as fuel cells, $CO_2$ reduction devices, and photoelectrochemical systems for conversion or diversified seasonal storage [4], [5], [6], [12], [13]. However, the scale of deployment turns materials constraints from curiosities at the lab test into system-level risk. However, as noted in previous analyses of electric vehicle (EV) battery supply chains and critical materials used across all applications, the competitive dynamics affect future resilience generation more than energy-density improvements with lower effective demand per km/travelled mile or per kWh delivered from vehicle energy storage, but chemistry choices are even more decisive, together with recycling [1], [2].

At least one functional length scale is in the 1–100 nm regime, which has a broadly defined class of materials and architectures known as nanomaterials. The reasoning behind this is that most electrochemical processes are interface-controlled, such as charge transfer, interphase formation, catalyst turnover, and degradation, all of which manifest at or near the surface. Increasing interfacial area and engineering of heterointerfaces via nano-structuring, coupled with nanoscale coatings to suppress unwanted parasitic pathways without necessarily compromising transport, are a few components in the toolbox. The mentioned principle is particularly apparent in silicon anodes, solid-state batteries, and catalyst-layer engineering [3], [4], [14]. Nano-enabling is not automatically beneficial. For example, high surface area may lead to enhanced electrolyte decomposition in batteries, catalyst dissolution or carbon corrosion in fuel cells, and also raise the risk of occupational exposure when handling the powder [10], [11]. The core challenge, then, is to engineer nano-bulky at the system scale without loss in stability of that material during manufacture. Table 1 gives an overview of important historical milestones related to the development of nanomaterials for energy storage and conversion technologies.

**Table 1.** Selected milestones linking nanomaterials to energy systems.

| Year | Milestone in nano-enabled energy research |
|---|---|
| **1991** | Commercial lithium-ion batteries were introduced, establishing a practical platform for energy-dense portable storage [15]. |
| **2004** | Graphene was isolated and characterized as an atomically thin conductive material, opening new directions in nanoscale energy materials research [16]. |
| **2011** | MXenes were introduced as a new family of two-dimensional carbides and nitrides with strong potential for electrochemical applications [17]. |
| **2021** | Gas-diffusion $CO_2$ electrolyzers were critically reviewed as a device-level pathway toward industrially relevant current densities [5]. |
| **2023** | Solid-state batteries were extensively assessed with emphasis on interfaces, power capability, and manufacturability [18]. |
| **2024** | Techno-economic analyses expanded to integrated photo-rechargeable storage systems and $CO_2$ conversion technologies [6]. |
| **2025** | Perovskite-driven photoelectrochemical devices demonstrated solar-driven $C_2$ hydrocarbon production in tandem configurations [7]. |

## 2. Review Scope and Approach

This work is a narrative review of nano-enabled energy storage and conversion systems, highlighting issues of interfacial engineering, nanostructured electrodes, and practical device-level limitations. The review focuses on representative, high-impact literature covering lithium-ion batteries, sodium-ion batteries, solid-state batteries, supercapacitors, fuel cells, electrochemical $CO_2$ reduction, and photoelectrochemical conversion systems. Instead of using formal systematic-review screening criteria, the manuscript synthesizes foundational manuscripts, recent review articles, and selected publications to classify major classes of materials, bottlenecks in their performance, and stabilization methods, as well as newly proposed directions. This is not an exhaustive bibliometric survey, but a synthetic technical review across domains.

## 3. Nano-Enabled Electrochemical Energy Storage

Coupled transport, reaction kinetics, and degradation processes govern electrochemical performance. Nano-structuring alters such couplings via shortening diffusion paths, such as with nanotubes, increasing density of reaction-site availabilities, or introducing interfacial effects, for example, with coatings, heterostructures, and grain boundaries that stabilize metastable phases or mitigate unwanted side reactions [3], [14], [18]. The same mechanisms generate trade-offs. This could also lead to stronger parasitic reactions and faster growth of solid-electrolyte interphase (SEI) or cathode-electrolyte interphase (CEI), resulting in increased impedance and cyclable ions being consumed more [3], [14]. It is, therefore, in the context of interfacial engineering that modern nano-enabled storage approaches are most appropriate. Not maximum surface area, but controlled surface chemistry with transport-accessible porosity is important.

## 4. Nanomaterials for Different Types of Batteries and Their Components

### 4.1. Cathodes

For high specific energy, high-Ni layered oxide cathodes are promising, but they demonstrate surface reactivity that couples to impedance rise and capacity fade. More recently, microcracking is seen as an effect due to surface instability rather than a cause, with the focus shifted to control of nanoscale surface chemistry [19], [20].

### 4.2. Anodes

To host massive volume change and maintain electrical percolation, silicon's high theoretical capacity drives extensive nanoengineering. Recent reviews in electrochemical-to-mechanical coupling reveal that stable cycling can be achieved with 3D silicon designs or nano-structured to accommodate large volume expansion; however, low tap density, a high first-cycle loss, and processing complexity are universal issues. These issues are becoming more and more important in terms of the feasibility of commercialization [3]. A secondary industry-oriented strategy is regulated prelithiation and interface engineering [21].

### 4.3. Solid-State Batteries

On the other hand, solid-state batteries have higher safety and potentially higher specific energy, but the main bottlenecks are still interfacial [14], [18]. Halide-based conductors are also being highlighted in solid electrolytes for their compatibility advantage, but toxic failure mechanisms ensure interfacial engineering is required [22]. One convergent nano-enabled approach is artificial interphases, which are thin, conformal layers applied by atomic layer deposition (ALD), sol-gel routes, or mechanochemical processing, to control reaction pathways and maintain low interfacial resistance across cycling [14].

## 5. Nano-Structuring in Sodium-Ion Batteries and Emerging Chemistries

Sodium-ion batteries have moved from a conceptual alternative to early commercialization interest because sodium is abundant and can reduce dependence on some supply-constrained battery materials [23], [24]. Roadmap analyses in [24] argue that techno-economic competitiveness depends on manufacturing learning rates, materials costs, and matching Na-ion performance to segments where energy density is good enough, rather than head-to-head competition with the highest-energy lithium-ion packs [24].

From a nano-enabled materials viewpoint, three families dominate near-term Sodium-ion battery (SIB) design, such as hard carbon anodes, layered oxide cathodes, and Prussian blue analogues (PBAs) [23], [24]. Recent roadmap and competitiveness analyses indicate that sodium-ion deployment will depend not only on chemistry performance but also on manufacturing scale, cost learning, and materials recovery as the technology matures [24], [25].

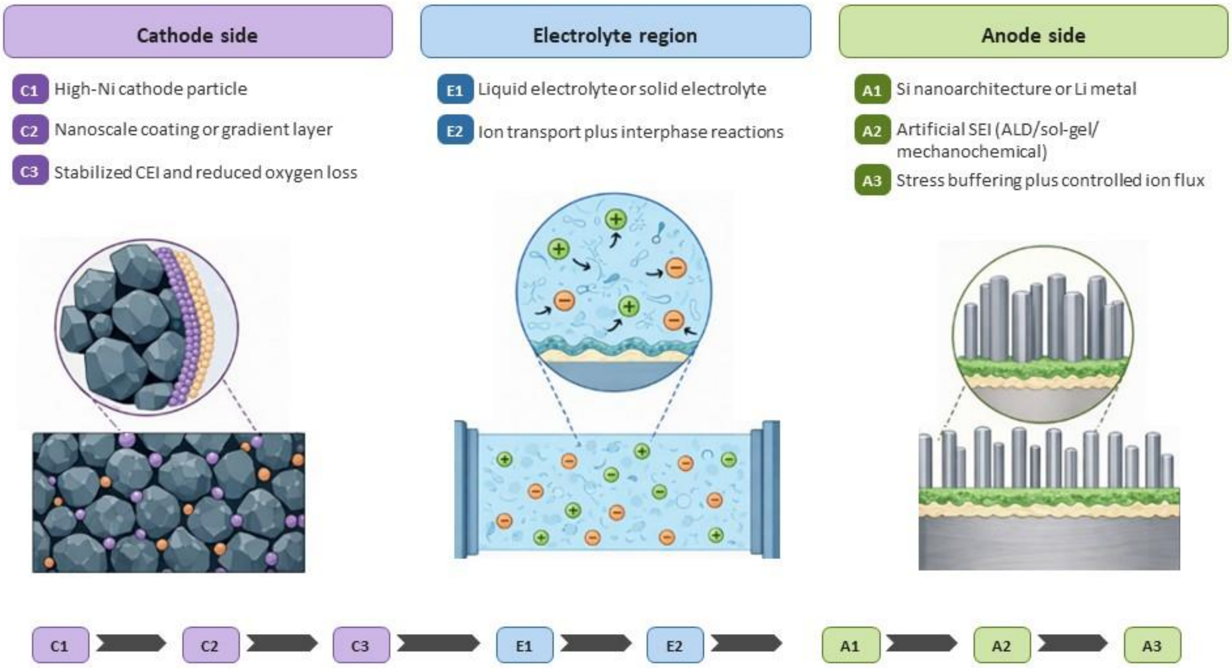

**Figure 1.** Conceptual schematic of nano-enabled interface regulation in representative battery systems, synthesized from the literature on silicon anodes, solid-state batteries, and interfacial engineering strategies [3], [14], [18], [19], [20], [21], [22].

## 6. Nanostructured Supercapacitors and Hybrid Capacitors

Supercapacitors occupy the performance space between conventional capacitors and batteries. They provide high power density and long cycle life but lower energy density, making them important for pulse power, regenerative braking, and power smoothing [12], [13]. Nano-enabled supercapacitor design follows two principal routes. Firstly, electric double-layer capacitor enhancement using nanostructured carbons such as activated carbon, mesoporous carbons, carbon nanotubes, and graphene derivatives to maximize accessible surface area and tune pore size to electrolyte ions, and secondly, pseudocapacitive or hybrid architectures using transition-metal oxides, sulfides, conductive polymers, or two-dimensional materials such as MXenes, to add fast surface or near-surface redox storage while retaining high-rate behavior [12], [13], [17]. A useful quantitative framing is the Ragone relationship, in which batteries can achieve higher energy density, whereas supercapacitors can provide far higher specific power but traditionally lower energy density, which motivates ongoing efforts to increase device voltage and pseudo-capacitance [12], [13].

## 7. Comparative Analysis of Nano-Enabled Storage Materials

Table 2 compiled and synthesized representative material classes, synthesis approaches, and performance metrics, with an explicit focus on device-relevant measures using literature on high-Ni cathodes, silicon anodes, solid-state batteries, sodium-ion batteries, and supercapacitors [3], [12], [13], [14], [18], [19], [20], [21], [22], [23], [24].

**Table 2.** Representative nano-enabled energy storage materials, synthesis routes, and performance metrics [3], [12], [13], [14], [18], [19], [20], [21], [22], [23], [24].

| Technology | Representative nano-enabled materials | Common synthesis | Key performance metrics | Dominant degradation modes | Stabilization mechanisms |
|---|---|---|---|---|---|
| Li-ion cathodes | high-Ni layered oxides with nanoscale coatings or gradients | wet-chemical coating, sol-gel, nanoscale surface reconstruction control | high specific energy up to cell-level hundreds of Wh/kg | surface reconstruction, oxygen loss, impedance rise, microcracking linked to surface reactivity | conformal coatings, gradient compositions, interface regulation from nano to macro |
| Li-ion anodes | Si nanoarchitectures | templating, electrospinning-derived composites, carbon coating, prelithiation plus SEI engineering | higher specific capacity; improved initial Coulombic efficiency and pouch-cell cycle retention | volume-change driven fracture, unstable SEI, low tap density, first-cycle loss | stress-buffering architectures, conductive networks, robust SEI plus controlled prelithiation |
| Solid-state batteries | Sulfide or oxide or halide solid electrolytes plus artificial SEI or CEI | Atomic layer deposition (ALD) or Molecular layer deposition (MLD) coatings, sol-gel, mechanochemical routes | safety plus higher specific energy potential, power limited by composite transport and interfaces | interphase growth, contact loss, Li-metal instability, composite cathode transport limits | engineered interphases, particle-size or processing control, interface-compatible electrolyte selection |
| Sodium-ion batteries | hard carbon anodes, layered oxides, Prussian blue analogues (PBAs) | biomass-derived carbon tuning, defect or water control in PBAs, surface stabilization | low-T performance for targeted segments | interfacial instability, structural transitions, defect-mediated parasitics | Surface or defect engineering, dehydration control, scalable processing, plus recycling planning |
| Supercapacitors | nanoporous carbons, metal oxides, conductive polymers, MXenes or 2D hybrids | Activation or templating, hydrothermal or solvothermal, etching plus delamination, electrode architecture control | high power (kW/kg class), long cycle life | electrolyte decomposition at high voltage, pore blockage, redox material dissolution | Pore or ion matching, stable electrolytes, hybrid electrode design, termination, or interlayer tuning |

## 8. Nanomaterials in Electrochemical Conversion Systems

Nano-enabled energy conversion systems rely on many of the same interfacial design principles that govern advanced batteries, but their dominant bottlenecks often arise at catalyst layers, gas-liquid-solid interfaces, and photoactive junctions. In these systems, gains in activity or selectivity at the nanoscale are meaningful only when they remain stable under realistic mass-transport, crossover, and integration constraints [4], [5], [6], [7]. Nanoscale catalyst layers, ionomer distribution, transport limitations, and durability in fuel cells [4]. Nanomaterials also constitute the basis of all electrochemical $CO_2$ reduction, including gas-diffusion electrodes, catalyst restructuring, flooding or drying, and stability at the device level [5]. These nanomaterials have been extensively used in photoelectrochemical systems and integrated photo-rechargeable architectures from light harvesting, charge separation, to tandem designs, as well as integrated conversion storage concepts [6], [7].

## 9. Discussion

This manuscript has demonstrated through a short literature review that the metric of surface area or particle size is no longer at face value an indicator of nanomaterial worth in energy systems. In contrast, best-reproduced improvements arise from engineering this interface in a controlled manner, such as when nanoscale design is applied carefully to boost ionic conduction, charge transfer, catalytic turnover, and bulk stability without significantly increasing parasitic processes or process complexity. It is not limited to lithium-ion, sodium-ion batteries, solid-state batteries or supercapacitors, reflected in the recent trend of shifting focus from just further scaling down the physical dimensions of electrodes via nano-structuring to surface coating and artificial interphase formation focusing on interface processes, defect regulation, component self-stabilization and hierarchical architecture-design, focused on structural stability [3], [12], [13], [14], [18], [19], [20], [21], [22], [23], [24]. This indicates a similar trend in energy-conversion systems. Nanoscale catalysts can increase the density of active sites and tune reaction pathways in fuel cells, $CO_2$ electroreduction devices, and photoelectrochemical platforms. However, device performance is ultimately limited by mass transport, interfacial degradation, product crossover, i.e., flooding or drying, and long-term stability. This implies that catalyst-level improvements need to be critically analyzed alongside an appropriately engineered electrode architecture, electrolyte environment, as well as system integration [4], [5], [6], [7]. Another significant takeaway is that minimum-effective nanoscale design tends to be more credible than random nano-structuring. Nanomaterials have the characteristic of shortening diffusion lengths and enhancing kinetic processes, but they also intensify side reactions, increase processing complexity, and may result in greater safety and lifecycle burdens [8], [9], [10], [11], [14].

## 10. Conclusion

Nano-enabled energy storage and conversion systems pose significant opportunities for enhancing electrochemical performance, although their real-world use requires the design of stable, manufacturable, and sustainable devices that fully realize the effectiveness of the nanoscale approach, reports. Despite the increase in rate capability, catalytic activity, and available reaction sites that nano-structuring can provide, these gains are frequently limited by interphase growth, structural degradation, transport bottlenecks such as active ion movement from the bulk to the surface, and scale-up issues, according to this review. In summary, the most promising path is not that of maximum utilization of nanoscale features but rather a rapid and appropriate application of nano-engineered interfaces only where they are most beneficial in terms of performance versus durability, safety, cost, and lifecycle. The focus should be on achieving these objectives with interface stability measurable over at least months, reproducible studies at scales in the kg to ton range, device-level validation of devices beyond half-cells and the development of circularity-aware materials strategies.

## Author Contributions

Both authors participated in the study design, manuscript preparation, and approval of the final version of the manuscript.

## Conflict of Interest

The authors declare no conflicts of interest.

## Funding

This study was not supported by external funding.

## Acknowledgment

The authors sincerely acknowledge all individuals and organizations whose support and cooperation contributed to the successful completion of this study.

## Abbreviations

Carbon Dioxide ($CO_2$), Gas-Diffusion Electrodes (GDEs), Photoelectrochemical (PEC), Electric Vehicle (EV), Solid-Electrolyte Interphase (SEI), Cathode-Electrolyte Interphase (CEI), Atomic Layer Deposition (ALD), Sodium-Ion Battery (SIB), Prussian Blue Analogues (PBAs), Molecular Layer Deposition (MLD).

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Journal of Nanotechnology and Innovative Materials

Research Article

# Effects of Gamma Irradiation on the Dielectric Properties of Polypropylene-Based Composites

**Durdana F. Rustamova**[1] **and Madina F. Nabili**[2]

[1]Department of Mechanics and Mathematics, School of Advanced Technologies and Innovation Engineering, Western Caspian University, Ahmad Rajabli 17A, III Parallel, AZ1001 Baku, Azerbaijan
[2]First Chayli Secondary School named after Kamil Samadov, Ministry of Science and Education, First Chayli Village, AZ5600 Shamakhi, Azerbaijan

Received: 27.01.2026 Accepted: 02.03.2026 Published: 31.03.2026

https://doi.org/10.54414/KFFE1230

## Abstract

This work investigates the effect of gamma irradiation on the dielectric properties of polypropylene/α $SiO_2$ nanocomposites. The non-polar nature of polypropylene has allowed it to be used as an insulating material. At the same time, this property makes polypropylene a suitable matrix for nanoparticle-filled composites. In the study, the PP + α-$SiO_2$ composite was obtained by melt mixing at a temperature of 170−190 °C, and then samples were prepared from it by pressing, and the thickness of the prepared samples was 90 µm. The resulting composites were irradiated with gamma rays. Then, the effect of absorbed dose on the electrophysical parameters of composite samples after irradiation was studied. During the study, a comparative analysis of the electrophysical parameters of non-irradiated and irradiated samples was conducted. It was found that the resulting nanocomposites increase the absorption of electromagnetic waves. As the absorbed dose of radiation increases, the degree of crystallization of the material decreases, the crystalline structure gradually disintegrates, and at high doses it completely disappears. The value of ε increases significantly at the beginning and remains constant at subsequent values of dose increase, leading to a sharp increase in dielectric losses.

**Keywords:** polypropylene, polymer composites, agglomeration, electromagnetic, aerosil, dielectric permeability

## 1. Introduction

Nanotechnology enables the creation of new materials with unusual properties. Such materials are widely used in various fields of science and technology, biotechnology, the military industry, construction, and other areas [1], [2]. Polypropylene is a material widely used in household and technical applications. Its resistance to physical and chemical factors and non-polarity have led to its use as an insulating material. At the same time, the addition of nanoparticles makes polymers promising for use as one of their main ingredients.

Recently, extensive research has been devoted to the study of the effects of γ-irradiation on various types of polymers and polymer composites. Such research is aimed at obtaining new types of nanocomposites with elastic and antistatic, electroactive, physical-mechanical, electret, and radiation-resistant properties and expanding their application possibilities. When nanoparticles with high chemical activity are incorporated into a polymer, the physicochemical, electrical, optical, and other properties of the polymer change dramatically depending on the size, shape, agglomeration state, and volume fraction of the particles [3], [4].

In the preparation of electroactive composite materials as promising materials, researchers are also considering studying other effects (temperature, frequency of external electric field, various types of radiation) on the electrical, dielectric, magnetic, and other properties of composites [5], [6].

The electrical conductivity of polyaniline-polymethacrylic/$SiO_2$ nanocomposites synthesized by chemical oxidation increases with frequency, and the nanocomposites obtained by incorporating $SiO_2$ nanoparticles into the copolymer increase the absorption of electromagnetic waves [7], [8].

## 2. Materials and Methods

In the study, PP + α-$SiO_2$-based composite samples were prepared. During the preparation of composite samples, the particle size did not exceed 90 nm, while the thickness of the prepared samples was 90 µm. The α-$SiO_2$ content of the filler was taken as 5% and 10% (by volume). Sometimes α-$SiO_2$ nanoparticles are technically called aerosil. PP + 10% α-$SiO_2$ composites were obtained by melt mixing at a temperature of 170–190 °C, and then samples were prepared from them by pressing. The resulting composites were irradiated with gamma rays. Next, the effect of absorbed dose on the electrophysical parameters of the composite samples exposed to irradiation was studied. During the study, a comparative analysis of the electrophysical parameters of non-irradiated and irradiated samples was conducted.

## 3. Results and Discussion

Figure 1 shows the variation of dielectric permittivity (ε) as a function of D for composites with a volume fraction of pure PP and PP + α-$SiO_2$ filler of up to 5% and 10% before and after γ-irradiation. As can be seen from the figure, when the concentration of α-$SiO_2$ nanofiller increases, at room temperature ($T = 293$ K), $\varepsilon = 2.2$ (PP) increases to 3.75 (PP + 10% aerosil). When the radiation dose increases, ε increases very weakly in the PP + 10% aerosil composite sample. As can be seen from the graph, in samples with a filler volume fraction of 5% and 10%, the ε value increases significantly at the beginning and remains constant with subsequent dose increases. At the indicated exposure dose, the value of ε in the PP + 10% aerosil composite sample is 5.34, so a 1.42-fold increase was observed. Such dependence of ε on the absorbed radiation dose is explained by the formation of intra- and intermolecular radicals and their interaction with oxygen according to the reaction:
$R^{\cdot} + O_2 \rightarrow ROO^{\cdot}$ [6], [7], [8].

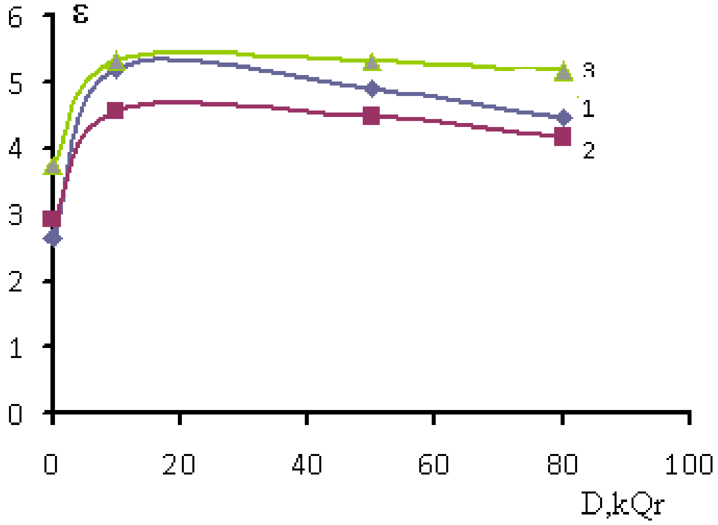


**Figure 1.** Dependence of the dielectric permittivity of composite samples with aerosil filler volume fraction $\varphi = 5\%$ and $\varphi = 10\%$ on the radiation dose $\varepsilon = f(D)$: 1 – initial PP; 2 – PP + 5% α-$SiO_2$; 3 – PP + 10% α-$SiO_2$.

On the other hand, as the absorbed dose of radiation increases, the degree of crystallization of the material decreases, the crystalline structure gradually disintegrates, and at high doses it completely disappears. The main factor that determines the change in the properties of the polymer matrix and all composites based on it is the process of disruption of the order of the crystal structure.

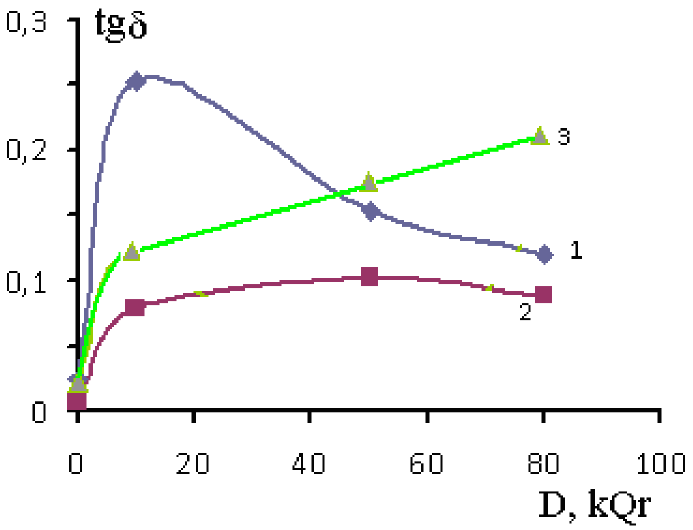


**Figure 2.** Dependence of the dielectric loss angle of composite samples with aerosil filler volume fraction φ = 5% and φ = 10% on the radiation dose tgδ = f(D): 1 – initial PP; 2 – PP + 5% α-$SiO_2$; 3 – PP + 10% α-$SiO_2$.

The results of the change in the dielectric loss angle tangent of the studied samples depending on the radiation dose (D) are given in Figure 2. A certain increase in ε up to the indicated values of the dose leads to a sharp increase in dielectric losses after the subsequent (up to 80–100 kGr) radiation dose (Figure 2). This may be due to the fact that at low doses, the rate of formation of spatial building bonds in the matrix prevails over the rates of destructive processes, while at high doses, D > 10 kGr, the rate of breaking of single bonds increases and the polymer matrix becomes brittle. In addition, studies of the sensitivity of nano-α-$SiO_2$ filler to γ and neutron radiation [9], [10] have shown that the effect of ionizing radiation leads to a decrease in dielectric loss tgδ. An interesting point, and at the same time contradictory to modern ideas, is that when nano-α-$SiO_2$ is irradiated with n-rays, the value of ε increases by up to 27 times. As can be seen from the figure, when the concentration of aerosil filler increases, tgδ = 0.0747 in pure PP at room temperature (T = 293 K) decreases from 0.0747 to 0.052 (PP + 5% α-$SiO_2$), and further decreases to 0.0163 (PP + 10% α-$SiO_2$).

Similar critical values are not obtained in the PP/nano-α-$SiO_2$ samples we studied. We believe that in the case of nanocomposites, $SiO_2$ nanoparticles can play the role of crystallization centers (Figure 3).

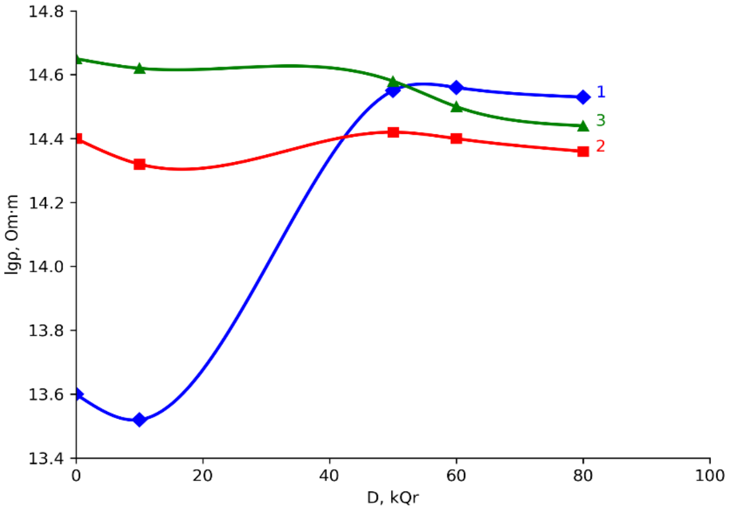
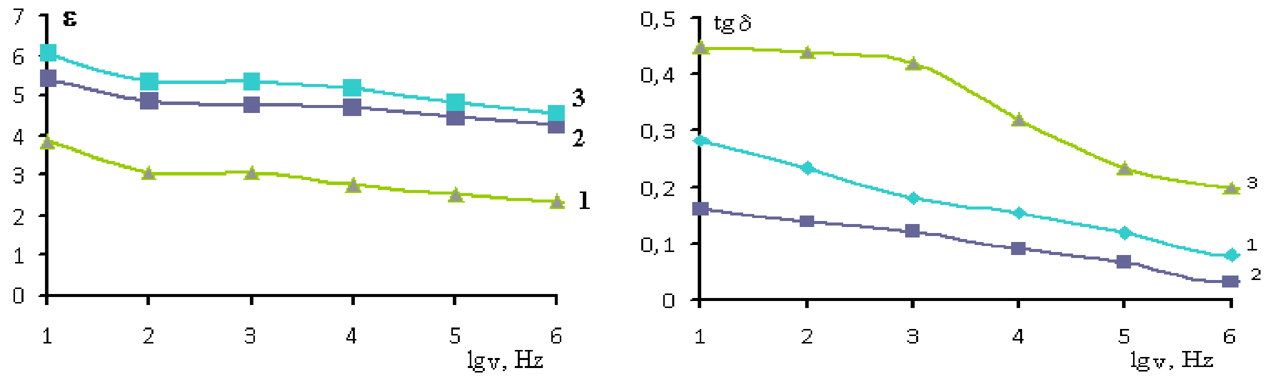


**Figure 3.** Dependence of the specific resistance of composite samples with aerosil filler volume fraction φ = 5% and φ = 10% on the radiation dose lgρ = f(D): 1 – initial PP; 2 – PP + 5% α-$SiO_2$; 3 – PP + 10% α-$SiO_2$.

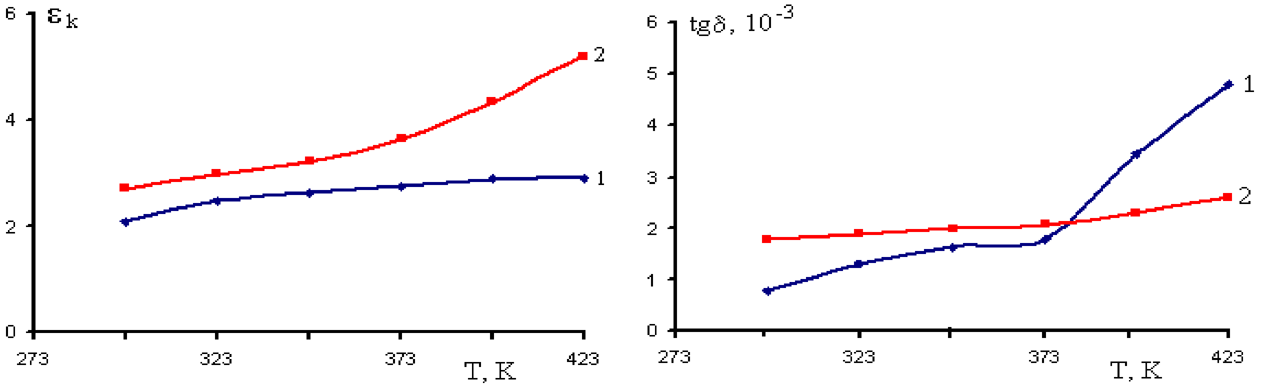
After samples with a volume fraction of α-$SiO_2$ nanofiller φ = 5% and φ = 10% were irradiated with a γ-irradiation dose of D = 10 kGr, the ε = f(ν) and tgδ = f(ν) dependences of the dielectric properties of PP-initial, PP + 5% α-$SiO_2$, and PP + 10% α-$SiO_2$ composite samples after γ-irradiation were studied and compared in the frequency range of 25–$10^6$ Hz (Figure 4).



(a) (b)

**Figure 4.** Frequency dependences of dielectric permittivity **(a)** and dielectric loss angle **(b)** of polypropylene/α-$SiO_2$ nanocomposite samples ε = f(ν) (a), tgδ = f(ν) (b): 1 – D = 0; 2 – D = 10 kGr; 3 – D = 20 kGr.

Figure 5 shows the dependences of ε = f(T) and tgδ = f(T) of pure PP, PP + 10% aerosil, composites after 10 kGr γ-irradiation at room temperature (T = 293 K). The behavior of the initial PP ε = f(T) dependence does not change significantly.



(a) (b)

**Figure 5.** Temperature dependences of dielectric permittivity **(a)** and dielectric loss **(b)** of PP/α-$SiO_2$ nanocomposite samples after 10 kGr irradiation ε = f(T) (a), tgδ = f(T) (b). 1 – pure PP, 2 – PP + 10% α-$SiO_2$.

However, in samples with a volume fraction of aerosil filler φ = 10%, after irradiation with a γ-radiation dose of D = 10 kGr, its dielectric permittivity increases at the initial values of the frequency, but then decreases. At the same time, after irradiating samples with a volume fraction of aerosil filler φ = 10% with a γ-radiation dose D = 10 kGr, their dielectric losses decrease very rapidly (Figure 5). A characteristic feature of the dependences given in Figure 5 is that at higher temperatures, both the dielectric loss angle and the dielectric permittivity increase. Therefore, the addition of α-$SiO_2$ nanofiller reduces the structural homogeneity of the sample up to a dose value of D = 10 kGr.

The effect of γ-rays on polypropylene/α-$SiO_2$ nanocomposites has been poorly studied. In terms of structure, it can be expected that the nanoaerosil filler will change the surface molecular structure of PP. At the same time, the study of the role and mechanism of action of γ-irradiation should be considered as a guiding factor in modification processes. It is known that PP-based composites have a thermostabilizing effect at doses of D = (3–5) kGr [11], [12]. This is due to the fact that interchain crosslinking processes predominate at low doses of $\gamma$-rays [11], [12]. At relatively high doses, the rate of destruction processes in PP increases, and the quality parameters of the composite decrease [13], [14].

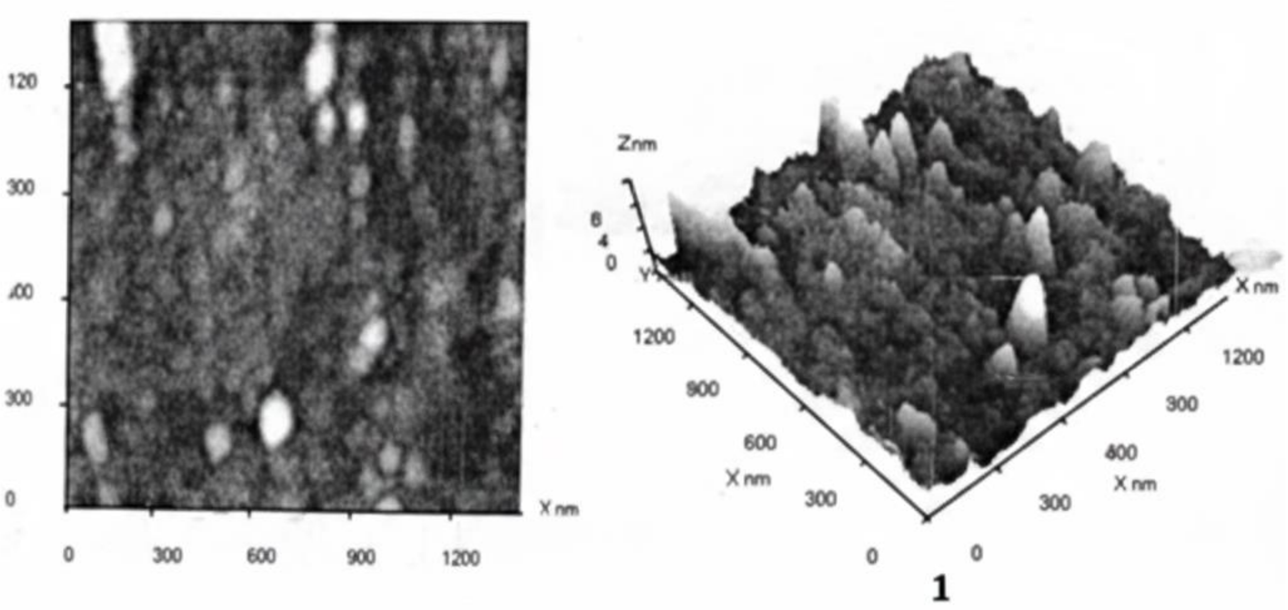


**Figure 6.** AFM image of a PP/$\alpha$-SiO$_2$ (95:5 vol.%) sample irradiated with $\gamma$-quanta in air with a dose of D = 5 kGr.

Figure 6 shows the AFM image of PP/$\alpha$-SiO$_2$ (95:5%) nanocomposite samples. The surface morphology appears uniform. In addition, the filler is evenly distributed throughout the matrix [13], [14]. Studies show that when the amount of amorphous $\alpha$-SiO$_2$ in polypropylene exceeds 10% (by volume), the heterogeneity of nanocomposite samples increases, affecting other structural parameters in the form of agglomerates in the nanoparticles.

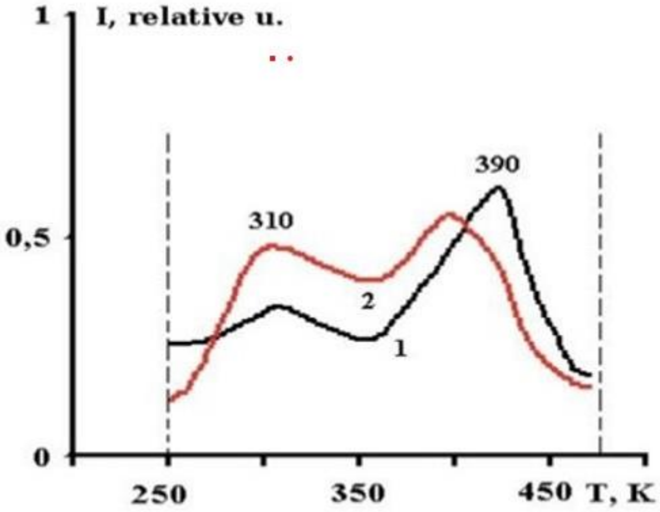


**Figure 7.** RTL spectra of PP + 5% $\alpha$-SiO$_2$ nanocomposite samples: 1 – D = 0; 2 – D = 50 kGr.

It can be seen from the obtained radiothermoluminescent curves that the intensities of the high-temperature radiation peaks at 310 K and 300 ± 2 K were redistributed by the effect of $\gamma$-radiation, that is, the first peak shifted to lower temperatures by 5–80 $^{0}$C. Both facts clearly demonstrate the possible structural changes as a result of irradiation and the role of $\alpha$-SiO$_2$ nanofiller as a nanofiller in these changes. Microscopic studies show that the $\alpha$-SiO$_2$ filler prevents the formation of large spherulites in the polymer Spherulite and radial crystallites. The crystallization process ("secondary" crystallization) in PP does not increase the size of spherulites in the material, but rather their number. These structural changes allow for the radiation-induced tracks to be evenly distributed in the polymer and, as a result, allow for the prediction of radiation modification processes.

## 4. Conclusion

Recently, extensive attention has been paid to the study of the effect of γ-irradiation on various types of polymers and polymer composites such as PP/nano-α-$SiO_2$. In the study, PP + α-$SiO_2$-based composite samples were prepared. During the preparation of composite samples, the particle sizes did not exceed 90 nm. The α-$SiO_2$ content of the filler was taken as 5% and 10% (by volume). PP + α-$SiO_2$ composites were obtained by melt mixing at a temperature of 170–190 °C, and then samples were prepared from them by pressing. The resulting composites were irradiated with gamma rays. Then, the effect of absorbed dose on the electrophysical parameters of composite samples after irradiation was studied. During the study, a comparative analysis of the electrophysical parameters of non-irradiated and irradiated samples was conducted.

The variation of dielectric permittivity (ε) as a function of D was studied for composites with pure PP and PP + α-$SiO_2$ filler volume fractions of up to 5% and 10% before and after γ-irradiation. It was found that as the concentration of α-$SiO_2$ nanofiller increases, ε = 2.2 (PP) increases to 3.75 (PP + 10% aerosil) at room temperature (T = 293 K). As can be seen from the graph, in samples with a filler volume fraction of 5% and 10%, the ε value increases significantly at the beginning and remains constant with subsequent dose increases. Such dependence of ε on the absorbed dose of radiation is explained by the formation of intra- and inter-chain radicals and their destruction by the reaction: $R^{\cdot} + O_2 \rightarrow ROO^{\cdot}$.

The tgδ = f(ν) dependences of PP + 10% α-$SiO_2$ composite samples before and after γ-irradiation show that the dielectric losses of the irradiated composite change little. However, after 10–50 kGr of radiation, although the value of tgδ increases sharply at the initial frequency, stabilization is observed later. After 50 kGr of radiation, the value of tgδ decreases sharply. It has been observed that the nanocomposites obtained by incorporating $SiO_2$ nanoparticles increase the absorption of electromagnetic waves.

At the same time, the dielectric losses of samples with aerosil filler volume fractions of φ = 5% and φ = 10% decrease very rapidly after being irradiated with a γ-irradiation dose of D = 10 kGr. At higher temperatures, both the dielectric loss angle and dielectric permittivity increase. Therefore, up to a dose value of D = 10 kGr, the α-$SiO_2$ nanofiller reduces the homogeneity (in terms of structure) of the sample. The reason for the changes is that radiation-destruction or crosslinking processes, as a result of the influence of radiation, change the mobility of various structural units (segments, lamellae, crystallites, etc.) in the polymer.

On the other hand, as the absorbed dose of radiation increases, the degree of crystallization of the material decreases, the crystalline structure gradually disintegrates, and at high doses it completely disappears. The main factor determining the change in the properties of the polymer matrix and all composites based on it is the process of disruption of the order of the crystal structure.

### Author Contributions

Both authors reviewed, edited, and approved the manuscript.

### Conflict of Interest

The authors declare no conflicts of interest.

### Funding

This research received no external funding.

### Acknowledgment

The authors declare no acknowledgments.

### Abbreviations

Silicon Dioxide ($SiO_2$), Atomic Force Microscopy (AFM).

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*Journal of Nanotechnology and Innovative Materials*

**Research Article**

# Studying the Effect of Nanoparticles on the Morphogenesis of Maize (*Zea mays* L.)

**Murad L. Aliyev**[1] and **Saltanat A. Aghayeva**[1]

[1]Department of Natural Sciences, School of Advanced Technologies and Innovation Engineering, Western Caspian University, 17 A, Ahmad Rajabli Street, III Parallel, AZ1072 Baku, Azerbaijan

Received: 20.02.2026 Accepted: 21.03.2026 Published: 31.03.2026

https://doi.org/10.54414/BFLC2695

## Abstract

In recent years, the impact of nanoparticles on plant morphogenesis has emerged as a significant research area in the fields of plant biology and materials science. The development and morphological characteristics of plants, such as maize (*Zea mays* L.), can be positively or negatively influenced by the application of nanoparticles. The objective of this study is to examine the impact of nanoparticles of various sizes and compositions on the morphogenesis process in maize plants. Due to their small size and high surface area, nanoparticles interact more effectively with plant cells and can affect many mechanisms that stimulate or limit their development. In this study, the effect of nanoparticles on seed germination, root development, leaf shape, and overall plant growth of maize plants was evaluated. The effect of nanomaterials on plant morphogenesis can vary depending on the genetic and physiological characteristics of the plants. In the study, various morphological characteristics of maize (e.g., leaf width, root length, plant height, etc.) and yield indicators were observed after the application of nanoparticles. Additionally, with the application of nanoparticles, cases such as an increase in plants' resistance to stress, an increase in yield, or conversely, a decrease in yield were encountered.

**Keywords:** nanoparticles, maize, morphogenesis, plant, seed, root, leaf

## 1. Introduction

Nanoparticles are materials that have gained significant importance in the fields of science and technology in recent years. Known for their small size and high surface area, nanoparticles can have both positive and negative effects on plant development and responses to the environment. The introduction of nanoparticles into plant biological systems can lead to significant changes in plant morphogenesis, stress resistance, productivity, and overall health status. The development and productivity of major agricultural crops, such as maize (*Zea mays* L.), are closely related to the morphogenesis of these plants. As maize is one of the most widely grown and consumed grains in the world, various technologies are used to improve its development [1]. The effect of nanoparticles on plant development stems from their interaction with plant cells. Due to their small size, nanoparticles can enter plant cells and cause significant changes in their metabolism. These effects can alter the morphology, physiology, and genetic characteristics of plants. For example, the application of nanoparticles can stimulate the germination rate, root and leaf development of plants, as well as enable them to reach high levels of productivity and sustainability [2]. The aim of this study is to study the effect of nanoparticles on morphogenesis in maize plants. Morphological and physiological parameters such as seed germination, root development, leaf shape, plant height, and yield will be investigated in relation to the application of nanoparticles to maize plants. Also, the results of this study will contribute to the development of new methods to evaluate the potential of nanomaterials in agriculture and optimize plant growth [3].

This study also aims to determine how nanoparticles affect plant hormones and their interactions with the environment. The information obtained as a result of the application of nanoparticles will open up new avenues for more sustainable and productive crop production in agriculture [4].

The effect of nanoparticles on plant morphogenesis may vary depending on their properties, composition, and size. The results of applying nanoparticles to maize (*Zea mays* L.) plants may vary under different experimental conditions. In this review, various aspects will be addressed based on the results obtained to evaluate the effects of nanoparticles on different developmental stages of maize plants. First of all, the effect of nanoparticles on the germination of maize seeds is noteworthy. It can be observed that the germination rate increases with the application of nanoparticles and that the seeds germinate faster and stronger. This could allow nanoparticles to more easily enter plant cells and change their physical and chemical properties, accelerating cellular metabolism. As a result, the seeds grow faster and have a stronger root system [5].

Root development is also an important parameter that indicates the effect of nanoparticles on plant morphogenesis. Nanoparticles can stimulate plant root development. This effect enhances the activity of root cells, enabling plant cells to absorb a greater amount of water and nutrients. Consequently, the plant's overall health and resilience are enhanced by the expansion and protection of its root system [6].

Leaf development is an additional critical factor that is associated with the effects of nanoparticles. The application of nanoparticles has resulted in modifications to the size and structure of the leaves of the maize plant [7]. The introduction of nanoparticles has the potential to enhance the cellular activity that is essential for photosynthesis in the leaf plasma. This enables the plant to more effectively absorb light and conduct photosynthesis. Nanoparticles can therefore boost a plant's energy, resulting in improved growth and output [8].

The use of nanoparticles can lead to higher yields in terms of productivity. Due to the effects of nanoparticles on plants, plants have a stronger root system, expanded leaf area, and faster growth, which increases overall productivity. However, there are positive results that nanoparticles can enhance the resistance of plants to natural stresses, making yields more stable. The fact that nanoparticles make plants more resilient to stress conditions (high heat, water stress, or pests) is also a beneficial aspect of using nanomaterials in agricultural applications [9].

However, negative effects of the application of nanoparticles may also be possible. High concentrations of nanoparticles can be harmful to plants and limit their growth. Also, some nanomaterials can have toxic effects on plant cells, which can slow down plant development. For this reason, the concentration of nanoparticles and the application dose must be carefully determined [10].

Overall, although the effect of nanoparticles on morphogenesis in maize plants is positive, more research is needed to optimize this effect. Different types and sizes of nanoparticles have different mechanisms of action, and these differences require researchers to develop more specific and effective approaches to applying these materials to plant development.

The data presented in Table 1 reflect the effect of nanoparticles on the morphogenesis of maize plants. The nanoparticles used are nanomaterials with different sizes and compositions. From the results shown in Table 1, it is clear that the application of nanoparticles to plants can cause significant changes in their various morphological and physiological characteristics.

Analysis of germination rate shows that small-sized nanoparticles cause seeds to germinate faster. This occurs as a result of the nanoparticles entering plant cells more easily and accelerating their metabolism. The results obtained on root development indicate that the application of mineral-based nanoparticles leads to strengthening and expansion of the root system. This allows the plant to absorb more nutrients and water and improves its overall health.

The size and shape of the leaves are also affected by the effects of nanoparticles. As a result of the application of silica-based nanoparticles, an increase in leaf area and enhanced photosynthetic activity are observed. This allows the plant to absorb more light and carry out the photosynthesis process more efficiently.

In terms of productivity, carbon-based nanoparticles increase plant yields by 20–30%. This is due to the fact that plants develop better and produce more. At the same time, nanoparticles enhance plants' resistance to stress. For example, zinc oxide nanoparticles make plants more resilient to high heat and water shortages [11].

However, high concentrations of nanoparticles can be harmful to plants and have toxic effects. Nanoparticles applied in high doses can slow or stop plant growth. Therefore, it is important to determine the correct dose and concentration when administering nanoparticles.

**Table 1.** Evaluation of the effect of nanoparticles on morphogenesis in maize plants.

| Parameter | Applied Nanoparticles | Outcome | Additional Comments |
|---|---|---|---|
| Germination rate | Small-sized nanoparticles | Increase | Nanoparticles cause faster seed germination. |
| Root development | Mineral-based nanoparticles | Strengthening and expansion | The root system becomes stronger, and the plant absorbs more nutrients and water. |
| Leaf size | Silica-based nanoparticles | Growth | Leaf surface increases, providing more light for photosynthesis. |
| Productivity | Carbon-based nanoparticles | Increase (20–30%) | Higher yield is obtained; plants grow and develop better. |
| Stress resistance | Zinc oxide nanoparticles | High resistance | Plants become more resistant under high temperatures and water-deficient conditions. |
| Toxic effect | High-concentration nanoparticles | Damage | Toxic effects may be observed at high concentrations. |
| Photosynthesis activity | Gold nanoparticles | Activation | Increase in photosynthesis activity and higher oxygen production. |

In general, although nanoparticles have a positive effect on the morphogenesis of maize plants, the effect of each nanoparticle type and dose on plant development may be different. For this reason, more research should be conducted on this topic.

## 2. Materials and Methods

### 2.1. Materials

Maize (*Zea mays* L.) seeds were used in the study. Seeds were purchased from a local agricultural store. The nanoparticles used in the experiment were selected as materials that would interact with plant seeds and affect plant development. The nanoparticles used are as follows:

1. Silica-based nanoparticles: Nanomaterials known for their positive effects on leaf growth and photosynthesis.
2. Carbon-based nanoparticles: Selected to promote overall plant growth and productivity.
3. Mineral-based nanoparticles: Used to stimulate root development.
4. Zinc oxide nanoparticles: Selected to increase the resistance of plants to high heat and water deficit conditions.

Nanoparticles were synthesized by chemical methods, and their size distribution (10–50 nm) was adjusted according to standard procedures. Nanoparticles were applied at concentrations of 0.1%, 0.5%, and 1%, and dose-dependent effects were assessed.

### 2.2. Experimental Design

The investigation was conducted in a laboratory environment that was highly controlled. The conditions were established in the following ways:

- Temperature: 25 ± 2 °C
- Light: 12 hours light/12 hours dark cycle
- Humidity: 60% ± 5%
- Soil: sterilized commercial agricultural soil

Each nanoparticle was divided into four groups of three replicates:

- Control group (no nanoparticles),
- Low concentration (0.1% nanoparticles),
- Medium concentration (0.5% nanoparticles),
- High concentration (1% nanoparticles).

Once a week after germination, the seeds were planted in standard-sized pots and treated with nanoparticles. The nanoparticles were used as a suspension in water.

### 2.3. Methods

1. Seed Germination: The number of seeds that germinated during a seven-day period was used for recording the germination rate. The germination rate was calculated as the ratio of germinated seeds to total seeds, and the time of first germination was noted.

2. Root and Shoot Growth: After four weeks, the root length and shoot height were measured. Measurements were taken in centimetres. The root-to-shoot ratio was used to assess the plant's growth distribution.

3. Leaf Development: Image processing software was employed to determine leaf area through a collection of photographs. Leaf length and width were measured, and the effect of nanoparticles on leaf development was evaluated.

4. Photosynthesis Activity: The rate of photosynthesis was assessed using a chlorophyll meter to measure the chlorophyll content in the leaves.

5. Yield Measurement: After harvesting the mature plants, the yield (seed number and crop weight) was measured.

6. Stress Resistance Test: Plants treated with zinc oxide nanoparticles were exposed to high temperature (38 °C) and water deficit conditions (no irrigation for 7 days). The ability of plants to recover from stress was assessed.

7. Statistical Analysis: All data were analyzed by analysis of variance (ANOVA). Differences between respective groups were assessed by Tukey's test. Results were considered significant if the P value was less than 0.05.

## 3. Results and Discussion

In this research study, the effect of nanoparticles on morphogenesis, i.e., tissue and organ development, of maize (*Zea mays* L.) plants was analyzed based on the literature. Various studies show that nanoparticles have both positive and negative effects; these effects mainly vary depending on the type of particles, concentration, application method, and plant species.

According to literature data, silver nanoparticles (AgNPs) can improve the germination and root shoot initiation of maize seeds, which increases the resistance of seeds to the effects of aging and provides better adaptation to stress conditions. AgNP treatment not only increases root and shoot length but also activates the activity of antioxidant enzymes, thereby supporting the stability of cell membranes.

Application of nanoparticles as a pre-planting priming increases stress resistance (e.g., drought, salinity, and cold conditions), increases the number and length of root hairs, and supports overall vegetative growth of the plant.

Furthermore, the mechanisms of translocation of nanoparticles into plant tissue are complex, and particle targeting, molecular signaling, and gene expression can alter not only morphogenesis but also metabolic and hormonal responses [12].

On the other hand, the application of nanoparticles increases the risk of phytotoxicity under specific conditions, especially at high concentrations, which can damage cell membrane structures through the formation of reactive oxygen species (ROS), which can lead to inhibitory effects on plant growth.

Consequently, the impact of nanoparticles on morphogenesis in maize plants is multifaceted and context-dependent. They have promise for utility, but in order to fully realise this potential, thorough and methodical research is needed.

## 4. Conclusion

In the area of applying nanoparticles and researching their impact on morphogenesis, the following suggestions are made:

1. Optimisation of concentration and application protocols: The optimal concentration range and application method must be standardised in order for nanoparticles to have a positive impact on maize plants. Toxic effects may result from high concentrations.
2. Analysis of molecular mechanisms: It is necessary to conduct a more comprehensive investigation of the molecular effects of nanoparticles on gene expression, hormonal homeostasis, and intracellular signalling. This will provide a more comprehensive explanation of the phenotypic changes that are observed during the development of plants.
3. Performing experiments in various environments: For instance, the impacts of applying nanoparticles should be compared with the effects of stress conditions (drought, salinity, heat, cold, etc.) on the morphogenesis of maize plants. This will facilitate the assessment of the functional advantages of the nanoparticles that have been applied in practical agricultural settings.
4. Assessment of ecological and biosystem risks: The risk of bioaccumulation, interactions, and the long-term effects of nanoparticles in soil and water systems should be the primary objective of ecological studies.
5. Multidimensional indicator integration: To ascertain how the effects of nanoparticles impact overall plant performance, genetic, physiological, biochemical, and morphometric variables should be examined collectively [11].

## Author Contributions

Murad L. Aliyev conducted the experimental work, data collection, analysis, and manuscript drafting. Assoc. Prof. Saltanat A. Aghayeva supervised the research process, contributed to the study design and methodology, reviewed the results, and revised the manuscript critically for important intellectual content. All authors read and approved the final version of the manuscript.

## Conflict of Interest

The authors declare no conflicts of interest.

## Funding

This research was not supported by external funding.

## Acknowledgment

The authors express their sincere gratitude to Western Caspian University for providing academic and laboratory support for this research. Special thanks are extended to Assoc. Prof. Saltanat A. Aghayeva for her valuable supervision, scientific guidance, and continuous support throughout the study.

## Abbreviations

Silver Nanoparticles (AgNPs), Analysis of Variance (ANOVA), Reactive Oxygen Species (ROS).

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*Journal of Nanotechnology and Innovative Materials*

*Review Article*

# Application of Nanomaterial-Based Smart Sensors in Mechatronic Systems and Biomedical Devices

**Elnara F. Firdus**[1] and **Telman T. Atakishi**[2]

[1]Department of Mechanics and Mathematics, School of Advanced Technologies and Innovation Engineering, Western Caspian University, 17 A, Ahmad Rajabli Street, III Parallel, AZ1072 Baku, Azerbaijan
[2]Azerbaijan State Oil and Industry University, Azadlıq Prospekti 20, AZ1010 Baku, Azerbaijan

Received: 18.02.2026 Accepted: 06.03.2026 Published: 31.03.2026

https://doi.org/10.54414/MDWR6644

## Abstract

This paper investigates the application of nanomaterial-based smart sensors in mechatronic systems and biomedical devices and examines their advantages compared to conventional sensor technologies. Measurement accuracy and response speed are among the key factors determining the effectiveness of control and monitoring processes in mechatronic systems and biomedical devices. Conventional sensor technologies are characterized by limitations such as low sensitivity, high inertia, and delayed response time. The high surface-to-volume ratio and unique electrical and mechanical properties of nanomaterials enable the mitigation of these limitations. This paper provides a systematic analysis of the working principles, advantages, and application prospects of nanomaterial-based sensors in mechatronic systems and biomedical devices.

**Keywords:** nanomaterials, smart sensors, mechatronic systems, biomedical devices, sensor sensitivity, response time

## 1. Introduction

The widespread application of mechatronic systems in modern industry, automation, and high-tech fields has necessitated the rapid development of sensor technologies. Robotics, automated production lines, aviation and space technologies, intelligent control systems, as well as medical monitoring and diagnostic devices operate based on data received from sensors. The signals obtained from the sensors are directly transmitted to the control, analysis, and monitoring algorithms; their accuracy, sensitivity, stability, and response time have a significant impact on the overall performance of the systems [1], [2], [3].

High-speed data processing, real-time control, and resistance to external influences are considered key requirements in modern mechatronic systems. In biomedical devices, accurate measurement of physiological parameters, detection of weak biological signals, and long-term reliable monitoring are of particular importance. For this reason, the sensors used are required to not only perform the measurement function, but also have high accuracy, low energy consumption, and fast response characteristics [2], [4], [5].

Conventional sensor technologies have been widely used in various industrial and medical applications for many years. However, the limited sensitivity of classical sensors based on macroscopic materials, their relatively long response time, and their sensitivity to external influences somewhat limit their application in modern high-precision systems [3], [4]. Reliable detection of small-scale signals, especially in real-time control systems and biomedical monitoring devices, poses a serious challenge for conventional sensors.

The rapid development of nanoscience and nanotechnology in recent years has led to the formation of nanomaterial-based sensor technologies. Graphene, carbon nanotubes, metal oxide nanostructures, and other nanomaterials have been widely studied in sensor technologies due to their properties such as high surface-to-volume ratio, high electrical conductivity, and small size [6], [7], [8]. The use of nanomaterials allows for increased sensitivity of sensors, reduced response time, and more accurate detection of weak physical and biological signals [8], [9], [10], [11], [12].

Nanomaterial-based sensors are currently considered a promising technology in mechatronic systems, smart robots, wearable electronic devices, implantable medical devices, and biosensor systems [11], [13], [14]. The application of these sensors not only increases the stability of control systems but also improves the quality of medical diagnostics and monitoring processes.

The purpose of this article is to comparatively analyze the main characteristics of nanomaterial-based sensors with conventional sensor technologies, investigate their application possibilities in mechatronic systems and biomedical devices, and analytically evaluate the advantages of nanosensors based on the existing scientific literature. The article comparatively examines key parameters such as sensitivity, response time, stability, and applicability.

## 2. Conventional Sensors

Conventional sensors have long been widely used in mechatronic systems, including biomedical measurement and monitoring devices, to measure physical, mechanical, and chemical parameters. These sensors are usually based on macro-sized materials, and the measurement process mainly occurs within the limited surface area of the sensor. Parameters such as temperature, pressure, force, vibration, and chemical environment are converted into electrical signals and transmitted to control and monitoring systems. However, conventional sensor technologies have a number of fundamental limitations:

- The low sensitivity of the sensors is due to the fact that only a small part of the material actively participates in the measurement process. This leads to the loss of weak physiological signals, especially in biomedical measurements [3], [4], [5]. As a result, measurement errors increase in mechatronic systems and biomedical devices that require high accuracy.
- The long response time of sensors is due to their relatively large size and mass. As a result, additional time is required for thermal, mechanical, and chemical effects to propagate within the material. This causes control delays in real-time mechatronic systems and vital biomedical devices [3].
- Conventional sensors are sensitive to external influences such as high temperature, vibration, and electromagnetic noise. During long-term operation, drift of measurement values, calibration instability, and reduced repeatability of results may be observed [3], [4].

The problems mentioned are particularly acute in biomedical devices, as the variability of the physiological environment, bioelectrical noise, and temperature fluctuations directly affect measurement accuracy [2], [15]. Ultimately, these factors indicate that conventional sensor technologies cannot fully meet the requirements of both modern highly dynamic mechatronic systems and biomedical devices that require high reliability and stability [3], [4].

## 3. Nanomaterial-Based Sensors

Nanomaterial-based sensors encompass modern sensor technologies that use nanometer-sized materials as the measuring element. These sensors enable more accurate and faster measurement of physical, mechanical, chemical, and biological effects in mechatronic systems and biomedical devices [6], [7], [8].

The high surface-to-volume ratio of nanomaterials increases the sensitivity of sensors and allows them to detect smaller changes, including weak biological signals, compared to conventional sensors [7], [8], [9].

The small size and low mass of nanomaterials ensure a reduction in the response time of sensors. This feature creates a significant advantage for mechatronic and biomedical systems operating in real-time [10], [11].

## 4. Application Possibilities in Mechatronic Systems and Biomedical Devices

A comparative analysis based on Table 1 demonstrates that nanomaterial-based sensors exhibit superior properties over conventional sensor technologies in key functional parameters, especially in terms of sensitivity, response time, and measurement stability. This scientifically justifies their promising application possibilities in mechatronic and biomedical systems. Nanomaterial-based sensors increase measurement accuracy, improve dynamic response characteristics, and enhance the stability of real-time control systems [14], [16].

**Table 1.** Comparison of conventional and nanomaterial-based smart sensors.

| Criteria | Conventional Sensors | Nanomaterial-based Smart Sensors |
|---|---|---|
| Size of sensitive element | Macroscale materials | Nanoscale structures |
| Surface-to-volume ratio | Low | High |
| Sensor sensitivity | Limited | Usually high [8], [9] |
| Detection of a weak signal | Limited | More effective detection capability [17], [18], [19] |
| Response time | Relatively long | Usually short [10], [11], [19] |
| Real-time applicability | Limited | More suitable for real-time applications |
| Stability of measurement parameters | Long-term drift may be observed | Relatively high, but requires further research |
| Need for calibration | Frequently required | In some cases, less is required |
| Resistance to external noise/ interference | More sensitive to external influences | Better durability has been observed in certain nanostructures |
| Sensitivity to temperature effects | High | May be lower depending on the material |
| Energy consumption | Relatively high | Usually low |
| Miniaturization capability | Limited | More opportunities are available |
| Use in mechatronic systems | Limited or partially suitable | Promising application opportunities exist [16], [20] |
| Use in biomedical devices | Noise and stability restrictions exist | Shows high potential for biomedical applications [14], [21], [22] |
| Wearable and implantable devices | Limited application capability | Promising for wearable systems [14] |

## 5. Problem Statement

The current limitations of conventional sensors make the problem of creating nanomaterial-based smart sensors and their integration into mechatronic systems, as well as biomedical devices, urgent. Existing sensor technologies cannot fully provide the necessary performance in applications requiring high accuracy and fast response, especially in real-time control and medical monitoring systems.

According to literature data, the sensitivity coefficient of graphene-based relative strain sensors has been shown to be significantly higher than that of conventional metal foil sensors [8], [9]. At the same time, reducing response time to the millisecond level is considered an important advantage for real-time mechatronic systems.

It has been found that nanocomposite elastic structures in pressure sensors based on carbon nanotubes (CNTs) show high sensitivity to small mechanical deformations [10]. This feature is important for biomedical applications, especially arterial pressure and respiratory monitoring.

It has been shown that in gas sensors made based on metal oxide nanomaterials, the interaction of the nanostructured surface with gas molecules is more intense, resulting in an increase in signal amplitude [12], [16], [20].

Faster response time and lower detection limit achieved when nanomaterial-based biosensors are applied to glucose monitoring [17], [18]. These results demonstrate the high efficiency of nanomaterials in detecting weak biological signals.

A summary of the research conducted shows that:

- High surface-to-volume ratio leads to increased sensitivity;
- Small size and low mass reduce reaction time;
- High electrical conductivity allows for clearer signal formation;
- Detection of weak physiological signals in biomedical environments becomes more reliable.

These facts indicate that the application of nanomaterial-based sensors in both mechatronic systems and biomedical devices is scientifically and practically justified.

## 6. Research Methodology

This study was conducted as a conceptual and review study based on a comparative analytical analysis of the existing scientific literature, rather than experimental measurements. The article compares the main characteristics of nanomaterial-based sensors and conventional sensor technologies based on results presented in various scientific sources.

During the research, existing scientific articles, review studies, and theoretical approaches on sensor systems based on graphene, carbon nanotubes, and metal oxide nanostructures were analyzed [8], [23], [24], [25], [26]. The following key parameters were taken into account during the comparison process:

- Sensitivity coefficient (Gauge Factor – GF);
- Reaction time;
- Surface-to-volume ratio;
- Signal-to-noise ratio;
- Energy consumption;
- Application possibilities in biomedical and mechatronic systems.

The results presented in the article are based on an analytical summary of results provided in various scientific sources, rather than on direct laboratory experiments or full mathematical modeling by the authors. For this reason, the assessments conducted are of a preliminary conceptual and analytical nature.

The main goal of the study is to identify the promising properties of nanomaterial-based sensors, demonstrate their comparative advantages over conventional sensor technologies, and identify key directions for future experimental research.

## 7. Comparative Analysis of Sensitivity and Response Time

The assessments presented in this section are based not on the authors' direct experimental measurements but on a comparative analysis of results provided in various scientific sources and a conceptual model approach. During the comparison, literature data on gauge factor (GF), response time, and signal characteristics were analyzed.

According to literature data, the sensitivity coefficient of conventional metal strain sensors usually varies in the range of $GF \approx 2–5$ [3]. It is noted that this indicator is significantly higher in graphene-based nanosensors [8], [9]. In some studies, $GF > 100$ has been observed in graphene-based structures [8], [9].

Sensors based on carbon nanotubes have been shown to record weak mechanical deformations more accurately due to their high surface-to-volume ratio and high electrical conductivity [10]. The small size of nanostructures allows for faster signal formation [11], [19]. The comparative analysis of the main characteristics of conventional and nanomaterial-based sensors is presented in Table 1.

## 8. Initial Comparison of Reaction Time

The comparison of reaction times was conducted based on an analytical analysis of experimental results presented in various scientific studies. According to literature data, the response time of conventional macro-scale sensors usually varies in the range of tenths of a millisecond [3]. In nanomaterial-based sensors, it has been shown that the response time is reduced to a few milliseconds or less due to the small size and low mass [10], [11].

In gas sensors based on metal oxide nanostructures, the high active surface area enhances the interaction with gas molecules and increases the response speed [12], [16]. Carbon nanotubes and graphene-based structures are considered superior for real-time systems because they provide faster signal transmission [8], [10].

Nanomaterial-based biosensors, especially glucose sensors, are characterized by lower detection limits and faster response times [17], [18]. Carbon-based nanostructures and metal oxide nanomaterials enable more efficient detection of biological molecules [24], [26].

These properties indicate that nanomaterial-based sensors have important advantages for real-time mechatronic control and medical monitoring systems.

Figure 1 presents a comparison of the surface-to-volume ratio for bulk materials and nanoscale structures. As can be seen from the figure, increasing the surface area in nanomaterials expands the active measurement zone of the sensor, resulting in increased sensitivity.

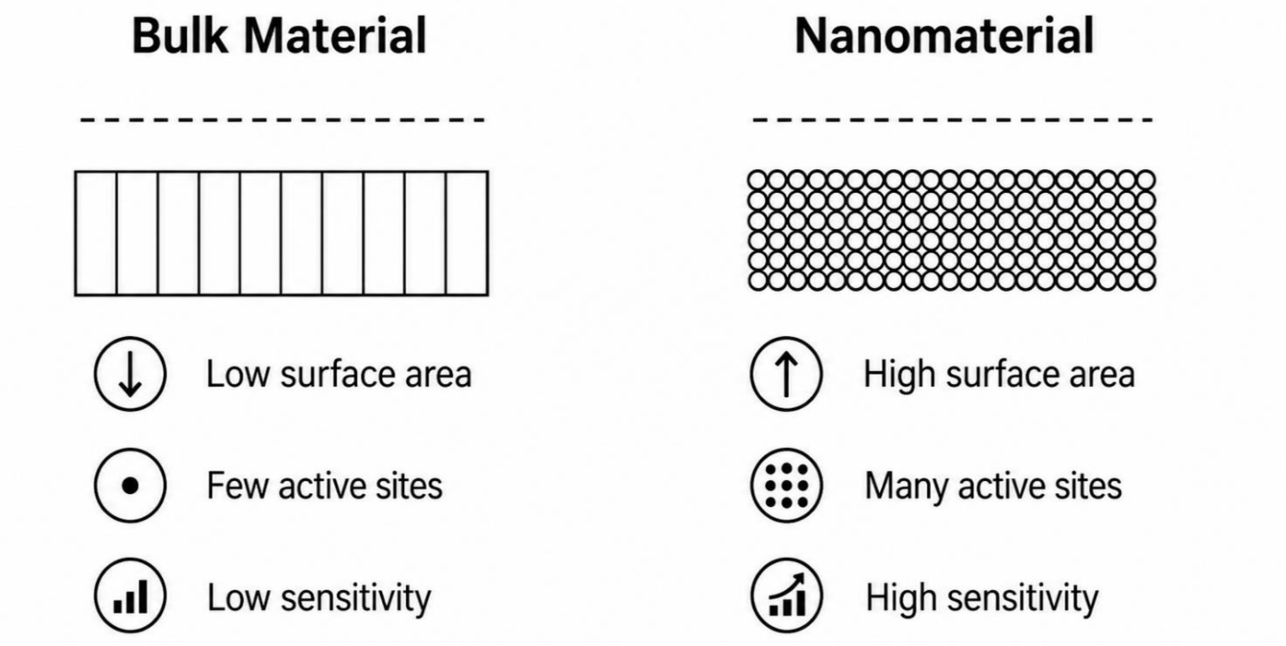

**Figure 1.** Comparative description of surface-to-volume ratio in large-scale and nanoscale materials.

Figure 2 compares the response time of conventional and nanomaterial-based sensors. The comparison shows that nanomaterial-based sensors have a shorter response time, making them more suitable for real-time mechatronic control and medical monitoring systems.

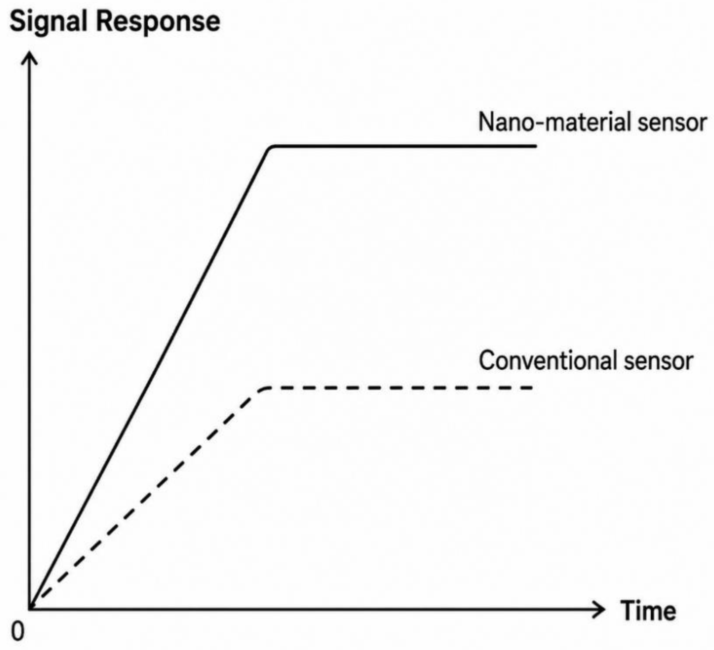

**Figure 2.** Comparison of response time in conventional and nanomaterial-based sensors.

## 9. Key Parameters for Future Experimental Validation

Based on the initial analytical evaluation, the following key measurement parameters were determined:

- Sensitivity coefficient (GF);
- Reaction time (t-response);
- Signal-to-noise ratio (SNR);
- Long-term stability;
- Temperature dependence.

Systematic measurement of these parameters in future experimental studies will allow for a quantitative assessment of the advantages of nanosensors.

However, the long-term stability, noise resistance, calibration processes, and temperature effects of nanomaterial-based sensors require further scientific research, especially for biomedical applications [15], [18].

## 10. Conclusion

The conducted analytical and comparative literature review shows that nanomaterial-based sensors demonstrate more promising properties than conventional sensor technologies in terms of sensitivity, response time, and detection of weak signals. The high surface-to-volume ratio and high electrical conductivity of sensors made especially from graphene, carbon nanotubes, and metal oxide nanostructures expand their measurement capabilities. The research shows that nanomaterial-based sensors have significant potential for improving real-time control processes in mechatronic systems, as well as for more accurate detection of weak physiological signals in biomedical devices [13], [14], [19], [25]. However, since the presented results are mainly based on an analytical summary of the existing scientific literature, the study can still be assessed as being in its conceptual and research phase.

The analysis revealed that issues such as long-term stability, calibration characteristics, temperature effects, and reliability in biological environments require further experimental studies for the practical application of nanomaterial-based sensors [15], [18], [26]. For this reason, it is considered appropriate to continue future research in the direction of conducting experimental measurements, comparative testing of various nanomaterials, and evaluating their application possibilities in real mechatronic systems.

Thus, although the preliminary analytical study conducted shows that nanomaterial-based sensors have high application prospects in mechatronic systems and biomedical devices, additional experimental and applied research is essential for their widespread practical application.

## Author Contributions

Both authors contributed to the conception, preparation, review, and final approval of the manuscript.

## Conflict of Interest

The authors declare no conflicts of interest.

## Funding

This study was not supported by external funding.

## Acknowledgment

The authors express their sincere gratitude to all those who contributed to the completion of this study.

## Abbreviations

Carbon Nanotubes (CNTs), Gauge Factor (GF), Signal-to-Noise Ratio (SNR).

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*Journal of Nanotechnology and Innovative Materials*

*Research Article*

# Study of the Oil-Collecting Properties of Cationic Salts

**Tarana A. Poladova**[1], **Tarana K. Guliyeva**[1], **and Fidan M. Vakilova**[2]

[1]Institute of Petrochemical Processes named after Academician Yusif Mammadaliyev, 30 Khojaly Avenue, Khatai District, AZ1025 Baku, Azerbaijan
[2]Institute of Education of the Republic of Azerbaijan, Afiyaddin Jalilov Street 86, AZ1029 Baku, Azerbaijan

Received: 16.02.2026 Accepted: 14.03.2026 Published: 31.03.2026

https://doi.org/10.54414/YYRJ9412

## Abstract

Octylamine, nonylamine, dodecylamine, and hexadecylamine were reacted with ethylenechlorohydrin in equimolar proportions, and the cationic salts octylethylammonium chloride (OEAC), nonylethylammonium chloride (NEAC), dodecylethylammonium chloride (DDEAC), and hexadecylethylammonium chloride (HDEAC) were obtained, respectively. The composition and structure of the salts obtained were identified by IR and UV spectroscopy methods. The specific electrical conductivity of aqueous solutions of the salts obtained by the electron conductometric method was measured, and their electrolyte nature was determined. The surface tension values of the cationic salts were calculated at the air boundary in a tensiometer. It was shown that all four of the salts are surfactants. It was determined that as the length of the alkyl radical in the cationic increases, its surface activity increases. The oil-collecting abilities of OEAC, NEAC, DDEAC, and HDEAC cationic salts were studied in laboratory conditions. In the conducted studies, oil (Pirallahi field oil) was poured onto 3 types of water with different mineral content - distilled, fresh water, and seawater, and formed a thin layer. It was determined that cationic salts demonstrate high oil-collecting abilities both in the form of 100% product and 5% solution. It was shown that in all cases the oil-collecting ability of 100% products is superior to that of aqueous solutions. The oil-accumulating abilities of OEAC and DDEAC salts and their aqueous solutions are the same. The oil-accumulating abilities of the first and third cationic salts among NEAC, DDEAC, and HDEAC are higher. The oil-collecting abilities of OEAC and DDEAC salts and their aqueous solutions lag behind those of the HDEAC salt. It was concluded that an increase in the length of the alkyl radical in the salt composition has a positive effect on the oil-accumulating ability.

**Keywords:** cationic salts, specific electrical conductivity, surface activity, oil accumulation coefficient, oil collecting

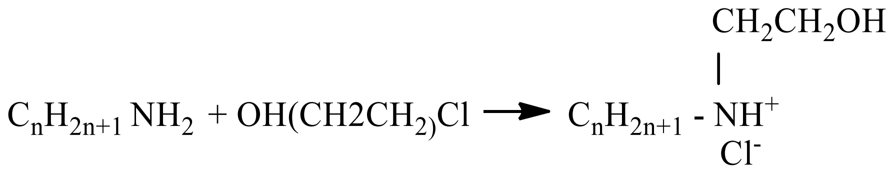
## 1. Introduction

When oil and petroleum-derived pollutants enter aquatic environments, volatile components evaporate first. Their evaporation is particularly intense at first. Then the evaporation process weakens, which is characteristic of crude oils. It has been shown that crude oils release up to 90% of their components into the atmosphere, diesel fuel up to 75%, and heavy oils and oil residues up to 10%. Thus, oil products that fall into water bodies, which are considered environmentally hazardous, pollute both the hydrosphere and the atmosphere. Unfortunately, it should be noted that the world's waters are very seriously polluted with oil and oil products, and pollution continues. Preventing pollution of water bodies and cleaning polluted waters is one of the main global problems in the world [1], [2]. Oil spills and oil products on the surface of a water body are cleaned by mechanical, physical, and chemical methods. It is possible to clean oil stains with a thickness of more than 0.1 mm by mechanical methods. When the thickness of the spilled oil layer is less than 0.1 mm, it is usually convenient to use surfactants to remove it from the water surface, and various surfactants are used for this purpose [3], [4]. The emulsifying ability of surfactants is considered valuable when removing oil-based pollutants from the water surface. A number of surfactants have the ability to convert the oil layer into a thin dispersion. In this case, the surfactant must have sufficient stabilizing ability in relation to the oil particles. It is convenient to use organic and polymeric surfactants to cover and collect oil on the water surface [5], [6].

According to the ability to remove a thin oil layer, surfactants are divided into oil collectors and oil dispersants [7]. The use of reagents with a collecting effect is of particular interest. These reagents prevent oil from being spilled on the water surface and collect it in a single spot. The principle of action of collecting reagents with a surface-active nature is based on their spontaneous flow and the formation of surface pressure when applied to the surface of the water-air phase separation. When collecting, reagents are applied along the perimeter of the oil layer; its area decreases, and its thickness increases significantly. Their effect is based on the pressure created by the monomolecular layer of surfactant when it flows along the water surface. The main indicators that determine the effectiveness of the reagent and the possibility of their practical application are the flow rate, the formation of a monolayer, long-term stability, low consumption, and low toxicity. From this point of view, it is practically very convenient to use the property of cationic compounds, such as surfactants, to remove a thin oil layer on the water surface.

## 2. Materials and Methods

Octylamine, nonylamine, dodecylamine, and hexadecylamine were reacted with ethylenechlorohydrin in equimolar ratios to obtain octylethylammonium chloride (OEAC), nonylethylammonium chloride (NEAC), dodecylethylammonium chloride (DDEAC), and hexadecylethylammonium chloride (HDEAC) salts, respectively. The general scheme of the reactions performed is as follows:



$$C_nH_{2n+1}\,NH_2 + OH(CH2CH_{2)}Cl \longrightarrow C_nH_{2n+1} - \underset{Cl^-}{\overset{\overset{CH_2CH_2OH}{|}}{NH^+}}$$

here n = 8, 9, 12, 16

The structure and composition of the obtained cationic salts were identified by IR spectroscopy. IR spectra were recorded on an ALPHA Fourier spectrometer (Bruker, Germany) at a wavelength of 600–4000 cm$^{-1}$. The results of the analysis of the spectroscopy of cationic salts. As can be seen from the values of the absorption bands in the IR spectra of the mentioned salts are similar.

NEAC and HDEAC cationic salts were also characterized by UV–Vis spectroscopy. The UV–Vis spectra were recorded in ethanol using a Specord UV–Vis spectrometer. The analysis results showed that in both cases, ammonium groups are observed at a wavelength of 211 nm.

The electrical conductivity of OEAC, NEAC, DDEAC, and HDEAC cationic salts was determined on a conductometer of the "Anion-4120" brand (made in the Russian Federation). For this, aqueous solutions of salts with different concentrations were prepared. The results of the conducted research are given in Table 1.

**Table 1.** Measurement results of the specific electrical conductivity of cationic salts (in μC/cm).

| Concentration of cationic salt, % by mass | OEAC | NEAC | DDEAC | HDEAC |
|---|---|---|---|---|
| 0.0001 | 30.0 | – | 5.1 | – |
| 0.0005 | 64.1 | – | 6.7 | – |
| 0.001 | 87.8 | – | 8.9 | – |
| 0.025 | – | 59.0 | – | 60.2 |
| 0.05 | 98.6 | – | 11.3 | – |
| 0.1 | 117.7 | – | 12.4 | – |
| 0.7 | – | 214.8 | – | 226.0 |

## 3. Results and Discussion

As can be seen from Table 1, the value of electrical conductivity increases as the concentration of the solution increases. The increase in specific electrical conductivity proves that the cationic salts OEAC, NEAC, DDEAC, and HDEAC have polar properties.

The surface activity of the obtained cationic salts was determined in a "Sigma-702" tensiometer. Therefore, aqueous solutions of cationic salts OEAC, NEAC, DDEAC, and HDEAC with different concentrations were prepared, and the surface tension values at the interface with air were calculated. The results of the research work carried out are given in Table 2.

**Table 2.** The surface tension values of cationic salts OEAC, NEAC, DDEAC, and HDEAC at the water-air interface (in mN/m).

| Concentration of cationic salt, % by mass | OEAC | NEAC | DDEAC | HDEAC |
|---|---|---|---|---|
| 0.0001 | 49.3 | – | – | – |
| 0.00025 | 45.1 | – | – | – |
| 0.0005 | 39.7 | – | – | – |
| 0.00075 | 37.1 | – | – | – |
| 0.01 | 32.4 | – | 29.4 | – |
| 0.05 | 28.4 | – | 28.2 | – |
| 0.75 | 25.2 | – | 27.6 | – |
| 0.1 | 23.3 | – | 25.3 | – |
| 0.2 | 21.6 | 40.8 | 24.1 | 33.3 |
| 0.5 | – | 31.9 | – | 25.5 |
| 0.7 | – | 26.4 | – | 29.5 |

From the results given in Table 2, it is clear that with an increase in the concentration of aqueous solutions of cationic salts, the surface tension values decrease. In other words, their surface-activity properties increase. From the point of view of surface activity, the OEAC cationic salt demonstrates higher efficiency. Thus, the tension value at a concentration of 0.2 decreases to 21.6 mN/m. In the case of the DDEAC cationic salt, the surface tension value at the same concentration is equal to 24.1 mN/m. In general, it can be concluded from the values shown in the table that the longer the length of the alkyl radical in the cationic, the greater its surface tension value.

Studies of the oil-collecting ability of OEAC, NEAC, DDEAC, and HDEAC cationic salts were carried out in laboratory conditions according to the methodology [2]. In the studies, oil taken from the Pirallahi field (density 0.9244 $g/cm^3$ at 20 °C, kinematic viscosity 105 sSt at 30 °C), distilled, potable (density 0.996 $g/cm^3$ at 20 °C, hardness 4.5 mg-eq/g) and seawater (Caspian Sea water, density 1.0098 $g/cm^3$ at 20 °C, total hardness 69 mg-eq/g) are applied and a thin layer of ~ 0.165 mm is formed. The oil collection efficiency of the obtained cationic salts is evaluated by the change in the area of the oil slick on the water surface due to the action of the reagent. Cationic salts are used in these studies as a 100% product and a 5% solution. The oil-collecting activity is estimated by the accumulation rate, in other words, the ratio of the area of the oil layer to the area of the oil spot formed by the action of the reagent (K) and the retention time of the collected oil (t). The results of the studies conducted to determine the oil-accumulating ability of the obtained cationic salts are given in Table 3.

**Table 3.** Oil-collecting ability of cationic salts OEAC, NEAC, DDEAC, and HDEAC.

| Reagent status | Distilled water | | Fresh water | | Sea water | |
|---|---|---|---|---|---|---|
| | τ, time | K | τ, time | K | τ, time | K |
| **OEAC salt** | | | | | | |
| **100% product** | 0–0.5<br>1.0–2.0<br>3.0–15.0<br>24.0–168.0 | 30.4<br>42.3<br>53.2<br>60.8 | 0–0.5<br>1.0–2.0<br>3.0–168.0 | 20.5<br>51.7<br>40.5 | 0–0.5<br>1.0–2.0<br>3.0–15.0<br>24.0–168.0 | 19.4<br>40.2<br>57.6<br>60.8 |
| **5% product** | 0–0.5<br>1.0–2.0<br>3.0–168.0 | 8.6<br>26.8<br>30.4 | 0–0.5<br>1.0–2.0<br>3.0–168.0 | 9.6<br>23.9<br>30.4 | 0–0.5<br>1.0–2.0<br>3.0–168.0 | 19.4<br>22.5<br>30.4 |
| **NEAC salt** | | | | | | |
| **100% product** | 0–0.5<br>1.0–2.0<br>3.0–15.0<br>24.0–190.0 | 30.5<br>42.3<br>53.2<br>72.5 | 0–0.5<br>1.0–2.0<br>3.0–15.0<br>24.0–190.0 | 38.1<br>46.6<br>58.9<br>71.5 | 0–0.5<br>1.0–2.0<br>3.0–15.0<br>24.0–190.0 | 30.5<br>58.7<br>60.8<br>80.6 |
| **5% product** | 0–0.5<br>1.0–2.0<br>24.0–190.0 | 40.5<br>53.7<br>60.5 | 0–0.5<br>1.0–2.0<br>3.0–190.0 | 40.5<br>59.8<br>60.5 | 0–0.5<br>1.0–2.0<br>3.0–190.0 | 38.7<br>60.8<br>80.6 |
| **DDEAC salt** | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **100% product** | 0–0.5<br>1.0–2.0<br>3.0–15.0<br>24.0–168.0 | 30.4<br>42.3<br>53.2<br>60.8 | 0–0.5<br>1.0–2.0<br>3.0–168.0 | 20.5<br>51.7<br>40.5 | 0–0.5<br>1.0–2.0<br>3.0–15.0<br>24.0–168.0 | 19.4<br>40.2<br>57.6<br>60.8 |
| **5% product** | 0–0.5<br>1.0–2.0<br>3.0–168.0 | 8.6<br>26.8<br>30.4 | 0–0.5<br>1.0–2.0<br>3.0–168.0 | 6.6<br>23.9<br>30.4 | 0–0.5<br>1.0–2.0<br>3.0–168.0 | 19.4<br>22.5<br>30.4 |
| **HDEAC salt** | | | | | | |
| **100% product** | 0–0.5<br>1.0–2.0<br>3.0–15.0<br>24.0–168.0 | 30.9<br>55.2<br>60.8<br>80.6 | 0–0.5<br>1.0–2.0<br>3.0–15.0<br>24.0–168.0 | 35.1<br>43.2<br>55.7<br>60.8 | 0–0.5<br>1.0–2.0<br>3.0–15.0<br>24.0–168.0 | 38.4<br>55.3<br>60.8<br>80.6 |
| **5% product** | 0–0.5<br>1.0–2.0<br>3.0–168.0 | 30.4<br>42.5<br>79.2 | 0–0.5<br>1.0–2.0<br>3.0–168.0 | 45.1<br>53.9<br>60.7 | 0–0.5<br>1.0–2.0<br>3.0–168.0 | 43.6<br>65.5<br>80.6 |

The experimental results given in Table 3 show that the OEAC cationic salt exhibits a strong oil recovery ability from waters with different mineralization levels, both as an aqueous 5% solution and as an undiluted product. The maximum oil recovery coefficient is 60.8 in the case of a 100% product, and the duration of reagent action is t ~ 7 days. When this salt is applied in the form of a 5% reagent, the maximum K value is recorded at 30.4, t ~ 7 days. The NEAC cationic salt also has higher oil recovery properties than all three waters. The maximum K value is 80.6, and in fresh and distilled water, respectively, it is 60.5 and 72.5. The effective action time of the reagent is more than 190 hours. In the case of the DDEAC cationic salt, when using a 100% product, K = 60.8, t ~ 7 days. When applied as a 5% reagent, the accumulation coefficient of this salt is 30.4, recorded at t ~ 7 days. When using the HDEAC cationic salt as an oil-collecting reagent, it accumulates the oil layer on the surface of seawater and distilled water into a single spot with a maximum oil collection coefficient of 80.6, and in fresh water, 60.8.

## 4. Conclusion

From the oil recovery efficiency of the cationic salts of OEAC, NEAC, DDEAC, and HDEAC themselves and their 5% aqueous solutions, it can be concluded that the oil recovery activity of OEAC, DDEAC salts, and their aqueous solutions is the same. In all cases, the oil-collecting ability of 100% products of the salts is superior to the same property of their 5% aqueous solutions. Among the investigated salts, NEAC and HDEAC salts demonstrated higher oil-collecting efficiency. The oil recovery efficiency of the HDEAC salt and its 5% aqueous solution is higher than the oil-collecting ability of OEAC and DDEAC salts and their aqueous solutions. Therefore, an increase in the length of the alkyl radical in the salt increases the oil-collecting ability. The duration of the reagent action is more than 7 days.

## Author Contributions

All authors contributed to the conception, investigation, analysis, writing, and revision of the manuscript. All authors have read and approved the final version of the manuscript.

## Conflict of Interest

The authors declare no conflicts of interest.

## Funding

This research was not supported by external funding.

## Acknowledgment

The authors express their gratitude to all individuals and institutions who supported this research and the preparation of the manuscript.

## Abbreviations

Octylethylammonium Chloride (OEAC), Nonylethylammonium Chloride (NEAC), Dodecylethylammonium Chloride (DDEAC), Hexadecylethylammonium Chloride (HDEAC), Ultraviolet–Visible Spectrometer (UV–Vis spectrometer).

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Western Caspian University

# Journal of Nanotechnology and Innovative Materials

Vol 1, No 3
March, 2026

Editorial Office Address: 17 A, Ahmad Rajabli Street,

III Parallel, Baku, Azerbaijan

Phone: +994 12 565 39 77

Email: jnim@wcu.edu.az

https://jnim.wcu.edu.az/

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Submitted for collection: 27.01.2026
Signed for printing: 31.03.2026
Paper format: 60x84 1/16 17.75