



Original Article

Gamma-irradiation applied to the synthesis of selenium nanoparticles and its influence on physicochemical properties

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Abstract: Selenium nanoparticles (SeNPs) have attracted considerable attention due to their biocompatibility and potential biomedical applications; however, their physicochemical properties strongly depend on synthesis conditions. This study aimed to systematically evaluate the influence of gamma irradiation dose (25-100 kGy), precursor concentration (1-2 mM Na₂SeO₃), and ethanol as a hydroxyl radical scavenger on the radiolytic synthesis of SeNPs. The results demonstrated that increasing irradiation dose up to 75 kGy, higher precursor concentration, and ethanol presence led to an increase in hydrodynamic size, while a reduction at 100 kGy suggests a fragmentation effect. Zeta potential values ranged from -54.4 to +13.9 mV, indicating heterogeneous surface charge and a tendency toward aggregation, supported by elevated polydispersity index values. Elemental analysis by EDS confirmed high selenium incorporation (60.72%–91.54%), with higher contents associated with conditions favoring efficient radiolytic reduction. Semi-quantitative yield estimations indicated high selenium incorporation efficiency, particularly under intermediate irradiation doses and in the presence of ethanol. Morphological characterization revealed predominantly spherical nanostructures. Overall, the findings demonstrate that radiolytic synthesis is a controllable and environmentally friendly approach for producing SeNPs, in which irradiation dose, precursor concentration, and radical scavengers play a critical role in determining nanoparticle size, composition, and stability. These insights contribute to the rational design of SeNPs for future biomedical and technological applications.

Keywords: gamma irradiation, green chemistry, nanoparticle characterization, selenium nanoparticles.



Irradiação gama aplicada à síntese de nanopartículas de selênio e sua influência nas propriedades físico-químicas

Resumo: As nanopartículas de selênio (SeNPs) têm despertado grande interesse devido à sua biocompatibilidade e potencial aplicação biomédica; no entanto, suas propriedades físico-químicas dependem fortemente das condições de síntese. Este estudo teve como objetivo avaliar sistematicamente a influência da dose de irradiação gama (25–100 kGy), da concentração do precursor (1–2 mM de Na_2SeO_3) e da presença de etanol como sequestrador de radicais hidroxila na síntese radiolítica de SeNPs. Os resultados demonstraram que o aumento da dose de irradiação até 75 kGy, maiores concentrações de precursor e a presença de etanol levaram ao aumento do tamanho hidrodinâmico, enquanto a redução observada em 100 kGy sugere um possível efeito de fragmentação. Os valores de potencial zeta variaram de $-54,4$ a $+13,9$ mV, indicando heterogeneidade na carga superficial e tendência à agregação, corroborada pelos elevados valores de índice de polidispersão. A análise elementar por EDS confirmou alta incorporação de selênio (60,72%–91,54%), sendo os maiores teores associados a condições que favorecem a redução radiolítica eficiente. As estimativas de rendimento semiquantitativas indicaram alta eficiência de incorporação de selênio, particularmente sob doses intermediárias de irradiação e na presença de etanol. A caracterização morfológica revelou nanoestruturas predominantemente esféricas. De forma geral, os resultados demonstram que a síntese radiolítica é uma abordagem controlável e ambientalmente amigável para a produção de SeNPs, na qual a dose de irradiação, a concentração do precursor e a presença de sequestradores de radicais desempenham papel fundamental na determinação do tamanho, composição e estabilidade das nanopartículas. Esses achados contribuem para o desenvolvimento racional de SeNPs para futuras aplicações biomédicas e tecnológicas.

Palavras-chave: irradiação gama, química verde, caracterização de nanopartículas, nanopartículas de selênio.

1. INTRODUCTION

Nanomaterials are promising for advancing various fields [1], particularly biological and medical applications [2]. However, the amount of research conducted in this area is still far behind the availability of nanomedicines on the market [3]. Among these materials, selenium nanoparticles (SeNPs) have garnered significant attention due to their biocompatibility, exceptional reactivity, and low toxicity in mammals. SeNPs exhibit various beneficial properties, including anticarcinogenic, antioxidative, antidiabetic, antimicrobial, antifungal, and antiparasitic activities [4]. However, there are several challenges in translating the laboratory findings to real-world applications. For example, the key factors that influence therapeutic applications include the morphological characteristics, such as size, shape, and composition, and the surface chemistry of the nanoparticles (NPs) [5].

Green technology approaches have been employed to synthesize NPs in water using gamma radiation from a radioactive cobalt (^{60}Co) source, avoiding chemical residues from reducing agents, organic solvents, or high-temperature denaturation. A previous study utilized this "radiolytic" synthesis method to produce selenium NPs (SeNPs) [6]. This wet-chemical technique relies on radicals generated during the breakdown of water molecules, the most abundant substance in the solution, by the energy from ionizing radiation. Notably, as the water molecules break apart, oxidizing and reducing reactive products, such as hydrated electrons, hydrogen radicals, and hydroxyl radicals, are formed.

A key feature of this technique is the penetration power of gamma rays, which are composed of photons that, due to their higher energy and shorter wavelength, can pass through matter more effectively than other types of radiation. Moreover, gamma rays are electrically neutral, characterized by a low linear energy transfer (LET) gradient, producing fewer specific ionizations along their path. Therefore, gamma irradiators distribute energy randomly throughout the solvent more effectively than high-LET radiation [7]. Due to the

internal geometry of the irradiator, the energy from the incident ionizing radiation is also distributed evenly throughout the aqueous solution. Thus, since water is the most abundant chemical species, these excitations and ionizations break the water molecules (i.e., water radiolysis) and generate radiolytic products such as hydrated or solvated electrons (e_{aq}^-), or protons (H^+), hydrogen radicals ($H^\bullet$), hydroxyl radicals ($OH^\bullet$), hydrogen peroxide (H_2O_2), and hydrogen molecules (H_2) homogeneously throughout the solution. The solvated or hydrated electron (e_{aq}^-) product of the breakdown of the H_2O molecule becomes the primary reducing agent due to its very negative reduction potential [8]. The $H^\bullet$ molecules can also quickly reduce the metal to its zero-valence state [9,10]. Importantly, the produced $OH^\bullet$ molecules are highly reactive and possess strong oxidizing properties, often reverting the reaction to higher oxidation states. Thus, these reactions necessitate adding an $OH^\bullet$ scavenger.

Furthermore, the generation of water radiolysis products depends on the absorbed radiation energy (dose). The generation of these products immediately ceases when the ^{60}Co source is removed, allowing the control of product generation by adjusting the absorbed dose [11].

Therefore, the present study aims to systematically investigate the influence of gamma irradiation dose, precursor concentration, and the presence of an $OH^\bullet$ scavenger (ethanol) on the physicochemical properties of selenium nanoparticles (SeNPs), including size, morphology, composition, and surface charge.

2. MATERIALS AND METHODS

The following reagents were sourced from Sigma Chemical Co. (St. Louis, MO, USA): Sodium selenite (Na_2SeO_3 pentahydrate) and ethanol. Yeast extract, bacteriological peptone, and glucose were obtained from HiMedia (Mumbai, India). All other reagents used were of analytical grade.

2.1. SeNPs obtention

The samples, prepared using 1% yeast extract, 2% peptone, and 2% glucose (YPG medium), were supplemented with sodium selenite to achieve final concentrations of either 1 or 2 mM. Additionally, some samples were treated with 15% ethanol. These samples were positioned 50 cm away from a radioactive source and exposed to increasing doses of gamma radiation (0, 25, 50, 75, and 100 kGy) at a dose rate of 6120.68 Gy/h throughout the experimentation period. The samples underwent gamma radiation in a Panoramic Irradiator (model/serial number IR-214 type GB-127, MDS Nordion, Canada), which uses a ^{60}Co source emitting photons with energies of 1.17 and 1.33 MeV.

2.2. Nanoparticle characterization

The characterization was performed using several methodologies, including dynamic light scattering (DLS), UV–Vis analysis, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), X-ray diffraction (XRD), and transmission electron microscopy (TEM).

Briefly, DLS was utilized to measure the zeta potential, hydrodynamic size, and polydispersity index (PDI) of the isolated SeNPs using a Malvern 3000 Zetasizer (Malvern, Worcestershire, United Kingdom). Experiments were conducted in triplicate to calculate average values.

The UV–Vis spectra of the SeNPs synthesized in YPG medium under irradiation were obtained using a Perkin Elmer 2300 Multilabel Reader (Shelton, Connecticut, USA). The data were collected using Enspire software (Fort Wayne, Indiana, USA).

The morphology and size of the synthesized nanostructures were characterized using a SIGMA VP SEM Carl Zeiss (Oberkochen, Baden-Württemberg, Germany) in the UFMG microscopy center. The microscope is equipped with an EDS system (XFlash 410-M, Bruker Nano GmbH) controlled by ESPRIT software.

The TEM experiments were carried out using a Tecnai G2-20 SuperTwin FEI, Thermo Fisher Scientific (Waltham, Massachusetts, USA) operating at 200 kV in the same facility as the SEM. The materials were diluted with autoclaved water for the TEM samples and then dispersed using ultrasound (USC-1800 A) at 40 kHz and 132 W for 30 minutes. The resulting dispersion was then deposited onto copper grids coated with Holey Carbon.

2.3. Statistical analysis

The results are expressed as the mean $\pm$ standard deviation (SD) of three independent experiments performed in triplicate.

3. RESULTS AND DISCUSSIONS

3.1. SeNP synthesis

This study considers the synthesis methodology employed, radiolytic synthesis, to be environmentally friendly due to the absence of solvents or harmful agents, minimal energy consumption, and inexpensive equipment [12]. While acquiring and installing a gamma irradiator can be costly, once set up, it can serve a secondary function for radiolytic synthesis, even though this is not its primary purpose.

Using a liquid solution for the deposition of gamma irradiation ensures indiscriminate radical generation. However, depending on factors such as dose, dose rate, presence and type of organic molecules, and the scavenger used, this process can promote the rapid formation of atom clusters as a distinct event or facilitate the growth of previously formed clusters. This situation occurs because the rate of atom reduction is slower than the rate of ion association at the surface of the aggregates [13]. While the higher doses (25–75 kGy) augmented SeNP growth, a size reduction was observed at a higher dose (100 kGy), a phenomenon possibly associated with fragmentation [14, 15].

3.2. SeNP characterization

3.2.1 Color modification and UV-Vis spectra

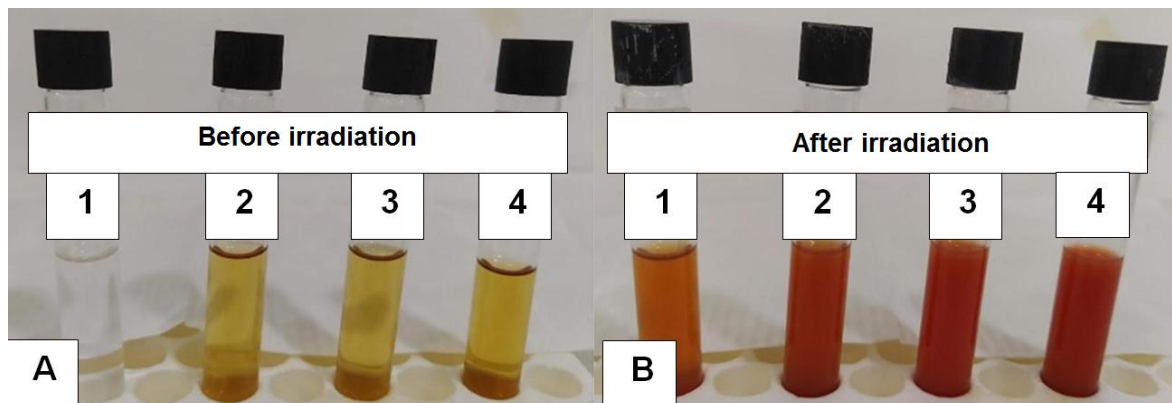
The experimental conditions used for visual evaluation are shown in Figure 1. In Figure 1A, the samples before irradiation consisted of: (1) 1 mM Na₂SeO₃ + 2% glucose; (2) YPG medium supplemented with 1 mM Na₂SeO₃; (3) YPG medium; and (4) YPG medium supplemented with 1 mM Na₂SeO₃ and 15% ethanol. In Figure 1B, the same samples are shown after exposure to 25 kGy of gamma radiation.

The initial indication of nanoparticle formation was a color change from transparent or brown to an intense red [16], which became more pronounced with increasing irradiation dose. The presence of ethanol also influenced this color change. The appearance of the red hue is attributed to the excitation of surface plasmon resonance (SPR), a characteristic feature of selenium nanoparticles (SeNPs). This phenomenon can occur at different wavelengths in the UV-Vis spectrum and depends on factors such as precursor concentration, pH, presence of scavengers, and synthesis conditions [17].

The UV-Vis spectra corresponding to different experimental conditions are presented in Figure 2. In Figure 2C, the spectra show the effect of increasing gamma irradiation doses (25, 50, 75, and 100 kGy) in samples containing 1 mM Na₂SeO₃. In Figure 2D, the spectra compare the effect of precursor concentration (1 and 2 mM Na₂SeO₃) and the presence of 15% ethanol at a fixed dose of 50 kGy. In Figure 2C, a shift in the absorption peak was observed with increasing irradiation dose, which is associated with an increase in the size of the SeNPs, as supported by the DLS results presented in Table 1. Similarly, variations in precursor concentration and the presence of ethanol influenced the spectral profile (Figure 2D), indicating changes in nanoparticle growth behavior.

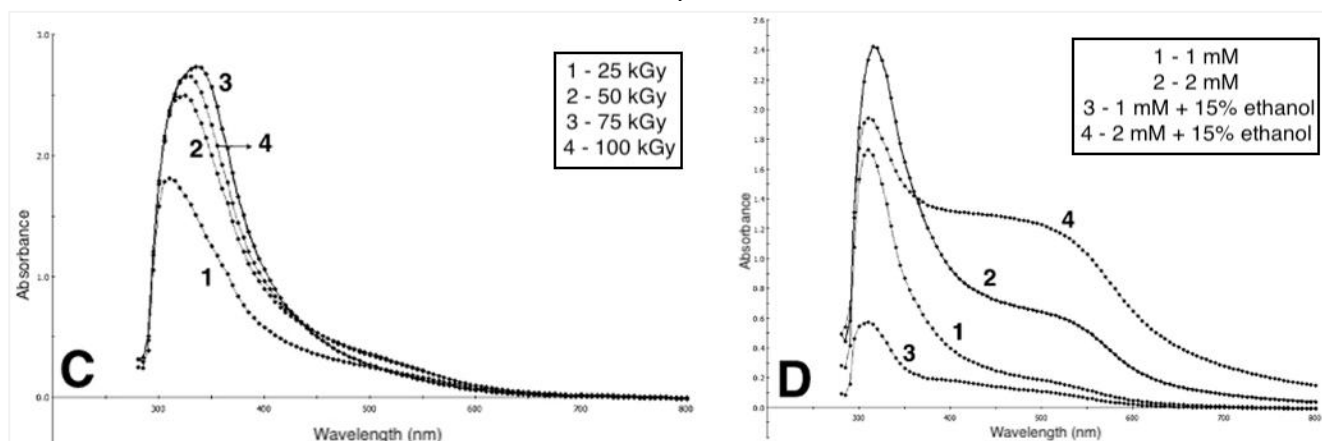
Additionally, the UV-Vis profile observed for the 25 kGy and 1 mM Na₂SeO₃ condition agrees with previous data reported by Pereira *et al.*, 2022 [18], reinforcing the reproducibility of this synthesis method.

Figure 1: Visual appearance of samples before (A) and after (B) gamma irradiation (25 kGy), showing the formation of selenium nanoparticles under different experimental conditions.



Source: the author, 2025.

Figure 2: UV–Vis spectra of SeNPs synthesized under different experimental conditions. (C) Effect of gamma irradiation dose. (D) Effect of precursor concentration and ethanol presence at a fixed dose of 50 kGy.



Source: the author, 2025.

After visually confirming the presence of NPs, the other parameters mentioned above were assessed. The samples were stored at 4 °C until these determinations were reached. Then, the samples were gently shaken by hand before use.

3.2.2 Zetasyzer parameters

Initially, the samples were submitted to the zetasyzer, and the hydrodynamic size, polydispersity index (PDI), and zeta potential were recorded (Table 1).

Table 1: Determination of DLS Parameters in different conditions: hydrodynamic size (nm), PDI, and zeta potential (mV).

Condition	Σ Size (nm)	Size distribution (nm)	σ	PDI	Zeta Potential (mV)
1mM 25 kGy	121.1	116.1–138.4	15.77	0.142/0.141/0.11 ₂	–13.8/–16.7/–18.5
2 mM 25 kGy	204.3	153.1–255.5	72.41	0.046/0.034/0.04 ₆	–13.9/–14.8 /–13.7
1mM 25 kGy + ethanol	223.8	199.3–248.3	34.65	0.051/0.043/0.01 ₈	–27.7/–42.7/–54.4
2 mM 25 kGy + ethanol	253.6	221.2–286.0	45.82	0.009/0.001/0.00 ₇	+6.33/–18.8/–42.1
1mM 50 kGy	159.7	118.4–201.0	58.41	0.062/0.087/0.03 ₅	–14.0
2 mM 50 kGy	194.9	156.2–233.6	54.73	0.046/0.054/0.11 ₂	–5.54/+6.43/–15.7
1mM 50 kGy + ethanol	207.8	178.3–237.3	41.72	0.087	–12.5/–17.8/–21.6
2 mM 50 kGy + ethanol	253.0	224.0–282.0	41.01	0.046/0.034/0.04 ₆	–7.78/–9.15/–11.1
1mM 75 kGy	169.3	138.5–200.1	43.56	0.085/0.110/0.08 ₀	–24.0/–12.7/–37.6
2 mM 75 kGy	220.8	172.2–269.4	68.73	0.106/0.103/0.10 ₂	–13.8/–14.5/–16.3
1mM 75 kGy + ethanol	333.5	280.8–386.2	74.53	1.09	–12.5/–13.7/–12.5
2mM 75 kGy + ethanol	488.7	428.6–548.8	84.99	1.05	–7.78/–9.13/–11.1
1mM 100 kGy	150.4	122.8–178.0	39.03	0.067	–9.75/–9.77/–10.9
2 mM 100 kGy	180.3	108.7–251.9	101.26	0.075/0.153/0.10 ₀	–29.7/–3.00/+13.9
1mM 100 kGy + ethanol	255.7	207.0–304.4	68.87	0.241/0.212/.019 ₃	–10.6/–11.8/–13.7
2mM 100 kGy + ethanol	275.0	210.2–339.8	91.64	0.075/1.53/0.100	–10.4/–12.4/–14.1

σ SD from Σ Size (nm) (SD: Standard Deviation) The triple values of PDI and Zeta potential shown above are relative to different peaks detected on the same sample.

As shown in Table 1, increased radiation dose, substrate concentration, and the presence of ethanol all lead to larger NP sizes, a result consistent with a previous study [19]. The dose irradiation used is a crucial factor to consider, according to Amin et al. (2021), who showed that increases in low-dose irradiation (10–60 Gy) from a cesium irradiator (^{137}Cs) lead to the formation of SeNPs, with sizes increasing with each dose increase [20]. However, the results differ at high doses (in the kGy range) [21]. The inverse relationship occurs when increases in dose lead to a reduction in size, which was observed in our study. This property is not evident at the 75 kGy dose; however, it is consistent with the zeta parameters, particularly the zeta size and PDI (Table 1). According to Belloni et al. 1998 [22] and Le Caër 2011 [7], it can be assumed that the significant aggregation observed hindered accurate measurements, which, in turn, promoted the secondary nucleation and the growth of NPs [23].

Multiple values were obtained regarding the zeta potential for the same sample (see Table 1). To interpret these results, it is important to understand that the zeta potential measures the voltage at the surface of a particle with respect to the surrounding liquid medium, assuming that ions, molecules, and other agents are not interacting with the particle's surface. However, because the samples were allowed to settle and then only manually shaken, without sonication, the NPs formed distinct clusters due to the attractive/repulsive forces at play, leading to a heterogeneous distribution in the liquid. This clustering has been reported to influence the zeta potential values observed [24].

The PDI is a measure that describes the degree of non-uniformity in the size distribution of NPs. It indicates how light is dispersed among NPs with varying sizes [25]. The PDI is a dimensionless value that ranges from 0 to 1. In practice, values smaller than 0.05 are rare, while values greater than 0.7 indicate that the particle sizes are too large for practical use in DLS measurements [26]. PDI values of 1 or higher were determined (Table 1), which strongly suggests agglomeration and broad size distribution.

The surface charge of NPs influences their agglomeration and toxicity. It is well established that the phospholipid membranes of organisms carry a negative charge. As a result,

NPs with a negative surface charge are endocytosed at lower rates than those with a positive charge [27]. A wide range of values for superficial charge was obtained, ranging from -54.4 to $+13.9$ mV, with the majority showing a negative superficial charge. However, Yu et al. 2012 [28] demonstrated that SeNPs with a negative surface charge are more effectively incorporated into mammalian and yeast cells, which are commonly used as experimental models in scientific research. It is also important to consider that the charge of yeast cells can vary depending on the growth phase, even though they are generally negatively charged [29].

3.2.3 Influences of ethanol, dose, and substrate concentration on SeNP size

The gamma irradiation procedure was conducted in an organic YPG medium rich in nucleotides, amino acids, and protein hydrolysates. These molecules undergo various degrees of chemical modification during the water radiolysis process. However, in high ethanol concentrations, protein aggregation may exhibit reversible characteristics [30].

In the presence of ethanol, the use of gamma (γ) rays generates electrons that react with water and ethanol, forming radicals [e.g., $H^\bullet$, $OH^\bullet$, superoxide anion (O_2^-), molecular oxygen (O_2), and H_2]. These radicals play a crucial role in reducing selenium ions (Se^{4+}) to Se^0 leading to an observed increase in the size of the NPs.

Literature indicates that NPs synthesized solely in alcohol tend to be smaller. In contrast, water and ethanol contribute to larger NP sizes [31] due to the rise of ethanol radicals, increasing the initial ion reduction rate. This event was followed by a rapid occurrence of primary nucleation, which promoted the autocatalytic process. With an excess of alcohol molecules in the solution (15%), the reaction slowed, allowing for more significant interactions between the dispersed molecules, increasing the size [32]. It has been reported that increasing the number of carbons in the alcohol (e.g., methanol vs. ethanol vs. propanol) can increase NP size, since the longer carbon chains offer more interactions with the NPs

[33]. In the present study, we utilized an intermediary alcohol with a minor effect on the hydrodynamic size of the synthesized NPs [34]. Indeed, ethanol encourages the formation of intermediate radical species since both ethanol and water molecules contain hydroxyl groups. This feature makes them easily soluble together and promotes the general stabilization of hydrogen bonds with water molecules. Moreover, these interactions form different radicals responsible for reducing Se^{+4} to Se^0 [35].

When the substrate concentration is increased by adding more precursor to the solution (1 and 2 mM Na_2SeO_3), the size of the NPs is observed. In this case, selenium atoms are formed separately and can combine, leading to a larger final NP size. This phenomenon was well described by Naghavi *et al.* 2010 [36].

3.2.4 SeNP composition obtained with SEM

The samples underwent analysis to determine their elemental composition. This determination is crucial as different elements influence how NPs interact with their environment. Consequently, the composition of these NPs impacts their chemical, physical, and mechanical properties. The proportion of Se atoms in the NP composition ranges from 91.54% to 60.72%. Notably, almost all NPs (except those treated at 25 kGy) contain at least 75% Se (Table 2). There is also a small amount of carbon (C), ranging from 20.7% to 5.7%, along with trace amounts of oxygen (O) and sulfur (S). The presence of the precursor element, in this case, Se, is an essential characteristic of the NPs since it provides a surface area that exceeds that of the bulk precursor [29].

Table 2: Elementary Composition of SeNPs determined by SEM.

Condition	Selenium % Se	Carbon % C
25 kGy 1mM	64.11	20.74
25 kGy 1mM + ethanol	60.72	4.75
25 kGy 2mM	72.74	20.90
25 kGy 2 mM + ethanol	86.40	12.41
50 kGy 1mM	76.96	12.41
50 kGy 1mM + ethanol	91.54	7.25
50 kGy 2mM	89.45	10.55
50 kGy 2 mM + ethanol	88.55	11.45
75 kGy 1mM	78.24	20.18
75 kGy 1mM + ethanol	82.37	13.10
75 kGy 2mM	83.06	14.46
75 kGy 2 mM + ethanol	86.01	8.90
100 kGy 1mM	79.25	15.10
100 kGy 1mM + ethanol	91.34	5.72
100 kGy 2mM	72.34	14.06
100 kGy 2 mM + ethanol	75.76	18.14

3.2.5 Energy-dispersive X-ray spectroscopy (EDS) analysis

All conditions outlined in Table 1 were subjected to EDS analysis, but only one set of results was presented, as the spectra were very similar. A semi-quantitative comparison between the expected trends in selenium incorporation and the EDS-determined composition is presented in Table 3. The expected trends were estimated based on precursor concentration, irradiation dose, and ethanol presence, considering their influence on radiolytic reduction efficiency. This comparison supports the consistency between experimental observations and the proposed radiolytic mechanisms.

The optical absorption bands of the spectra exhibited characteristic peaks at 1.5, 11.2, and 12.5 keV (Figure 3), typical of metallic selenium [37, 38]. The quantitative analysis revealed selenium contents ranges from 60.72% to 91.54%, depending on synthesis

conditions (Table 2). Higher selenium percentages were generally associated with intermediate irradiation doses (e.g., 50 kGy) and the presence of ethanol, suggesting more efficient reduction of Se^{4+} to Se^0 under these conditions.

Considering the initial selenium precursor concentrations (1-2 mM Na_2SeO_3), the theoretical selenium availability in solution based on precursor concentration, ranging from approximately $78.96 \text{ mg}\cdot\text{L}^{-1}$ to $157.92 \text{ mg}\cdot\text{L}^{-1}$. Although EDS does not provide absolute nanoparticle concentration, it is widely used as a semi-quantitative technique to assess elemental incorporation in nanomaterials. In this context, combining theoretical precursor availability with EDS-derived composition enables a consistent interpretation of selenium incorporation efficiency. The agreement between expected trends and experimental data supports the proposed radiolytic reduction mechanisms.

Table 3: Semi-quantitative comparison between theoretical selenium availability and EDS-determined composition.

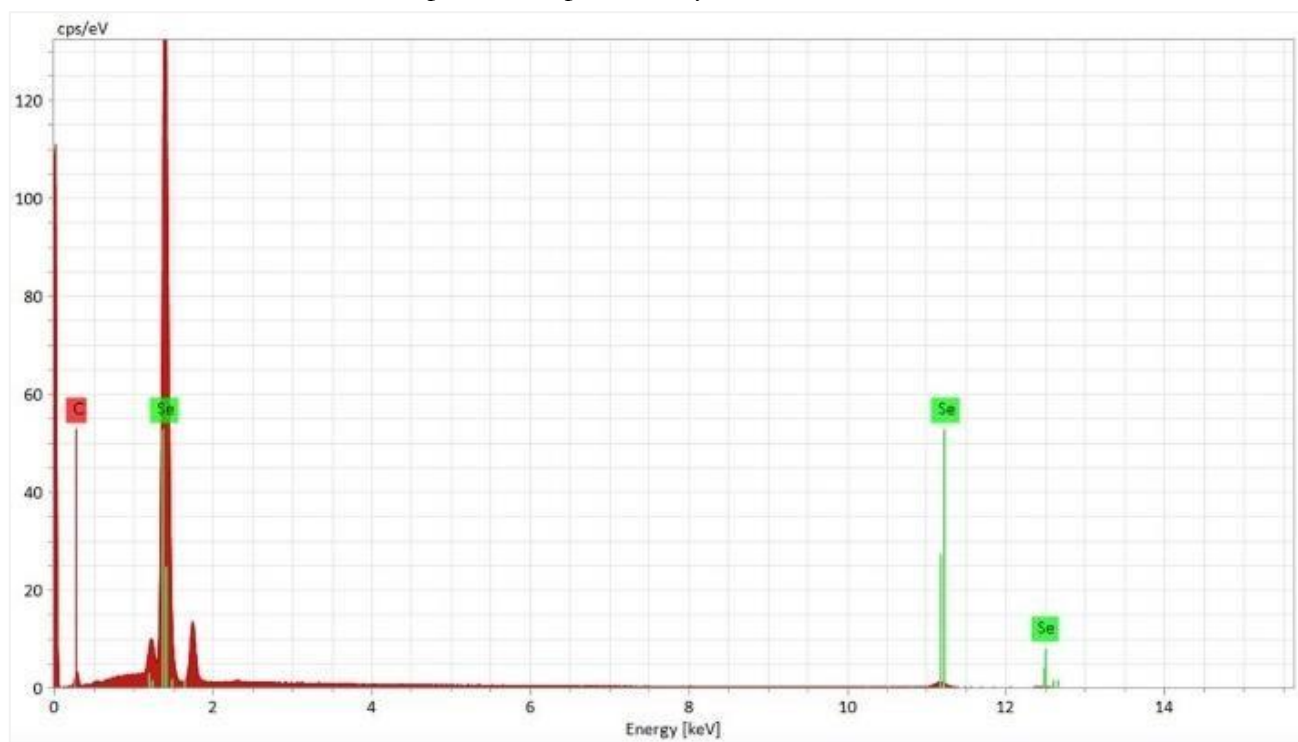
Condition	Expected trend % (quantitative estimation)	Se % EDS
25 kGy 1mM	60	64.11
25 kGy 1mM + ethanol	68	60.72
25 kGy 2mM	70	72.74
25 kGy 2 mM + ethanol	80	86.40
50 kGy 1mM	75	76.96
50 kGy 1mM + ethanol	88	91.54
50 kGy 2mM	85	89.45
50 kGy 2 mM + ethanol	90	88.55
75 kGy 1mM	80	78.24
75 kGy 1mM + ethanol	85	82.37
75 kGy 2mM	88	83.06
75 kGy 2 mM + ethanol	92	86.01
100 kGy 1mM	82	79.25
100 kGy 1mM + ethanol	90	91.34
100 kGy 2mM	75	72.34
100 kGy 2 mM + ethanol	78	75.76

A comparative analysis between theoretical expectations and the selenium contents determined by EDS demonstrates an overall satisfactory agreement, indicating that the proposed interpretation is consistent with the main mechanisms involved in the radiolytic synthesis of selenium nanoparticles. In particular, both approaches reproduce the increase in selenium fraction with increasing irradiation dose up to intermediate levels, which can be attributed to the enhanced generation of reducing species such as solvated electrons (e^-_{aq}) and solvent-derived radicals.

Additionally, the presence of ethanol consistently increased selenium content, supporting its role as a hydroxyl radical ($\bullet OH$) scavenger and as an indirect enhancer of the reducing environment. This effect is especially pronounced in lower precursor concentrations (1 mM), where the availability of reducing species becomes a more limiting factor.

However, localized discrepancies between theoretical expectations and EDS results were observed, particularly under conditions of low irradiation dose (25 kGy) and higher precursor concentration (2 mM). These deviations suggest that simplified theoretical assumptions do not fully capture complex phenomena such as competitive nucleation, nanoparticle aggregation, anisotropic growth, and possible reoxidation processes under high radical density conditions. Furthermore, it should be noted that EDS quantification may be influenced by matrix effects and sample morphology, which can introduce additional variability in heterogeneous systems.

Figure 3: Representative EDS spectrum of SeNPs synthesized by the radiolytic method, showing characteristic Se peaks. Sample: 50 kGy, 2 mM Na₂SeO₃, 15% ethanol.

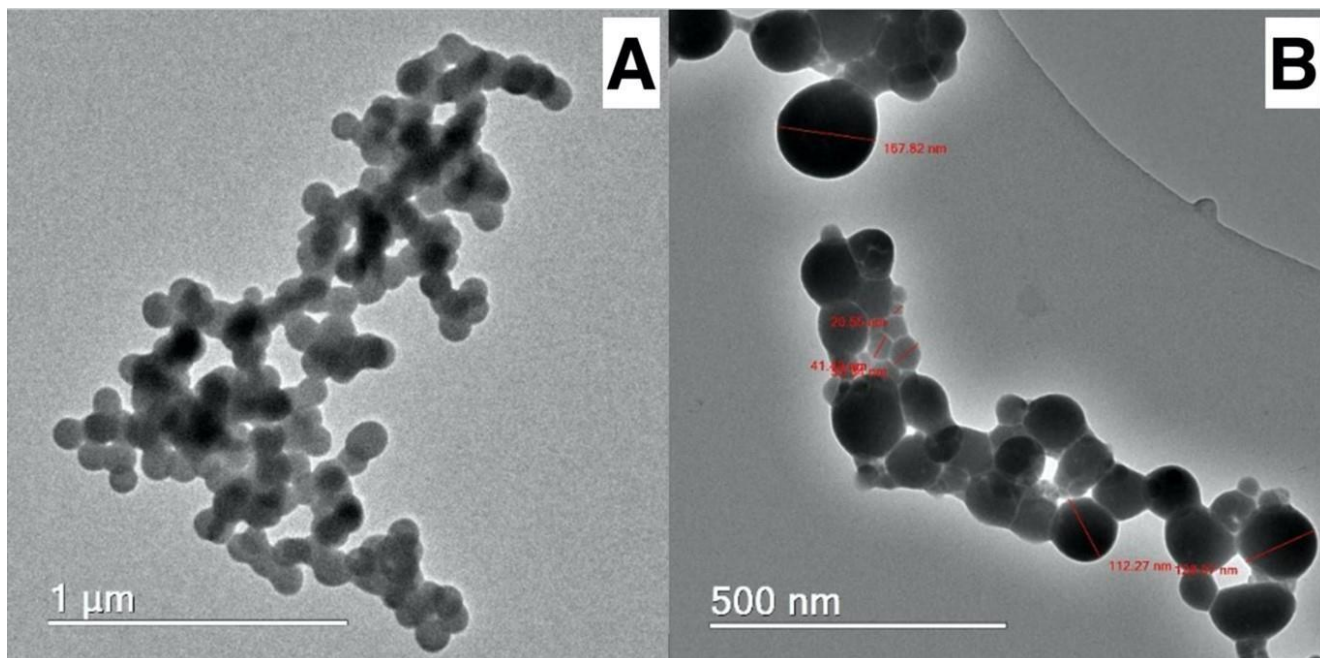


Source: the author, 2025.

3.2.6 Morphological characterization

The morphological characterization utilizing SEM and TEM revealed primarily rounded nanostructures forming intricate overlapping patterns. These structures still maintain a ball-like shape and vaguely resemble a diagram of a molecular chemical structure. In Figure 3, we present one sample from SEM (A) and one from TEM (B), as all the observed morphologies were similar.

Figure 4: Microscopic images of SeNPs produced by radiolytic synthesis obtained by scanning electron microscope A (SEM) and transmission electron microscope B (TEM). Scale: 1 μm (left) and 500 nm (right). A representative sample of morphologies obtained in SEM and TEM (specifically SEM of sample 25 kGy 1mM and TEM of 50 kGy 1mM).



Source: the author, 2025.

This work demonstrated that using gamma radiation to synthesize non-metallic NPs is viable and supports wet synthesis across most chemical elements in NP production. However, an important consideration regarding the radiolytic method is that the experimentation should be conducted within a few months, as the dose rate's effects become prominent due to the radioactive decay of the ^{60}Co source [38].

4. CONCLUSIONS

This study suggests that radiolytic synthesis is a promising and environmentally friendly approach for the production of selenium nanoparticles (SeNPs). By avoiding the use of organic solvents and allowing control of gamma irradiation parameters, it is possible to obtain SeNPs with high selenium content, ranging from 60.72% to 91.54%. The EDS results further indicate that selenium incorporation efficiency varies with synthesis parameters,

suggesting that irradiation dose and ethanol presence directly influence nanoparticle yield and composition. Furthermore, the semi-quantitative estimation of selenium incorporation based on EDS data and precursor concentration provides additional insight into nanoparticle formation efficiency, strengthening the interpretation of the radiolytic synthesis process.

The results indicate that the hydrodynamic size of the SeNPs is influenced by the presence of ethanol and precursor concentration, with larger sizes observed in samples containing 15% ethanol and higher Na_2SeO_3 concentrations (1 and 2 mM). The presence of ethanol likely contributes to the formation of intermediate radical species, which may promote nanoparticle growth. Additionally, increasing the radiation dose from 25 to 75 kGy was associated with particle growth, while a reduction in size at 100 kGy suggests a possible fragmentation effect.

A wide variation in zeta potential values was observed, indicating heterogeneity in surface charge and a tendency toward aggregation, which is supported by the elevated PDI values. Morphological analysis by SEM and TEM revealed predominantly spherical nanostructures, suggesting structural consistency among the synthesized materials.

Overall, these findings support the importance of controlling experimental parameters such as irradiation dose, precursor concentration, and the presence of scavengers, in order to tailor the physicochemical properties of SeNPs. The physicochemical characteristics observed in this study suggest that the synthesized SeNPs may be suitable for various applications, particularly in the biomedical field. Particle size, surface charge, and composition are key parameters influencing cellular uptake, biodistribution, and biological activity. The predominantly negative zeta potential and spherical morphology observed here may favor interactions with biological systems, while the high selenium content supports potential applications in antioxidant, antimicrobial, and anticancer strategies. In addition to biomedical uses, the controlled synthesis enabled by gamma irradiation also highlights potential applications in catalysis, environmental remediation, and the development of functional nanomaterials [39, 40, 41].

Finally, it is important to consider that experiments involving radiation dose and dose rate should be conducted within controlled timeframes, as variations due to radioactive decay of the ^{60}Co source may influence the reproducibility of the results.

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CONTRIBUTORSHIP

Conceptualization: GHDF, MJN

Investigation: GHDF, TFS, LMCM, AGP, LGLG

Writing – review and editing: GHDS, TFS, LMCM, AGP, LGLG, MJN

CONFLICT OF INTEREST

We have no conflicts of interest to disclose.

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The authors declare that the data supporting the results of this study are available within the article. Derived data supporting the findings of this study that are not found in the article may be requested from the corresponding author.

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