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The Role of Selenium in Human Health: Biochemical Functions, Antioxidant Mechanisms, and Clinical Perspectives

Selenyumun İnsan Sağlığındaki Rolü: Biyokimyasal Fonksiyonlar, Antioksidan Mekanizmalar ve Klinik Perspektifler

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ABSTRACT

Selenium (Se) is an essential trace element with a pivotal role in human health. Through its incorporation into selenoproteins, Se contributes to antioxidant defense, thyroid hormone metabolism, immune regulation, and maintenance of redox balance. Both deficiency and excess intake are linked to significant clinical outcomes. Deficiency has been associated with cardiovascular, endocrine, neurological, and immune dysfunctions, while excessive intake can lead to selenosis and toxicity. This review summarizes the digestion, absorption, and metabolism of Se; its biochemical significance through selenoproteins; its metabolic functions and associations with various diseases; analytical methods used for its measurement; and the emerging biomedical applications of selenium nanoparticles. Comparative insights with other trace elements are also provided. Evidence from epidemiological and clinical studies highlights the importance of maintaining Se levels within physiological ranges. Furthermore, national studies from Turkey indicate that the consequences of Se deficiency and excess on public health require further detailed investigation. Future research perspectives include randomized controlled trials, bioinformatics-based exploration of selenoprotein networks, and the clinical evaluation of Se nanoparticles as therapeutic agents. Public health approaches, including targeted supplementation and fortification programs, remain essential in Se-deficient regions.

Keywords: Selenium; antioxidants; selenoproteins; oxidative stress; nanoparticles

ÖZET

Selenyum (Se), insan sağlığı açısından kritik öneme sahip temel bir eser elementtir. Selenoproteinlere katılımı yoluyla antioksidan savunmaya, tiroid hormon metabolizmasına, immün sistemin düzenlenmesine ve redoks dengesinin korunmasına katkı sağlar. Hem yetersizliği hem de fazlalığı önemli klinik sonuçlarla ilişkilidir. Eksiklik kardiyovasküler, endokrin, nörolojik ve immün işlev bozuklukları ile ilişkiliyken; aşırı alım selenozis ve toksisiteye yol açabilmektedir. Bu derleme, Se'nin sindirimi, emilimi ve metabolizmasını; selenoproteinler aracılığıyla biyokimyasal önemini; metabolik fonksiyonlarını ve hastalıklarla ilişkisini; ölçüm yöntemlerini ve selenyum nanopartiküllerinin biyomedikal uygulamalarını özetlemektedir. Ayrıca diğer eser elementlerle karşılaştırmalı bilgiler de sunulmaktadır. Epidemiyolojik ve klinik veriler, Se düzeylerinin fizyolojik sınırlar içinde tutulmasının önemini vurgulamaktadır. Türkiye'de yapılan ulusal çalışmalar ise Se yetersizliği ve fazlalığının toplum sağlığı üzerindeki etkilerinin daha ayrıntılı şekilde incelenmesi gerektiğini göstermektedir. Gelecek araştırmalar arasında randomize kontrollü çalışmalar, selenoprotein ağlarının biyoinformatik tabanlı incelenmesi ve Se nanopartiküllerinin terapötik potansiyelinin klinik olarak değerlendirilmesi yer almaktadır. Halk sağlığı yaklaşımları kapsamında, hedeflenmiş takviye ve gıda fortifikasyonu, Se eksikliği yaygın bölgelerde önemini korumaktadır.

Anahtar kelimeler: Selenyum; antioksidanlar; selenoproteinler; oksidatif stres; nanopartiküller

Introduction

Selenium (Se) is a trace element belonging to Group VI-A of the periodic table. Although present in the human body in very small amounts, it is indispensable for various biological functions. First discovered in the 19th century, Se was long recognized primarily for its toxic properties; however, by the mid-20th century it was established as an essential dietary element[1,2]. Today, the role of Se in human health extends far beyond

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that of a simple micronutrient and is closely associated with critical biochemical processes such as the maintenance of cellular redox balance, regulation of oxidative stress, thyroid hormone metabolism, and modulation of the immune system[3,4]. In Turkey, comprehensive biochemical reviews addressing the role of Se in human health have been published since early periods[5].

Globally, Se levels exhibit considerable geographical variability. Soil composition and dietary habits directly influence individual intake. Deficiency is associated with endemic disorders such as Keshan disease and Kashin–Beck disease, while excessive intake may result in selenosis, a toxic condition. Therefore, maintaining Se concentrations within physiological limits is essential for both clinical practice and public health[3,6]. According to the World Health Organization (WHO) and the Food and Agriculture Organization (FAO), the recommended dietary allowance for adults is 55 μg/day, increasing to 60–70 μg/day during pregnancy and lactation[7,8]. Studies conducted in Turkey have shown that Se levels in soil and food sources vary regionally, directly influencing individual intake[9,10].

The majority of Se's biological effects are mediated through selenoproteins, which incorporate the amino acid selenocysteine. These proteins, including glutathione peroxidases and thioredoxin reductases, play a central role in antioxidant defense systems. They also contribute to thyroid hormone metabolism, DNA synthesis, apoptosis, and immune regulation[11,12].

Recent research has drawn attention to the association between Se levels and chronic conditions such as cardiovascular disease, cancer, diabetes, and neurodegenerative disorders. However, the literature remains inconsistent; variability in geographic factors, genetic polymorphisms, Se form (organic, inorganic, or nanoparticle), and dosing regimens contribute to heterogeneity in the findings. These discrepancies also highlight methodological limitations, including small sample sizes and a lack of randomized controlled trials.

This review will provide an overview of Se digestion, absorption, and metabolism; its biochemical significance and metabolic functions; analytical approaches for its measurement; and its associations with human health and disease. Comparative evaluations with other trace elements and recent biomedical applications will also be addressed. Furthermore, the clinical potential of Se and directions for future research will be discussed.

Digestion, Absorption, and Metabolism of Selenium

Selenium (Se) is an essential micronutrient that can only be obtained through dietary intake. The chemical form of Se in the diet is the major determinant of its bioavailability and metabolic effects in the human body[13]. In human nutrition, Se exists in two principal forms:

Organic forms: selenomethionine (SeMet) and selenocysteine (SeCys), which are typically found in plant- and animal-based foods.

Inorganic forms: selenate (SeO_4^{2-}) and selenite (SeO_3^{2-}), usually present in food additives and drinking water.

Absorption: Se absorption predominantly occurs in the small intestine.

- SeMet is actively transported via methionine transporters and can be directly incorporated into body proteins in place of methionine.
- SeCys is absorbed through specific transport systems in intestinal epithelial cells and directly utilized in selenoprotein biosynthesis.
- Selenate is absorbed mainly via active transport mechanisms.
- Selenite absorption occurs primarily by passive diffusion.

The absorption efficiency depends on the chemical form and ranges between 50% and 95%, with organic forms generally exhibiting higher bioavailability[14].

Distribution and Transport: Once absorbed, Se is primarily transported in the circulation by selenoprotein P (SePP). SePP, synthesized in the liver, delivers Se to target organs such as the brain, testes, and kidneys. Approximately half of the total Se in plasma is bound to SePP[15].

Metabolism and Excretion: The liver is the central organ of Se metabolism. Inorganic forms such as selenite and selenate are reduced to selenide, which is subsequently incorporated into SeCys for selenoprotein synthesis[16]. Excess Se is detoxified via methylation pathways into volatile compounds such as dimethyl selenide and trimethylselenonium, which are excreted through urine and breath. This mechanism plays a pivotal role in maintaining Se homeostasis and preventing toxicity[17].

Factors Affecting Bioavailability: Se bioavailability is influenced not only by its chemical form but also by dietary protein intake, the presence of other minerals (notably sulfur, arsenic, zinc, and iron), soil composition, genetic polymorphisms, and inter-individual metabolic variability[13,18]. Figure 1 illustrates the principal pathways of Se digestion, absorption, transport, and metabolism.

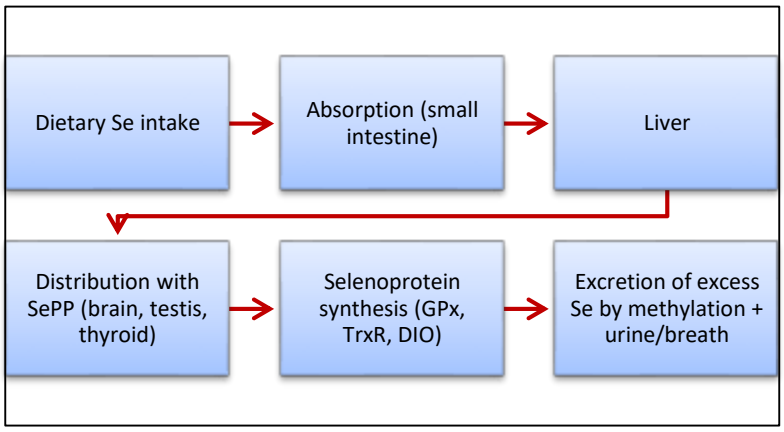

Figure 1. Pathways of selenium digestion, absorption, and metabolism
Illustration of the absorption routes of organic and inorganic selenium forms, their transport via selenoprotein P, and excretion pathways. Abbreviations: DIO, Deiodinase enzymes; GPx, Glutathione peroxidase; ROS, Reactive oxygen species; SePP, Selenoprotein P; TrxR, Thioredoxin reductase. Source: Authors, created based on literature.

Biochemical Importance of Selenium

The majority of the biological effects of selenium (Se) are mediated by selenoproteins, which contain selenocysteine, recognized as the 21st amino acid. To date, approximately 25 distinct selenoproteins have been identified in humans, each with unique biological functions (see Table 2). These proteins are involved in critical processes such as antioxidant defense, redox homeostasis, thyroid hormone metabolism, immune regulation, and energy metabolism. The diversity of selenoproteins underscores the multifaceted roles of Se in human biology.

Glutathione Peroxidases (GPx)

One of the most important contributions of Se is its role in antioxidant defense. Glutathione peroxidases (GPxs) are the key enzymes in this system. GPxs catalyze the reduction of hydrogen peroxide (H_2O_2) and lipid hydroperoxides, thereby protecting cellular membranes, DNA, and other biomolecules from oxidative damage. Four major GPx isoforms have been identified in humans: cytosolic GPx (GPx1), plasma GPx (GPx3), gastrointestinal GPx (GPx2), and phospholipid hydroperoxide GPx (GPx4). By utilizing glutathione (GSH) as a substrate, GPxs convert harmful reactive oxygen species (ROS) into water and alcohols, thereby maintaining cellular redox balance[19-21].

Thioredoxin Reductases (TrxR)

Thioredoxin reductases (TrxRs) represent another crucial group of selenoproteins. Using NADPH as an electron donor, TrxRs maintain thioredoxin in its reduced state, a process essential for DNA synthesis, ribonucleotide reductase activity, transcription factor regulation, cell proliferation, and apoptosis. The Trx/TrxR system also cooperates with other antioxidants such as vitamin C and glutathione, providing an integrated network that safeguards intracellular redox homeostasis. Consequently, TrxRs are indispensable for cell growth, survival, and defense against oxidative stress[22-24].

Selenoprotein P (SePP)

Selenoprotein P (SePP) functions both as the primary carrier of Se in plasma and as an important antioxidant component. Approximately half of the Se present in plasma is bound to SePP. Synthesized in the liver, SePP transports Se to target organs such as the brain, kidneys, and testes. Its multiple selenocysteine residues confer redox-active properties, enabling SePP to regulate Se homeostasis while simultaneously contributing to antioxidant defense[4,25].

Iodothyronine Deiodinases

The thyroid gland is highly dependent on Se for its normal function. Iodothyronine deiodinases (DIO1, DIO2, and DIO3), which regulate the activation and inactivation of thyroid hormones, are Se-dependent enzymes. They catalyze the conversion of thyroxine (T4) to the biologically active triiodothyronine (T3), as well as the degradation of T4 and T3 into inactive metabolites such as reverse T3 (rT3). By controlling both activation and inactivation, these deiodinases ensure thyroid hormone homeostasis and energy metabolism[26-28].

Immune Regulation

Se is also essential for immune homeostasis. Adequate Se levels strengthen host defenses against infections while preventing excessive inflammation. It enhances the phagocytic activity of neutrophils, promotes natural killer (NK) cell function, and regulates T lymphocyte proliferation and differentiation. Moreover, Se modulates cytokine production, influencing both antiviral and antibacterial responses[29-31]. Many of these effects are mediated through selenoproteins such as GPx and TrxR, which reduce oxidative stress within immune cells and thereby prevent uncontrolled inflammatory responses[32]. A review conducted in Turkey has also highlighted the regulatory role of Se in immune functions and infection processes[33].

In addition, Se closely interacts with other trace elements such as zinc, copper, and iron, all of which contribute to redox balance and antioxidant defense (see Table 1). For example, Cu/Zn-superoxide dismutase (Cu/Zn-SOD) and GPx act sequentially to neutralize ROS. However, imbalances among these elements may impair their synergistic effects: excess copper may increase radical production, zinc deficiency can weaken Cu/Zn-SOD activity and indirectly impair Se-dependent enzymes, and high iron levels may enhance oxidative stress, counteracting Se's protective role[34-36]. Therefore, the biological efficacy of Se depends not only on its own metabolism but also on its complex interplay with other trace elements.

Table 1. Biochemical comparison of selenium with other trace elements

Element	Main biochemical role	Function in antioxidant defense	Deficiency consequences	Excess/Toxicity
Se	Selenoprotein synthesis, redox balance, thyroid dejodinase activity	GPx, TrxR, ROS elimination via SePP	Keshan disease, thyroid disorders, immune weakness	Selenosis: nail breakage, hair loss, neurological disorder
Zn	Cofactor of >300 enzymes, gene expression, immune function	Critical in Cu/Zn-SOD activity	Growth retardation, skin lesions, immunosuppression	Decreased absorption of copper, gastrointestinal complaints
Cu	Electron transfer, iron metabolism, connective tissue synthesis	ROS control via Cu/Zn-SOD, ceruloplasmin	Anaemia, neurological disorders, connective tissue weakness	Increased ROS production, oxidative stress, Wilson's disease
Fe	Haemoglobin, cytochromes, energy metabolism	Cofactor in catalase and peroxidases	Iron deficiency anaemia, fatigue, cognitive impairment	Haemochromatosis, free radical production, tissue damage

Abbreviations: GPx, Glutathione peroxidase; ROS, Reactive oxygen species; SePP, Selenoprotein P; SOD, Superoxide dismutase; TxR, Thioredoxin reductase; Se, Selenium; Zn, Zinc; Cu, Copper; Fe, Iron. Source: Authors, adapted from relevant literature.

Metabolic Functions of Selenium and Its Association with Diseases

Selenium (Se) participates directly or indirectly in numerous biochemical processes, ensuring the proper functioning of the organism. Its metabolic roles encompass energy production, modulation of immune responses, cardiovascular protection, neurological integrity, and regulation of thyroid hormone metabolism. Maintaining adequate Se levels is therefore essential both for health preservation and disease prevention.

Most of these mechanisms are mediated through the specific functions of individual selenoproteins[3,37,38]. (see Table 2).

Table 2. Major selenoproteins identified in humans and their biological functions.

Selenoprotein	Primary Function	Tissue/Organ Distribution	Associated Process
GPx1	Detoxification of H_2O_2 and lipid hydroperoxides	Widely distributed (erythrocytes, liver, kidney)	Antioxidant defense
GPx2	Control of ROS in intestinal epithelium	Gastrointestinal tract	Maintenance of mucosal barrier
GPx3	Elimination of extracellular ROS	Plasma, kidney	Systemic antioxidant defense
GPx4	Reduction of lipid hydroperoxides, regulation of ferroptosis	Testis, brain, heart	Membrane stability
GPx6	Possible antioxidant role	Nasal epithelium	Redox defense
TrxR1 (TXNRD1)	Thioredoxin reduction, DNA synthesis	Cytoplasm	Redox homeostasis
TrxR2 (TXNRD2)	Mitochondrial redox balance	Mitochondria	Energy metabolism
TrxR3 (TGR/TXNRD3)	Disulfide isomerase activity	Testis	Spermatogenesis
SePP (SELENOP)	Selenium transport, antioxidant activity	Plasma, liver	Se distribution
DIO1	Conversion of T4 → T3	Liver, kidney	Thyroid hormone activation
DIO2	Local T3 production	Brain, skeletal muscle	Energy metabolism
DIO3	Inactivation of T4 and T3	Fetal tissue, brain	Developmental regulation
Sep15 (SELENOF)	Protein folding	Endoplasmic reticulum	Protein quality control
SELS (VIMP)	ER stress response	Endoplasmic reticulum	Inflammation regulation
SELK	Calcium signaling, inflammation	ER membrane	Immune response
SELM	Redox regulation	Brain	Neuronal function
SELT	Antioxidant function	Widespread	Redox balance
SELH	Transcriptional regulation	Nucleus	Gene expression
SELW	Redox signaling	Muscle, brain	Cellular stress response
MSRB1 (SelR)	Methionine sulfoxide reduction	Cytoplasm	Protein repair
SELN (SEPN1)	Muscle function, linked to muscular dystrophy	Muscle	Muscle integrity
SELV	Function not fully defined	Testis	Reproductive health
SELON (Selenoprotein O)	Mitochondrial protein modification	Widespread	Energy metabolism
SELQ (Selenoprotein Q)	Mitochondrial function, muscle development	Heart, muscle	Muscle contraction
SELMA / SELMB	Functions not fully characterized, redox-related	Various tissues	Under investigation

Abbreviations: DIO, Deiodinase; GPx, Glutathione peroxidase; SePP, Selenoprotein P; TrxR, Thioredoxin reductase.
Source: Authors, adapted from relevant literature.

Energy Metabolism

Se plays a critical role in sustaining cellular energy metabolism. It protects pancreatic β-cells from oxidative stress and modulates insulin signaling pathways. Deficiency impairs insulin secretion, whereas excessive Se intake may increase insulin resistance. Several studies have revealed a bidirectional, dose-dependent relationship between Se levels and type 2 diabetes risk[39-40]. Se-dependent enzymes, including glutathione peroxidases (GPxs) and thioredoxin reductases (TrxRs), detoxify mitochondrial reactive oxygen species (ROS), thereby preserving mitochondrial membrane integrity and supporting the functionality of ATP-generating enzyme complexes. Deficiency has been associated with elevated oxidative stress, mitochondrial dysfunction, and increased apoptosis[41,42]. A study from Turkey has also reported a potential association between Se levels and diabetes mellitus[43].

Immune Response

Se is a key regulator of both innate and adaptive immunity. The mechanisms underlying these immunomodulatory effects are described in the Biochemical Importance section above. Low Se levels have

been associated with disease progression and higher mortality in infections such as HIV, Coxsackievirus, and SARS-CoV-2[44-46].

Cardiovascular Function

The cardioprotective effects of Se are mainly attributed to its antioxidant and anti-inflammatory properties. Deficiency is directly linked to Keshan disease, an endemic cardiomyopathy in certain regions of China. Se limits lipid peroxidation and low-density lipoprotein (LDL) oxidation, thereby reducing atherosclerosis risk. Adequate levels may preserve myocardial function and decrease ischemic injury. Nevertheless, the role of Se supplementation in preventing cardiovascular disease remains controversial, and further randomized controlled trials are needed[3,47,48].

Neurological Processes

The brain is highly susceptible to oxidative damage due to its elevated oxygen consumption and lipid content. Se, primarily through selenoprotein P, is delivered to the central nervous system and contributes to neuronal antioxidant defense. Low Se status has been linked to cognitive decline in neurodegenerative diseases such as Alzheimer's and Parkinson's. Adequate Se intake is thus considered important for maintaining neuronal integrity and neuroprotection[42,49-51].

Thyroid Function

Se is indispensable for thyroid hormone metabolism. Deiodinases (DIO1, DIO2, DIO3) are Se-dependent enzymes that regulate the conversion of thyroxine (T4) into the biologically active triiodothyronine (T3). In Se deficiency, T4-to-T3 conversion is impaired, potentially leading to hypothyroidism-like symptoms. In Hashimoto's thyroiditis, Se supplementation has been reported to reduce autoantibody levels, although its efficacy depends on the dose, form of Se, and baseline patient status[52-54]. Pharmaceutical and biochemical reviews conducted in Turkey have emphasized the role of Se in thyroid functions and Hashimoto's thyroiditis[55].

Selenium Status and Public Health Implications in Türkiye

Türkiye presents a heterogeneous selenium landscape that warrants dedicated attention. Soil selenium concentrations vary considerably across regions, with notably lower levels reported in parts of Central and Eastern Anatolia compared with coastal areas, directly influencing the selenium content of locally grown crops and the dietary intake of the population[9,10]. A twenty-year review of selenium levels in Turkish foods documented this regional variability and underscored the need for systematic monitoring of dietary selenium adequacy at the national level[9]. Early biochemical reviews from Türkiye drew attention to selenium's essential functions in human health, establishing a domestic research tradition that has continued to grow[5]. More recent national studies have reported a potential association between selenium status and diabetes mellitus, consistent with the bidirectional dose-response relationship described in the international literature[43]. In the field of immunology, a review from Türkiye highlighted selenium's regulatory role in immune responses and its relevance to infection outcomes[33]. Similarly, national pharmaceutical and biochemical research has examined the relationship between selenium, selenoproteins, and Hashimoto's thyroiditis, reflecting the particular public health relevance of thyroid autoimmunity in the region[55,56]. Taken together, these findings suggest that selenium deficiency may represent an underappreciated public health concern in Türkiye. Future epidemiological studies, including population-representative surveys of serum selenium levels and selenoprotein P concentrations, regional soil and food selenium mapping, and targeted intervention trials, are needed to translate this evidence into evidence-based dietary and public health policy.

Cancer

The potential anticancer effects of Se involve reducing DNA damage, promoting apoptosis, and inhibiting tumor cell proliferation. Protective effects have been observed in prostate, colon, lung, and breast cancers.

However, epidemiological and clinical evidence remains inconsistent: while low Se status is linked to higher cancer risk, high-dose supplementation does not consistently provide additional benefit and may even increase toxicity risk[57-59].

Meta-analyses indicate that Se may offer cardiovascular protection, though this effect diminishes at high doses3,60. Similarly, U-shaped associations between Se intake and the risk of cancer or diabetes have been frequently reported[57-59]. These findings emphasize that both deficiency and excess of Se can be detrimental, highlighting the importance of maintaining Se concentrations within physiological ranges. Interpreting the available evidence critically, however, requires attention to several methodological limitations. A substantial proportion of epidemiological studies on Se and chronic disease risk are cross-sectional or prospective cohort designs that measure baseline selenium status without accounting for subsequent changes in diet, supplementation, or disease-related alterations in selenium metabolism. Residual confounding by smoking, body mass index, dietary pattern, and socioeconomic status is difficult to eliminate fully[61]. Randomized controlled trials (RCTs) provide stronger causal evidence, but many Se supplementation trials have enrolled populations with already-adequate baseline selenium levels, in whom additional supplementation would not be expected to confer benefit and may shift participants into the supraphysiological range associated with harm[61]. Genetic variability adds a further layer of complexity: single nucleotide polymorphisms in genes encoding selenoproteins (e.g., GPx1, SELENOP, TXNRD1) influence both the efficiency of selenium utilisation and individual susceptibility to deficiency or toxicity. These polymorphisms are rarely accounted for in observational studies, contributing to between-study heterogeneity[62,63]. Finally, differences in the chemical form of selenium used (selenomethionine, selenite, selenate, or enriched yeast), dose, duration of intervention, and the biomarker chosen to assess selenium status (serum selenium vs. selenoprotein P vs. erythrocyte glutathione peroxidase activity) make cross-study comparisons inherently difficult[64,65]. Taken together, these considerations underscore the need to interpret reported associations as hypothesis-generating rather than definitive, and highlight the value of well-designed, adequately powered RCTs that stratify participants by baseline selenium status and genotype.

Analytical Approaches and Measurement Methods

Serum, Hair, and Urine Biomarkers

Reliable methods for selenium (Se) determination are critical to understanding its biological functions. In humans, Se status is commonly assessed in biological specimens such as serum/plasma, whole blood, urine, hair, and nails. Serum or plasma Se concentrations are the most widely used biomarkers, reflecting short-term intake and current nutritional status. However, they provide limited information about long-term stores. In contrast, hair and nail analyses reflect tissue accumulation and are therefore considered more reliable indicators of long-term exposure, particularly in studies of environmental exposure or chronic conditions. Urinary Se levels, on the other hand, directly reflect excretion and are useful in evaluating toxicity and excessive intake.

Analytical Techniques

Analytical methods used for Se determination vary in sensitivity, selectivity, cost, and applicability (see Table 3). Among these, inductively coupled plasma–mass spectrometry (ICP-MS) is regarded as the most accurate and widely applied method in clinical research, owing to its low detection limits and high sensitivity. However, ICP-MS is limited by high operational costs, potential contamination during sample preparation, and matrix effects that may compromise measurement accuracy. Consequently, the validity of ICP-MS results depends heavily on stringent sampling and preparation protocols[66].

The choice of analytical method is also determined by the parameter of interest (e.g., total Se concentration, selenoprotein levels, or specific Se species). For instance, HPLC–ICP-MS is considered the gold standard in speciation analysis, as it enables the separation and quantification of distinct Se species (selenite, selenate, SeMet, SeCys), providing valuable insights into bioavailability, metabolism, and toxicity[67]. Graphite furnace atomic absorption spectrometry (GF-AAS) offers high sensitivity with small sample volumes, though its limited multi-element capability makes it more suitable for non-clinical or screening purposes[68-70]. ICP–optical emission spectrometry (ICP-OES) is a cost-effective and rapid alternative, though it has higher

detection limits and potential spectral interferences compared to ICP-MS[71]. X-ray fluorescence (XRF) allows non-destructive measurement of keratinized tissues such as hair and nails, making it a promising approach for long-term exposure assessment[72]. In contrast, colorimetric and fluorometric assays are inexpensive and rapid but lack the sensitivity and specificity required for advanced clinical or research applications[73].

Table 3. Comparison of Analytical Methods for Selenium Determination

Method	Principle of Measurement	Analyte/Parameter	LOD	Advantages	Disadvantages
FAAS	Absorption of light by atomized Se in a flame	Total Se	~10–50 μg/L	Low cost, widely available	Low sensitivity, prone to matrix interferences
GF-AAS	Atomization in a graphite furnace followed by absorption measurement	Total Se (serum, plasma)	~0.1–1 μg/L	High sensitivity, small sample volume	Time-consuming, limited multi-element capacity
ICP-OES	Atomic emission spectrometry in plasma	Total Se	~1–5 μg/L	Multi-element analysis, rapid throughput	Higher LOD compared to ICP-MS, spectral interferences
ICP-MS	Ionization in plasma followed by mass spectrometric detection	Total Se, isotopic analysis	~0.01–0.1 μg/L	Very high sensitivity, multi-element capability, ultra-low LOD	High cost, requires expertise, contamination risk
HPLC–ICP-MS	Chromatographic separation combined with ICP-MS for element-specific detection	Se speciation (selenite, selenate, SeMet, SeCys)	~0.01–0.05 μg/L	Species separation, bioavailability and metabolism studies	Complex preparation, expensive instrumentation
Fluorometric/Colorimetric	Formation of fluorescent or colored complexes with chemical reagents	Total Se	~10–100 μg/L	Simple, inexpensive, rapid	Low specificity and sensitivity, limited quantitative accuracy
XRF	X-ray excitation and measurement of Se-specific fluorescence	Se in hair and nails	~0.5–5 μg/g	Minimal sample preparation, non-destructive	Limited clinical application, lower sensitivity

Abbreviations: AAS, Atomic absorption spectrometry; FAAS, Flame atomic absorption spectrometry; GF-AAS, Graphite furnace atomic absorption spectrometry; HPLC, High performance liquid chromatography; ICP-MS, Inductively coupled plasma mass spectrometry; ICP-OES, Inductively coupled plasma optical emission spectrometry; LOD, Limit of detection; MS, Mass spectrometry; XRF, X-ray fluorescence. Source: Authors, adapted from relevant literature.

Furthermore, Se shares biochemical similarities with sulfur, leading to its substitution in sulfur-containing biomolecules. This phenomenon, termed selenium–sulfur antagonism, may alter the three-dimensional structure and function of proteins, with both beneficial and potentially toxic consequences[74,75]. Therefore, precise quantification of Se in biological samples requires highly sensitive and specific techniques, particularly ICP-MS and HPLC–ICP-MS, which remain indispensable in clinical and toxicological investigations[76].

Beyond the accurate measurement of selenium status in biological specimens, a parallel line of investigation has emerged from the field of nanotechnology. The same physicochemical properties of selenium that make its precise quantification analytically challenging its multiple oxidation states, the reactivity of its reduced forms, and its tendency to interact with sulfur-containing biomolecules have inspired researchers to engineer selenium at the nanoscale in order to modulate its bioavailability, reduce toxicity, and expand its therapeutic applications. The following section reviews the current evidence on selenium nanoparticles (SeNPs) as emerging biomedical agents.

Selenium Nanoparticles in Nanotechnology and Emerging Approaches

Advances in nanotechnology have prompted a re-evaluation of the pharmacological and therapeutic potential of trace elements. Selenium nanoparticles (SeNPs) have attracted increasing attention because they exhibit lower toxicity, higher biocompatibility, and a greater surface-to-volume ratio compared with conventional inorganic and organic selenium compounds (see Figure 2). Furthermore, their ability to act as targeted drug delivery systems highlights their promise for future clinical applications.

Antioxidant and Anti-Inflammatory Effects

SeNPs have been reported to be more effective than classical Se forms in reducing oxidative stress and suppressing inflammation. These effects are mainly attributed to modulation of signaling pathways such as NF-κB and inhibition of pro-inflammatory cytokine production[48,77].

Anticancer Potential

Preclinical studies have demonstrated that SeNPs can induce apoptosis, arrest the cell cycle, and exert selective cytotoxicity in tumor cells. In models of breast, lung, colon, and liver cancers, SeNPs have shown synergistic effects when combined with chemotherapeutic agents[78-81].

Antimicrobial and Antiviral Properties

SeNPs have been shown to disrupt bacterial biofilms and exhibit antiviral activity against RNA viruses[82,83].

Applications in Drug Delivery Systems

Through surface functionalization, SeNPs can be engineered to enable targeted and controlled release of anticancer drugs. This approach enhances therapeutic efficacy while minimizing systemic toxicity[84,85].

Clinical Research and Future Perspectives

Most current studies on SeNPs remain at the level of cell culture and animal models. It is important to contextualise the existing SeNP literature carefully. The large majority of studies reporting antioxidant, anticancer, and antimicrobial effects of SeNPs have been conducted in vitro or in rodent models, and extrapolation to human physiology requires caution. Dose-response relationships observed in cell lines or small animals may not translate directly to safe and effective human dosing, particularly given that selenium has a narrow therapeutic window and that the physicochemical properties of nanoparticles (size, surface coating, charge, and agglomeration state) vary substantially between preparations and laboratories. Nanotoxicological data, although generally more favourable for SeNPs than for inorganic selenium salts, remain incomplete: long-term accumulation in organs, potential genotoxicity, and interactions with the immune system have not been fully characterised[86]. Regulatory pathways for nanomedicine products are complex and jurisdiction-specific, adding a further translational barrier. Standardised synthesis protocols, robust pharmacokinetic data, and Good Manufacturing Practice-compliant production methods are prerequisites for clinical development[86]. Although clinical trial data are limited, preliminary findings suggest favorable safety and efficacy profiles[87,88]. In the coming years, it is anticipated that SeNPs will not only be explored for cancer therapy but also for neuroprotective, immunomodulatory, and anti-inflammatory applications.

Overall, SeNPs offer distinct advantages over conventional Se forms, particularly in terms of antioxidant and anticancer properties. However, as current evidence is predominantly preclinical, comprehensive clinical trials are required to establish their long-term safety and therapeutic efficacy. Figure 2 illustrates the major cellular mechanisms of action of selenium nanoparticles, including ROS elimination, NF-κB suppression, induction of apoptosis, and inhibition of cell proliferation.

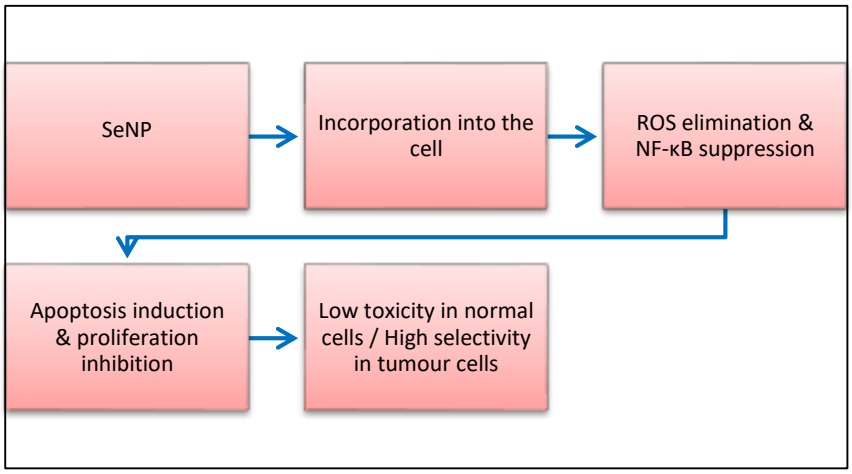

Figure 2. Mechanisms of selenium nanoparticles in cellular systems.

Diagram illustrating the major biological effects of selenium nanoparticles, including antioxidant activity, suppression of NF-κB signaling, induction of apoptosis, inhibition of cell proliferation, and applications in targeted drug delivery. Abbreviations: NF-κB, Nuclear factor kappa-light-chain-enhancer of activated B cells; SeNPs, Selenium nanoparticles; ROS, Reactive oxygen species. Source: Authors, created based on literature.

Conclusion and Future Perspectives

Selenium (Se) is an essential trace element with critical importance for human health. Through its incorporation into selenoproteins, Se plays a central role in antioxidant defense, thyroid hormone metabolism, immune regulation, and maintenance of redox homeostasis. Deficiency can lead to cardiovascular, endocrine, neurological, and immune disorders, whereas excessive intake may result in selenosis and toxicity. Maintaining Se levels within the physiological range is therefore indispensable for both preventive medicine and clinical practice. National studies in Turkey indicate that the effects of Se deficiency and excess on public health should be further investigated in greater detail[99,33,43].

Recent studies have highlighted the potential role of Se not only in its classical biochemical functions but also in the pathogenesis of chronic diseases such as cancer, diabetes, and neurodegenerative disorders. Nevertheless, the available findings are heterogeneous, largely due to methodological limitations, population differences, and variability in Se form and dosage. More randomized controlled trials are required to clarify its therapeutic effects and establish evidence-based guidelines.

Selenium nanoparticles (SeNPs) have emerged as promising candidates for future biomedical applications due to their high bioavailability, reduced toxicity, and potential for targeted delivery. Preclinical studies have reported strong antioxidant, anticancer, and neuroprotective effects. However, clinical evidence remains scarce, and long-term safety and efficacy must be systematically evaluated in well-designed trials.

From a clinical standpoint, Se supplementation should be reserved for individuals with confirmed deficiency. Routine supplementation in the general population carries a risk of toxicity without proven additional benefits. In regions with Se-deficient soils, community-based interventions such as Se fortification of flour or cereal products may provide a feasible strategy. Targeted supplementation in high-risk groups (e.g., pregnant women, elderly individuals, and patients with chronic illnesses) could also contribute to public health. Furthermore, national nutrition monitoring programs and mapping of soil Se concentrations would allow early detection of deficiency risks and inform evidence-based interventions. Collaboration between agricultural and food safety authorities is essential to ensure sustainable solutions at the population level.

Future research directions include:

- Comparative clinical evaluation of organic, inorganic, and nanoparticle forms of Se in terms of bioavailability and toxicity.
- Population-based cohort and Mendelian randomization studies to clarify causal associations between Se levels and chronic disease risks.
- Bioinformatics approaches to investigate Se-dependent protein networks in models of Alzheimer's and Parkinson's disease.
- Long-term preclinical and clinical studies on SeNPs to assess their safety, efficacy, and potential in oncology, neurology, and immunology.
- Phase II/III clinical trials testing the combined use of SeNPs with chemotherapy and other treatment modalities.

In conclusion, the expanding body of knowledge on the biochemical and clinical significance of Se continues to provide guidance for both public health strategies and the development of novel therapeutic approaches.

References

1. Flohe L, Andreesen JR, Brigelius-Flohe R, Maiorino M, Ursini F. Selenium, the element of the moon, in life on earth. IUBMB Life. 2000;49:411–20.
2. Beckett GJ, Arthur JR. Selenium and endocrine systems. J Endocrinol. 2005;184:455–65.
3. Rayman M. Selenium and human health. Lancet. 2012;379:1256–68.
4. Steinbrenner H, Sies H. Selenium homeostasis and antioxidant selenoproteins in brain: implications for disorders in the central nervous system. Arch Biochem Biophys. 2013;536:152–7.
5. Hincal F AN. The role of selenium in human health. FABAD J Pharm Sci. 1989;14:23–38.
6. Schrauzer GN. Selenomethionine: a review of its nutritional significance, metabolism and toxicity. J Nutr. 2000;130:1653–6.
7. Monsen ER. Dietary reference intakes for the antioxidant nutrients: Vitamin C, vitamin E, selenium, and carotenoids. American Dietetic Association Journal of the American Dietetic Association. 2000;100:637–40.
8. Efsa Panel on Nutrition NF, Food A, Turck D, Bohn T, Castenmiller J, de Henauw S, et al. Scientific opinion on the tolerable upper intake level for selenium. EFSA J. 2023;21:e07704.
9. Unusan N, Dağ A. KTO Karatay Üniversitesi Sağlık Bilimleri Dergisi. 2021;2:20–7.
10. Topal N, Topuz A. Selenyumun Bitki Metabolizması ve Tarımsal Kullanımı. Uşak Üniversitesi Fen ve Doğa Bilimleri Dergisi. 2021;5:87–99.
11. Gladyshev VN, Arner ES, Berry MJ, Brigelius-Flohe R, Bruford EA, Burk RF, et al. Selenoprotein Gene Nomenclature. J Biol Chem. 2016;291:24036–40.
12. Qi Z, Duan A, Ng K. Selenoproteins in Health. Molecules. 2024;29(1).
13. Fairweather-Tait SJ, Collings R, Hurst R. Selenium bioavailability: current knowledge and future research requirements. Am J Clin Nutr. 2010;91:1484S–91S.
14. Patterson BH, Combs GF, Jr., Taylor PR, Patterson KY, Moler JE, Wastney ME. Selenium Kinetics in Humans Change Following 2 Years of Supplementation With Selenomethionine. Front Endocrinol (Lausanne). 2021;12:621687.
15. Wastney ME, Combs GF, Jr., Canfield WK, Taylor PR, Patterson KY, Hill AD, et al. A human model of selenium that integrates metabolism from selenite and selenomethionine. J Nutr. 2011;141:708–17.
16. Burk RF, Hill KE. SELENOPROTEIN P: An Extracellular Protein with Unique Physical Characteristics and a Role in Selenium Homeostasis. Annual Review of Nutrition. 2005;25:215–35.
17. Combs GF, Jr. Biomarkers of selenium status. Nutrients. 2015;7:2209–36.
18. Kipp AP, Strohm D, Brigelius-Flohé R, Schomburg L, Bechthold A, Leschik-Bonnet E et al. Revised reference values for selenium intake. J Trace Elem Med Biol. 2015;32:195–9.
19. Brigelius-Flohé R, Maiorino M. Glutathione peroxidases. Biochim Biophys Acta. 2013;1830:3289–303.
20. Toppo S, Flohé L, Ursini F, Vanin S, Maiorino M. Catalytic mechanisms and specificities of glutathione peroxidases: variations of a basic scheme. Biochim Biophys Acta. 2009;1790:1486–500.
21. Lubos E, Loscalzo J, Handy DE. Glutathione peroxidase-1 in health and disease: from molecular mechanisms to therapeutic opportunities. Antioxid Redox Signal. 2011;15:1957–97.
22. Arnér ES. Focus on mammalian thioredoxin reductases--important selenoproteins with versatile functions. Biochim Biophys Acta. 2009;1790:495–526.
23. Lu J, Holmgren A. The thioredoxin antioxidant system. Free Radic Biol Med. 2014;66:75–87.
24. Handy DE, Loscalzo J. Redox regulation of mitochondrial function. Antioxid Redox Signal. 2012;16:1323–67.
25. Burk RF, Hill KE. Regulation of Selenium Metabolism and Transport. Annu Rev Nutr. 2015;35:109–34.
26. Köhrle J. Thyroid hormone deiodinases--a selenoenzyme family acting as gate keepers to thyroid hormone action. Acta Med Austriaca. 1996;23:17–30.
27. Zimmermann MB, Köhrle J. The impact of iron and selenium deficiencies on iodine and thyroid metabolism: biochemistry and relevance to public health. Thyroid. 2002;12:867–78.

28. Schomburg L, Köhrle J. On the importance of selenium and iodine metabolism for thyroid hormone biosynthesis and human health. Mol Nutr Food Res. 2008;52:1235–46.
29. Hoffmann PR, Berry MJ. The influence of selenium on immune responses. Mol Nutr Food Res. 2008;52:1273–80.
30. Avery JC, Hoffmann PR. Selenium, Selenoproteins, and Immunity. Nutrients. 2018;10:1203.
31. Steinbrenner H, Al-Quraishy S, Dkhil MA, Wunderlich F, Sies H. Dietary selenium in adjuvant therapy of viral and bacterial infections. Adv Nutr. 2015;6:73–82.
32. Zhang Y, Roh YJ, Han SJ, Park I, Lee HM, Ok YS et al. Role of Selenoproteins in Redox Regulation of Signaling and the Antioxidant System: A Review. Antioxidants (Basel). 2020;9:383.
33. Fisunoglu M. Selenium, Immune System and Infection Interactions. Turkiye Klinikleri J Nutr Diet-Special Topics. 2016;2:82–6.
34. Mistry HD, Broughton Pipkin F, Redman CW, Poston L. Selenium in reproductive health. Am J Obstet Gynecol. 2012;206:21–30.
35. Gao S, Jin Y, Hall KS, Liang C, Unverzagt FW, Ji R et al. Selenium level and cognitive function in rural elderly Chinese. Am J Epidemiol. 2007;165:955–65.
36. Tapiero H, Townsend DM, Tew KD. The antioxidant role of selenium and seleno-compounds. Biomed Pharmacother. 2003;57:134–44.
37. Kryukov GV, Castellano S, Novoselov SV, Lobanov AV, Zehtab O, Guigó R et al. Characterization of mammalian selenoproteomes. Science. 2003;300:1439–43.
38. Labunskyy VM, Hatfield DL, Gladyshev VN. Selenoproteins: molecular pathways and physiological roles. Physiol Rev. 2014;94:739–77.
39. Alfawaz W, Alharithy M, AL-Musharaf S, Aldhwayan M, Aljuraiban GS. Selenium intake and risk of type 2 diabetes among adults in Saudi Arabia. Front Endocrinol. 2025;16:1579223.
40. Rodriguez-Hernandez Z, Bel-Aguilar J, Moreno-Franco B, Grau-Perez M, Redon J, Gomez-Ariza JL et al. Differential association of selenium exposure with insulin resistance and β-cell function in middle age and older adults. Nutr Diabetes. 2025;15:5.
41. Arnér ES, Holmgren A. The thioredoxin system in cancer. Semin Cancer Biol. 2006;16:420–6.
42. Chen J, Berry MJ. Selenium and selenoproteins in the brain and brain diseases. J Neurochem. 2003;86:1–12.
43. Kangalgil M, Yardımcı H. Bozok Tıp Dergisi. 2017;7:66–71.
44. Ivory K, Prieto E, Spinks C, Armah CN, Goldson AJ, Dainty JR et al. Selenium supplementation has beneficial and detrimental effects on immunity to influenza vaccine in older adults. Clin Nutr. 2017;36:407–15.
45. Poudel-Tandukar K, Bertone-Johnson ER, Poudel KC. Serum Selenium and Inflammation in Individuals with Human Immunodeficiency Virus Infection. AIDS Research and Human Retroviruses. 2023;39:671–6.
46. Roldán-Bretón NR, Capuchino-Suárez AG, Mejía-León ME, Olvera-Sandoval C, Lima-Sánchez DN. Selenium serum levels in patients with SARS-CoV-2 infection: a systematic review and meta-analysis. J Nutr Sci. 2023;12:e86.
47. Alehagen U, Johansson P, Svensson E, Aaseth J, Alexander J. Improved cardiovascular health by supplementation with selenium and coenzyme Q10: applying structural equation modelling (SEM) to clinical outcomes and biomarkers to explore underlying mechanisms in a prospective randomized double-blind placebo-controlled intervention project in Sweden. Eur J Nutr. 2022;61:3135–48.
48. Zhu H, Wang X, Meng X, Kong Y, Li Y, Yang C, et al. Selenium Supplementation Improved Cardiac Functions by Suppressing DNMT2-Mediated GPX1 Promoter DNA Methylation in AGE-Induced Heart Failure. Oxid Med Cell Longev. 2022;2022:5402997.
49. Huang G, Liu Y, Zhu X, He L, Chen T. Exploring the Neuroprotective Role of Selenium: Implications and Perspectives for Central Nervous System Disorders. Exploration (Beijing). 2025;5:e20240415.
50. Chen Q, Hu X, Zhang T, Ruan Q, Wu H. Association between Parkinson disease and selenium levels in the body: A systematic review and meta-analysis. Medicine (Baltimore). 2024;103:e37919.
51. Vinceti M, Urbano T, Chiari A, Filippini T, Wise LA, Tondelli M et al. Selenoprotein P concentrations and risk of progression from mild cognitive impairment to dementia. Scientific Reports. 2023;13:8792.
52. Huwiler VV, Maissen-Abgottspon S, Stanga Z, Mühlebach S, Trepp R, Bally L et al. Selenium Supplementation in Patients with Hashimoto Thyroiditis: A Systematic Review and Meta-Analysis of Randomized Clinical Trials. Thyroid. 2024;34:295–313.
53. Peng B, Wang W, Gu Q, Wang P, Teng W, Shan Z. Effects of different supplements on Hashimoto's thyroiditis: a systematic review and network meta-analysis. Front Endocrinol. 2024;15:1445878.
54. Bano I, Hassan MF, Kieliszek M. A Comprehensive Review of Selenium as a Key Regulator in Thyroid Health. Biol Trace Elem Res. 2025.
55. Sur U, Erkekoglu P, Kocer-Gumusel B. Selenium, selenoproteins and Hashimoto's thyroiditis Selenyum, Selenoproteinler ve Hashimoto Tiroiditi. Fabad Journal of Pharmaceutical Sciences. 2020;45:45–64.
56. Erdal M, Sahin M, Hasimi A, Uckaya G, Kutlu M, Saglam K. Trace element levels in hashimoto thyroiditis patients with subclinical hypothyroidism. Biol Trace Elem Res. 2008;123:1–7.
57. Le NT, Pham YT, Le CT, Le LT, Le TD, Dao HV et al. A U-shaped association between selenium intake and cancer risk. Sci Rep. 2024;14:21378.
58. Brezina S, Chillon TS, Asaad S, Maieron A, Prosenz J, Seelig J, et al. Colorectal cancer mortality is associated with low selenoprotein P status at diagnosis. Redox Biology. 2025;84:103701.
59. He L, Zhang L, Peng Y, He Z. Selenium in cancer management: exploring the therapeutic potential. Front Oncol 2025;14:1490740.

60. Liang D, Liu C, Zhang X. Association between dietary selenium intake and the risk of cardiovascular disease in US adults: a population-based study. Scientific Reports. 2025;15:13427.
61. Vinceti M, Filippini T, Del Giovane C, Dennert G, Zwahlen M, Brinkman M, et al. Selenium for preventing cancer. Cochrane Database Syst Rev. 2018;1:CD005195.
62. Meplan C, Hesketh J. The influence of selenium and selenoprotein gene variants on colorectal cancer risk. Mutagenesis. 2012;27:177–86.
63. Schomburg L. Selenium, selenoproteins and the thyroid gland: interactions in health and disease. Nat Rev Endocrinol. 2011;8:160–71.
64. Hurst R, Armah CN, Dainty JR, Hart DJ, Teucher B, Goldson AJ et al. Establishing optimal selenium status: results of a randomized, double-blind, placebo-controlled trial. Am J Clin Nutr. 2010;91:923–31.
65. Thomson CD. Assessment of requirements for selenium and adequacy of selenium status: a review. Eur J Clin Nutr. 2004;58:391–402.
66. You Z, Winckelmann A, Vogl J, Recknagel S, Abad C. Determination of calcium, iron, and selenium in human serum by isotope dilution analysis using nitrogen microwave inductively coupled atmospheric pressure plasma mass spectrometry (MICAP-MS). Anal Bioanal Chem. 2024;416:3117–25.
67. del Castillo Busto ME, Ward-Deitrich C, Evans SO, Rayman MP, Jameson MB, Goenaga-Infante H. Selenium speciation studies in cancer patients to evaluate the responses of biomarkers of selenium status to different selenium compounds. Analytical and Bioanalytical Chemistry. 2024;416:2835–48.
68. Hagarová I, Nemček L. Reliable Quantification of Ultratrace Selenium in Food, Beverages, and Water Samples by Cloud Point Extraction and Spectrometric Analysis. Nutrients. 2022;14:3530.
69. Ridha RK, Alasady DH, Azooz EA, Mortada WI. Rapid synergistic cloud point extraction based on hydrophobic deep eutectic solvent combined with hydride generation atomic absorption spectrometry for determination of selenium in tea samples. Journal of Food Composition and Analysis. 2024;132:106286.
70. Gómez-Nieto B, Gismera MJ, Sevilla MT, R Procopio J. Direct solid sampling of biological species for the rapid determination of selenium by high-resolution continuum source graphite furnace atomic absorption spectrometry. Analytica Chimica Acta. 2022;1202:339637.
71. Recknagel S, Brätter P, Tomiak A, Rösick U. Determination of selenium in blood serum by ICP-OES including an on-line wet digestion and Se-hydride formation procedure. Fresenius' Journal of Analytical Chemistry. 1993;346:833–6.
72. Fleming DEB, Madani N, Kaiser MG, Kim JS, Keltie E, Drage N et al. Portable X-ray fluorescence of zinc and selenium with nail clippings–Mother and Infant Nutrition Investigation (MINI). PLOS ONE. 2024;19:e0310845.
73. Aimaitiniyazi M, Muhammad T, Yasen A, Abula S, Dolkun A, Tursun Z. Determination of Selenium in Selenium-Enriched Products by Specific Ratiometric Fluorescence. Sensors (Basel). 2023;23:9187.
74. Maia LB, Maiti BK, Moura I, Moura JJG. Selenium-More than Just a Fortuitous Sulfur Substitute in Redox Biology. Molecules. 2023;29:120.
75. Shahidin, Wang Y, Wu Y, Chen T, Wu X, Yuan W et al. Selenium and Selenoproteins: Mechanisms, Health Functions, and Emerging Applications. Molecules. 2025;30:437.
76. Zhang F, Li X, Wei Y. Selenium and Selenoproteins in Health. Biomolecules. 2023;13:799.
77. Zhu C, Zhang S, Song C, Zhang Y, Ling Q, Hoffmann PR et al. Selenium nanoparticles decorated with Ulva lactuca polysaccharide potentially attenuate colitis by inhibiting NF-κB mediated hyper inflammation. J Nanobiotechnology. 2017;15:20.
78. Huang Y, He L, Liu W, Fan C, Zheng W, Wong YS et al. Selective cellular uptake and induction of apoptosis of cancer-targeted selenium nanoparticles. Biomaterials. 2013;34:7106–16.
79. Wu H, Zhu H, Li X, Liu Z, Zheng W, Chen T et al. Induction of apoptosis and cell cycle arrest in A549 human lung adenocarcinoma cells by surface-capping selenium nanoparticles: an effect enhanced by polysaccharide-protein complexes from Polyporus rhinocerus. J Agric Food Chem. 2013;61:9859–66.
80. Yang Y, Zhang Z, Chen Q, You Y, Li X, Chen T. Functionalized Selenium Nanoparticles Synergizes With Metformin to Treat Breast Cancer Cells Through Regulation of Selenoproteins. Front Bioeng Biotechnol. 2021;9:758482.
81. Anjum S, Hashim M, Imran M, Babur S, Adnan S, Hano C et al. Selenium Nanoparticles in Cancer Therapy: Unveiling Cytotoxic Mechanisms and Therapeutic Potential. Cancer Rep (Hoboken). 2025;8:e70210.
82. Khurana A, Allawadhi P, Singh V, Khurana I, Yadav P, Sathua KB et al. Antimicrobial and anti-viral effects of selenium nanoparticles and selenoprotein based strategies: COVID-19 and beyond. J Drug Deliv Sci Technol. 2023;86:104663.
83. Serov DA, Khabatova VV, Vodeneev V, Li R, Gudkov SV. A Review of the Antibacterial, Fungicidal and Antiviral Properties of Selenium Nanoparticles. Materials (Basel). 2023;16:5363.
84. Xia Y, Chen Y, Hua L, Zhao M, Xu T, Wang C et al. Functionalized selenium nanoparticles for targeted delivery of doxorubicin to improve non-small-cell lung cancer therapy. Int J Nanomedicine. 2018;13:6929–39.
85. Ansari JA, Malik JA, Ahmed S, Manzoor M, Ahemad N, Anwar S. Recent advances in the therapeutic applications of selenium nanoparticles. Mol Biol Rep. 2024;51:688.
86. Maiyo F, Singh M. Selenium nanoparticles: potential in cancer gene and drug delivery. Nanomedicine (Lond). 2017;12:1075–89.
87. Amani H, Habibey R, Shokri F, Hajmiresmail SJ, Akhavan O, Mashaghi A et al. Selenium nanoparticles for targeted stroke therapy through modulation of inflammatory and metabolic signaling. Scientific Reports. 2019;9:6044.
88. Li W, Lu X, Jiang L, Wang X. Biosafety and pharmacokinetic characteristics of polyethylene pyrrolidone modified nano selenium in rats. BMC Biotechnology. 2024;24:98.