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Snails as Potential Bioindicators for Environmental Quality Assessment: A Comprehensive Review

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A B S T R A C T

Environmental pollution has emerged as one of the most significant global challenges, threatening ecosystem integrity, biodiversity, and human health. Rapid industrialization, urbanization, intensive agricultural practices, mining, and improper waste disposal have resulted in the widespread release of heavy metals and other toxic contaminants into terrestrial and aquatic environments. Continuous monitoring of environmental quality is therefore essential for the effective assessment and management of polluted ecosystems. Among the various biological monitoring tools, snails have gained considerable attention as reliable bioindicators because of their sedentary nature, wide geographical distribution, high bioaccumulation capacity, and sensitivity to environmental contaminants. It discusses the biological and ecological characteristics that make snails suitable bioindicators, including their feeding behaviour, habitat specificity, physiological responses, and the ability of their digestive gland and shell to accumulate toxic metals such as lead, cadmium, copper, zinc, mercury, and chromium. The review also summarizes the mechanisms of metal uptake, bioaccumulation, detoxification through metallothionein proteins, oxidative stress responses, and histopathological alterations that serve as biomarkers of environmental contamination. Furthermore, commonly employed analytical techniques, including Atomic Absorption Spectrophotometry (AAS), Inductively Coupled Plasma–Optical Emission Spectrometry (ICP- OES), and Inductively Coupled Plasma–Mass Spectrometry (ICP-MS), are highlighted for heavy metal determination in snail tissues. Recent case studies from different regions of the world demonstrate the effectiveness of snails in monitoring environmental pollution and assessing ecological health. The advantages, limitations, and future prospects of using snails as bioindicators are also critically discussed. Overall, this review emphasizes that snails provide an economical, sensitive, and scientifically reliable approach for long-term environmental monitoring and can significantly contribute to pollution assessment, ecological risk evaluation, and the development of sustainable environmental management strategies.

Introduction

Environmental pollution is one of the most pressing global environmental challenges, adversely affecting ecosystem health, biodiversity, and human well-being. Rapid industrialization, urbanization, intensive agricultural practices, mining activities, and the indiscriminate disposal of domestic and industrial wastes have significantly increased the release of hazardous pollutants into the environment. These pollutants contaminate air, water, and soil, disrupting ecological balance and threatening the survival of numerous organisms. Among environmental contaminants, heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), arsenic (As), copper (Cu), zinc (Zn), and nickel (Ni) are of particular concern because of their persistence, toxicity, non-biodegradable nature, and ability to bioaccumulate within biological systems (Ali *et al.,* 2019). Environmental pollution has become a major public health concern worldwide. According to the World Health Organization (WHO, 2021), millions of premature deaths each year are associated with environmental risk factors, particularly air, water, and soil pollution.Several terrestrial and freshwater snail species, including *Achatina fulica*, *Archachatina marginata*, *Helix aspersa*, *Biomphalaria glabrata*, *Lymnaea stagnalis*, and *Bellamya bengalensis*, have been successfully employed in biomonitoring studies across different parts of the world. Numerous investigations have demonstrated their effectiveness in assessing heavy metal contamination in agricultural lands, industrial zones, mining areas, urban ecosystems, and roadside environments. Modern analytical techniques such as Atomic Absorption Spectrophotometry (AAS), Inductively Coupled Plasma–Optical Emission Spectrometry (ICP-OES), and Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) have further improved the precision of heavy metal analysis in snail tissues, enhancing their application in environmental monitoring (Boshoff & Wolmarans, 2014). Bioindicators integrate contaminant exposure over time and provide valuable information regarding the ecological impact of pollution (Burger, 2006). Among the various bioindicator organisms, gastropod snails have received considerable scientific attention because of their unique biological and ecological characteristics. Snails are widely distributed in terrestrial, freshwater, and marine ecosystems and occupy an important ecological position as herbivores, detritivores, and decomposers. Their sedentary nature, limited dispersal ability, and continuous contact with soil, vegetation, and water enable them to reflect local environmental conditions accurately. Since snails remain within relatively small habitats throughout their lives, contaminants accumulated in their tissues are representative of site- specific pollution rather than contamination acquired from distant locations (Beeby & Richmond, 2002). Snails are effective bioindicators because they can accumulate heavy metals in their soft tissues and shells without immediate harmful effects. Contaminants are absorbed from polluted soil, water, and food, with the digestive gland (hepatopancreas) serving as the primary site for metal accumulation and detoxification through metallothionein proteins. Additionally, the shell stores metals over time, providing valuable information on long-term environmental contamination (Dallinger & Rainbow, 1993). Environmental pollutants, particularly heavy metals, trigger physiological and biochemical changes in snails, including oxidative stress, DNA damage, altered antioxidant enzyme activity, and tissue damage. These responses serve as sensitive biomarkers for the early detection of environmental pollution, making snail tissues valuable tools in ecotoxicological studies (Ben Saad *et al.,* 2016). Snails are widely used as bioindicators because they are abundant, easy to collect, inexpensive, and capable of accumulating pollutants over long periods. Their high bioaccumulation capacity and sensitivity to environmental changes make them valuable for assessing ecosystem health, although factors such as species, age, season, and habitat should be considered during interpretation.

Environmental Pollution and Environmental Quality

Environmental pollution is the introduction of harmful physical, chemical, or biological substances into the environment, adversely affecting ecosystems and living organisms. Rapid industrialization, urbanization, agriculture, mining, and population growth have increased pollution in air, water, and soil, threatening biodiversity and human health (Cunningham & Cunningham, 2020; Miller & Spoolman, 2021). Pollutants are classified as biodegradable or non-biodegradable. While biodegradable pollutants decompose naturally, non-biodegradable pollutants such as heavy metals, plastics, pesticides, and radioactive substances persist in the environment, causing long-term ecological damage and disrupting ecosystem balance (Sharma, 2020). Environmental pollution includes air, water, soil, noise, thermal, and radioactive pollution, mainly caused by industrial activities, vehicle emissions, agricultural practices, mining, and improper waste disposal. These pollutants degrade environmental quality, disrupt ecosystem functions, and negatively affect biodiversity (Odum & Barrett, 2005). Heavy metal pollution is of particular concern because metals such as lead, cadmium, mercury, arsenic, chromium, nickel, copper, and zinc are persistent and non-biodegradable. They accumulate in the environment and living organisms through bioaccumulation and biomagnification, posing serious risks to wildlife and human health, including neurological, kidney, and reproductive disorders (Alloway, 2013). Environmental quality describes the overall physical, chemical, and biological condition of the environment and its capacity to support healthy ecosystems and human well-being. Clean air, safe water, fertile soil, and rich biodiversity indicate good environmental quality, whereas pollution and habitat degradation reflect poor environmental conditions (Chapman & Reiss, 1999).

Regular assessment of environmental quality is essential for identifying pollution, monitoring ecosystem health, and guiding environmental management. It supports pollution control, conservation efforts, and the early detection of ecological changes, thereby promoting sustainable environmental development (European Environment Agency, 2020). The growing level of environmental pollution has increased the need for effective monitoring methods to evaluate long-term ecosystem health. Integrating chemical analyses with biological assessments provides a more comprehensive evaluation of environmental quality, as biological responses reflect the cumulative effects of pollutants over time. This combined approach is widely recognized as an effective strategy for environmental monitoring and conservation (United Nations Environment Programme, 2022).

Bioindicator: Concept and It Importance

Bioindicators are living organisms that reflect environmental conditions through changes in their abundance, physiological responses, or pollutant accumulation. They are widely used to assess ecosystem health because they indicate the long-term effects of environmental contamination more effectively than chemical analyses alone (Markert *et al.,* 2003; Burger, 2006).Various organisms, including microorganisms, plants, insects, molluscs, fish, and amphibians, serve as bioindicators depending on the type of ecosystem and pollutant. For instance, lichens are commonly used to monitor air pollution, while molluscs are effective indicators of heavy metal contamination due to their high capacity for pollutant accumulation (Cairns & Pratt, 1993). Bioindicators are valuable because they can detect environmental changes before visible ecological damage occurs. They provide information on pollutant exposure, ecosystem health, and biological responses, making them useful for environmental monitoring, pollution control, and biodiversity conservation.

Their sensitivity, low cost, and suitability for long-term monitoring support sustainable environmental management (Holt & Miller, 2011). Bioindicators are also widely used to evaluate the ecological effects of heavy metals, pesticides, and other pollutants. Their responses help identify contamination sources, assess environmental risks, and evaluate the success of pollution control measures, making them an essential part of modern biomonitoring programmes (Van der Oost *et al.,* 2003).

Bioindicators are useful for assessing environmental quality because they respond to physical, chemical, and biological changes in their surroundings. Changes in their growth, reproduction, survival, and behaviour provide early evidence of ecosystem disturbance and pollutant exposure, enabling the detection of environmental degradation before it becomes visibly apparent (Gerhardt, 2002).

Bioindicators are widely used in environmental monitoring because they reflect the biologically available portion of pollutants and their effects on living organisms. As a result, they play an important role in ecological risk assessment, pollution monitoring, habitat conservation, and environmental impact assessment (Franzle, 2003). An ideal bioindicator should be widely distributed, easy to collect, ecologically important, and sensitive to environmental changes. It should also produce consistent and measurable responses that accurately reflect variations in environmental quality across different ecosystems (Walker *et al.,* 2012).

Bioindicators play an important role in environmental management by supporting pollution control, ecosystem restoration, and conservation programmes. Long-term biomonitoring using bioindicators helps assess environmental changes, identify emerging threats, and promote the sustainable management of natural resources (Newman, 2015).

Snails as Bioindicators

Snails are increasingly recognized as reliable bioindicators for environmental quality assessment because of their ecological sensitivity, limited mobility, and ability to accumulate pollutants in their tissues and shells. Their close association with soil, vegetation, sediments, and water enables them to reflect local environmental conditions, making them suitable organisms for monitoring terrestrial and aquatic pollution. (Baroudi *et al.,* 2020). Heavy metals, pesticides, persistent organic pollutants, nanoparticles, and other environmental contaminants can accumulate in snails through food, soil, water, and direct contact with contaminated substrates. The digestive gland is the primary site for contaminant accumulation and detoxification, while the shell can retain certain metals over long periods, providing information on both current and historical pollution levels. (El-shenawy *et al.,* 2012).

Another important characteristic of snails is their ability to exhibit molecular and cellular responses following exposure to environmental contaminants. Changes in lysosomal membrane stability, DNA integrity, oxidative stress markers, heat-shock proteins, and immune-related responses occur even at relatively low contaminant concentrations.

These biomarkers enable the detection of sublethal pollution effects before reductions in population size or biodiversity become evident, thereby improving the sensitivity of environmental monitoring programmes. (Abdel Halim *et al.,* 2025). Unlike conventional monitoring methods that measure only pollutant concentrations, snails provide biologically relevant information by reflecting the cumulative effects of contaminant exposure over time. This characteristic enables a more realistic assessment of ecological health and pollutant bioavailability (Nica *et al.,* 2020).

Recent ecotoxicological studies have demonstrated that snails respond to environmental contaminants at multiple levels of biological organization, ranging from molecular and cellular alterations to physiological, behavioural, and population-level changes. Pollutant-induced modifications in gene expression, enzyme activities, metabolic pathways, and reproductive performance provide sensitive biomarkers for detecting sublethal environmental stress before irreversible ecological damage becomes apparent (Panda *et al.,* 2022). The digestive gland (hepatopancreas) of snails has attracted considerable attention because it functions as the primary organ for xenobiotic metabolism, detoxification, and metal sequestration. Within this organ, toxic metals are compartmentalized into lysosomes and bound to metallothioneins thereby minimizing cellular toxicity while allowing long-term storage of contaminants. Consequently, the digestive gland serves as one of the most reliable tissues for environmental biomonitoring and ecological risk assessment (Dallinger, 2024). Another important advancement is the application of multi-biomarker approaches**,** which combine chemical analyses with biochemical, histopathological, immunological, and molecular biomarkers. This integrated strategy improves the sensitivity and reliability of pollution assessment by simultaneously evaluating contaminant accumulation, oxidative stress, DNA integrity, cellular damage, and tissue pathology. Multi-biomarker indices are increasingly recommended for comprehensive environmental quality assessment because they provide a holistic understanding of ecosystem responses to pollution (Zaza *et al.,* 2020). Climate change is also influencing the effectiveness of snails as bioindicators. Variations in temperature, rainfall, soil moisture, and habitat conditions can alter pollutant bioavailability, accumulation rates, and physiological responses in snails. Therefore, recent monitoring programmes increasingly incorporate climatic variables together with contaminant analyses to improve the interpretation of biomonitoring data and predict future environmental risks.

Exposure to pollutants induces various physiological, biochemical, and behavioural changes in snails, including altered feeding activity, reduced growth, impaired reproduction, oxidative stress, DNA damage, changes in antioxidant enzyme activity, and histopathological alterations.

These measurable responses serve as sensitive biomarkers for the early detection of environmental contamination and ecological stress. Recent studies have demonstrated that terrestrial and freshwater snails effectively monitor contamination by heavy metals, pesticides, microplastics, and other emerging pollutants. Their high bioaccumulation capacity, ease of collection, wide distribution, and low maintenance requirements make them valuable organisms for biomonitoring programmes. Consequently, snails are increasingly used in environmental risk assessment, pollution surveillance, and ecosystem conservation. (Ibrahim *et al.,* 2021).

Examples of Snails as Bioindicators

Several terrestrial and freshwater snail species have been successfully used as bioindicators to monitor environmental pollution across different ecosystems.

Cornu aspersum **(Garden Snail):** *Cornu aspersum* is one of the most extensively studied terrestrial snails in ecotoxicology. It accumulates heavy metals such as cadmium (Cd), lead (Pb), copper (Cu), and zinc (Zn) in its digestive gland and shell. Due to its sedentary nature and high metal accumulation capacity, this species is widely used to assess industrial, agricultural, and urban pollution (Itziou & Dimitriadis, 2011).

Eobania vermiculata **(Chocolate-band Snail):** *Eobania vermiculata* has been widely applied in biomonitoring studies to evaluate heavy metal contamination and pesticide exposure. Changes in antioxidant enzyme activity, lipid peroxidation, DNA integrity, and histopathological alterations in its digestive gland make this species a sensitive indicator of terrestrial pollution (Radwan *et al.,* 2020).

Achatina fulica **(Giant African Snail):** *Achatina fulica* is recognized as an effective bioindicator because of its large body size, widespread distribution, and high capacity to accumulate heavy metals from contaminated soils and vegetation. This species has been used to assess environmental contamination in urban, agricultural, and mining areas, particularly in tropical and subtropical regions (Chatanga *et al.,* 2019).

Helix pomatia **(Roman Snail):** *Helix pomatia* has frequently been used in European biomonitoring programmes to evaluate long-term heavy metal pollution. Studies have reported significant accumulation of lead, cadmium, and mercury in the digestive gland, demonstrating its usefulness in assessing ecological risks associated with industrial emissions and road traffic pollution (Hlavac *et al.,* 2020).

Bellamya aeruginosa **(Freshwater Snail):** *Bellamya aeruginosa* is an important freshwater bioindicator for monitoring contamination in lakes, rivers, and wetlands. This species has been used to evaluate the toxic effects of organotin compounds, pesticides, and heavy metals through biochemical, histological, and molecular biomarkers, making it suitable for freshwater ecotoxicological studies (Wu *et al.,* 2020).

Biomphalaria glabrata **(Freshwater Snail):** *Biomphalaria glabrata* has become an important experimental model for evaluating the toxic effects of pharmaceuticals, nanoparticles, and heavy metals. Molecular and physiological studies on this species have contributed significantly to understanding pollutant-induced oxidative stress, immune responses, and gene regulation in freshwater ecosystems (Dvorak *et al.,* 2021).

Lymnaea stagnalis **(Great Pond Snail):** *Lymnaea stagnalis* is one of the most extensively used freshwater gastropods in ecotoxicological research. It has been employed to evaluate the effects of heavy metals, pesticides, pharmaceuticals, endocrine-disrupting chemicals, and nanomaterials. Alterations in growth, reproduction, embryo development, oxidative stress biomarkers, and gene expression make this species an excellent indicator of freshwater pollution (Filla *et al.,* 2021).

Physella acuta **(Acute Bladder Snail):** *Physella acuta* is widely distributed in freshwater habitats and has been used to monitor contamination by heavy metals and agricultural pesticides. Due to its rapid life cycle and high sensitivity to pollutants, this species is commonly used in laboratory toxicity tests and ecological risk assessment programmes (Dillon, 2019).

Pomacea canaliculata **(Golden Apple Snail):** *Pomacea canaliculata* has become an important bioindicator for assessing heavy metal contamination and pesticide toxicity in rice-growing ecosystems. Studies have demonstrated that cadmium, copper, and lead accumulate in its digestive gland, causing oxidative stress, histopathological changes, and reproductive impairment (Xu *et al.,* 2022).

Theba pisana **(White Garden Snail):** *Theba pisana* has been successfully used to monitor environmental pollution in Mediterranean coastal regions. Heavy metal accumulation in its tissues and shell reflects contamination from road traffic, industrial emissions, and agricultural activities, making it an effective terrestrial bioindicator (Nica *et al.,* 2020).

Megalobulimus paranaguensis: This terrestrial snail has recently been investigated as a bioindicator of forest ecosystem health. Its sensitivity to habitat disturbance, deforestation, and soil contamination makes it valuable for evaluating the ecological impacts of land-use changes and conservation practices in tropical ecosystems (Miranda *et al.,* 2021).

Biology and Ecology of Snails

Snails belong to the phylum Mollusca and class Gastropoda**,** the largest and most diverse group of molluscs. They inhabit a wide range of ecosystems, including terrestrial, freshwater, and marine environments, where they play essential roles in ecosystem functioning. Their remarkable ecological adaptability is attributed to physiological plasticity, efficient water conservation mechanisms, and behavioural adaptations that enable survival under diverse environmental conditions. Recent evolutionary studies indicate that gastropods have independently colonized terrestrial habitats multiple times, resulting in extensive diversification and ecological specialization across different climatic regions (Vermeij & Watson-Zink, 2022).

Snails contribute significantly to ecosystem processes by participating in nutrient cycling, organic matter decomposition, and energy transfer within food webs. Most terrestrial snails function as detritivores, herbivores, or fungal grazers, feeding on leaf litter, algae, fungi, decaying vegetation, and microorganisms. Through these feeding activities, they accelerate decomposition, improve nutrient availability, and influence soil microbial communities. In addition, snails serve as prey for numerous vertebrates and invertebrates, thereby linking lower and higher trophic levels within ecosystems. (Chen Z *et al.,* 2022)

The ecological distribution of snails is strongly influenced by abiotic factors such as temperature, moisture, soil pH, calcium availability, vegetation cover, and habitat structure. Calcium-rich soils are particularly important because calcium is required for shell formation, growth, and reproduction. Environmental stressors, including drought, habitat fragmentation, pollution, and land-use changes, can alter snail abundance, species composition, and community diversity. Consequently, snail assemblages are increasingly used to evaluate habitat quality and ecosystem integrity. (Neubauer *et al.,* 2022)

Recent ecological research has highlighted the importance of physiological plasticity in enabling snails to survive fluctuating environmental conditions. Many species regulate water loss through estivation, mucus secretion, reduced metabolic activity, and behavioural avoidance of thermal stress. These adaptive mechanisms increase survival during periods of drought and extreme temperatures while maintaining population persistence under changing climatic conditions. Such physiological flexibility also influences contaminant uptake and the suitability of snails for long-term environmental monitoring. (Wang *et al.,* 2022)

At the cellular level, the hepatopancreas functions as the principal organ responsible for digestion, nutrient storage, detoxification, and metabolism. This organ contains specialized cells capable of accumulating metals, xenobiotics, and other environmental contaminants while activating detoxification pathways that minimize cellular damage. These biological characteristics explain why the hepatopancreas is widely used in ecotoxicological studies and biomonitoring programmes for assessing environmental contamination. (Potapov *et al.,* 2022)

Advances in molecular ecology have further improved understanding of snail biology. Genome sequencing, phylogenomics, and population genetic studies have revealed genes associated with environmental adaptation, shell formation, stress tolerance, immune defence, and terrestrial evolution. These approaches provide valuable information on evolutionary relationships, adaptive mechanisms, and species resilience under environmental change, strengthening the use of snails in ecological and ecotoxicological research.

Mechanism of Heavy Metal Bioaccumulation in Snails

Heavy metal bioaccumulation in snails is a complex physiological process involving the uptake, transport, sequestration, detoxification, and storage of metals within specific tissues. Metals such as cadmium (Cd), lead (Pb), copper (Cu), zinc (Zn), mercury (Hg), and chromium (Cr) enter the snail's body primarily through ingestion of contaminated food, soil particles, and water, as well as through direct absorption across epithelial surfaces. The rate of metal uptake depends on environmental factors, including metal bioavailability, soil pH, moisture, and the chemical form of the metal. (Baroudi *et al.,* 2020). Following uptake, absorbed metals are transported via the haemolymph to metabolically active organs, particularly the digestive gland (hepatopancreas). This organ functions as the primary centre for nutrient metabolism, xenobiotic detoxification, and metal storage. Digestive cells actively internalize metal ions through membrane transporters and endocytosis, resulting in progressive accumulation within lysosomes and intracellular vesicles. Consequently, the hepatopancreas exhibits much higher metal concentrations than other tissues and is regarded as the most suitable organ for biomonitoring studies.

A key mechanism responsible for metal tolerance in snails is the synthesis of metallothioneins (MTs), which are low-molecular-weight, cysteine-rich proteins with a high affinity for metal ions. Metallothioneins selectively bind cadmium, copper, and zinc, reducing their free intracellular concentrations and minimizing oxidative damage. Recent studies have shown that gastropods possess metal-specific metallothionein isoforms that enhance their capacity to regulate essential metals while detoxifying toxic non-essential metals, thereby improving adaptation to contaminated environments. (Dallinger *et al.,* 2024)

In addition to metallothionein binding, snails detoxify heavy metals by compartmentalizing them within lysosomes and forming insoluble metal-rich granules. These granules isolate toxic metals from sensitive cellular components, thereby limiting their interaction with proteins, nucleic acids, and cell membranes. This lysosomal sequestration represents an important long-term detoxification strategy that enables snails to survive prolonged exposure to contaminated habitats.

Excessive metal accumulation can overwhelm these protective mechanisms and stimulate the production of reactive oxygen species (ROS). Increased ROS levels induce oxidative stress, leading to lipid peroxidation, protein oxidation, mitochondrial dysfunction, and DNA damage. To counteract these effects, snails activate antioxidant defence systems involving enzymes such as superoxide dismutase (SOD), catalase (CAT), glutathione-S-transferase (GST), and glutathione peroxidase (GPx). The coordinated activity of these antioxidant enzymes represents an important adaptive response to heavy metal toxicity (Dvorak *et al.,* 2020).

Recent studies indicate that heavy metal bioaccumulation is regulated not only by physiological processes but also by molecular mechanisms controlling gene expression. Exposure to heavy metals induces genes associated with metallothionein synthesis, antioxidant defence, cellular repair, apoptosis, and stress-response pathways. These molecular responses improve metal tolerance and provide highly sensitive biomarkers for environmental pollution monitoring, strengthening the role of snails in modern ecotoxicological research. (Hlavac *et al.,* 2020).

Digestive Gland as Bio Marker

The digestive gland, commonly referred to as the hepatopancreas, is the principal target organ for biomonitoring studies in snails because it plays a central role in digestion, nutrient absorption, detoxification, xenobiotic metabolism, and intracellular storage of contaminants. Owing to its high metabolic activity, this organ accumulates significantly greater concentrations of heavy metals and organic pollutants than other tissues, making it one of the most sensitive biomarkers for assessing environmental contamination. (Dhiman *et al.,* 2021)

Heavy metals such as cadmium (Cd), lead (Pb), mercury (Hg), copper (Cu), and zinc (Zn) are transported to the digestive gland through the haemolymph after entering the snail via contaminated food, soil, or water. Within the hepatopancreas, these metals are sequestered into lysosomes and bound to metallothionein proteins, thereby reducing metal toxicity while permitting long-term storage. The concentration of metals in the digestive gland therefore closely reflects the level of environmental pollution and is widely used for ecological risk assessment (Wu *et al.,* 2020).

The digestive gland is also highly responsive to pollutant-induced oxidative stress. Exposure to contaminants stimulates the production of reactive oxygen species (ROS), resulting in lipid peroxidation, protein oxidation, and DNA damage. Consequently, antioxidant enzymes including superoxide dismutase (SOD), catalase (CAT), glutathione-S-transferase (GST), and glutathione peroxidase (GPx) are frequently quantified in the digestive gland as biochemical biomarkers of environmental stress. Changes in the activities of these enzymes provide sensitive indicators of sublethal toxicity before external symptoms become evident (Radwan *et al.,* 2020).

Histopathological alterations of the digestive gland are considered reliable indicators of pollutant exposure. Common pathological changes include degeneration of digestive tubules, vacuolization, epithelial disorganization, lysosomal enlargement, necrosis, inflammatory responses, and cellular atrophy. These structural abnormalities are strongly associated with chronic exposure to heavy metals, pesticides, organotin compounds, and other environmental contaminants, making histological examination an effective tool in environmental biomonitoring.

Recent advances in ecotoxicology have further expanded the application of the digestive gland by integrating biochemical, histological, molecular, and transcriptomic biomarkers. Gene expression analyses involving metallothioneins, heat shock proteins, apoptosis-related genes, and antioxidant enzymes have improved the sensitivity of pollution assessment. Such multi-biomarker approaches enable early detection of contaminant-induced cellular dysfunction and provide a comprehensive evaluation of ecosystem health.

Because of its high contaminant accumulation capacity, rapid physiological response, and measurable biochemical and histopathological alterations, the digestive gland is regarded as the most informative organ for evaluating pollutant exposure in snails. Its analysis provides valuable information on contaminant bioavailability, toxicity mechanisms, and long-term environmental quality, supporting its widespread application in modern ecotoxicological research and biomonitoring programmes. (Hlavac *et al.,* 2020)

Heavy Metal Analysis Techniques

Accurate determination of heavy metals is essential for environmental monitoring, biomonitoring, and ecological risk assessment. Before analysis, biological samples such as snail tissues are generally washed, dried, homogenized, and digested using concentrated acids (commonly nitric acid with hydrogen peroxide) through microwave-assisted or hot-plate digestion. This process converts metals into soluble forms suitable for instrumental analysis. The selection of an analytical technique depends on the sample matrix, required detection limit, analytical precision, and the number of elements to be measured. Modern analytical methods provide rapid, sensitive, and simultaneous determination of multiple heavy metals in environmental and biological samples. (Adesina KE *et al.,* 2025)

Reliable heavy metal analysis depends not only on the analytical instrument but also on proper sample preparation and quality assurance procedures. Environmental and biological samples, including snail tissues, are commonly subjected to acid digestion using nitric acid (HNO_3) alone or in combination with hydrogen peroxide (H_2O_2). Microwave-assisted digestion is widely preferred because it minimizes contamination, reduces digestion time, and improves metal recovery compared to conventional digestion methods (Skoog *et al.,* 2018).

To ensure analytical accuracy, laboratories implement strict quality control measures, including the use of certified reference materials (CRMs), reagent blanks, duplicate samples, calibration standards, and recovery tests. Instrument calibration and regular performance verification are essential for obtaining precise and reproducible results. These quality assurance procedures improve the reliability and comparability of heavy metal data obtained from different studies (Harris, 2020).

Atomic Absorption Spectroscopy (AAS) is one of the most widely used techniques for heavy metal determination. It measures the absorption of element-specific light by free atoms produced in a flame or graphite furnace. Flame AAS is suitable for metals present at relatively high concentrations, whereas Graphite Furnace AAS (GF-AAS) provides much greater sensitivity for trace-level analysis. Although AAS is highly accurate and cost-effective, it generally determines one element at a time, limiting its efficiency for multi-element analysis. (Chen X *et al.,* 2024)

Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP-OES/ICP-AES) has become a standard technique for environmental studies because it simultaneously measures numerous elements with high precision. Samples are introduced into an argon plasma (approximately 6,000–10,000 K), where atoms and ions emit characteristic wavelengths of light. The emitted spectra are used to quantify heavy metal concentrations rapidly and accurately, making ICP-OES particularly suitable for routine analysis of soil, water, plant, and snail tissue samples.

Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) is regarded as the gold standard for trace metal analysis because of its exceptional sensitivity and extremely low detection limits (parts per billion to parts per trillion). In ICP-MS, ions generated in the plasma are separated according to their mass-to-charge ratio, allowing simultaneous determination of multiple elements and their isotopes. Owing to its high analytical performance, ICP-MS is extensively used in ecotoxicology, biomonitoring, food safety, and environmental quality assessment. (Ghosh *et al.,* 2025)

X-ray Fluorescence (XRF) Spectroscopy is a rapid and non-destructive analytical technique used to determine elemental composition without extensive sample preparation. Samples are irradiated with X-rays, causing atoms to emit characteristic fluorescent radiation that is measured to identify and quantify metals. Portable XRF instruments enable field-based screening of contaminated soils, sediments, shells, and rocks; however, their sensitivity for ultra-trace metals is generally lower than ICP-based techniques.

Recent advances include Laser Ablation ICP-MS (LA-ICP-MS), which enables direct analysis of solid samples with minimal preparation while providing spatial distribution maps of metals within tissues and shells. In addition, X-ray Absorption Spectroscopy (XAS) is increasingly used to determine the chemical forms (speciation) and oxidation states of heavy metals, whereas electrochemical techniques such as Anodic Stripping Voltammetry (ASV) offer highly sensitive detection of trace metals in environmental samples. The integration of these advanced techniques with biomonitoring improves the understanding of metal bioavailability, accumulation pathways, and ecological risks. (Moyo *et al.,* 2026)

Applications of Snails in Environmetal Monitoring

Snails have become important organisms in environmental monitoring because they integrate pollutant exposure from multiple environmental compartments, including soil, water, vegetation, and sediments. Their sedentary lifestyle, high bioaccumulation capacity, and physiological sensitivity enable them to reflect local environmental conditions more accurately than mobile organisms. Consequently, snails are widely employed in biomonitoring programmes to assess the ecological impacts of both natural and anthropogenic pollutants (Regoli & Fattorini, 2022).

One of the major applications of snails is the monitoring of heavy metal contamination in terrestrial and freshwater ecosystems. Metals such as cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), chromium (Cr), nickel (Ni), copper (Cu), and zinc (Zn) accumulate in snail tissues and shells in proportion to environmental exposure. Analysis of these tissues provides valuable information on contaminant distribution, bioavailability, and ecological risks associated with industrial activities, mining, agriculture, and urbanization (Nica *et al.,* 2020).

Snails are also increasingly used for monitoring agricultural pollution**,** particularly contamination caused by pesticides, herbicides, and fertilizers. Exposure to agrochemicals induces changes in antioxidant enzyme activity, reproduction, feeding behaviour, growth, and tissue morphology. These biological responses help evaluate the ecological effects of intensive agricultural practices and support the development of sustainable farming strategies (Radwan, El-Gendy, & Gad, 2020).

Another important application is the assessment of emerging contaminants**,** including pharmaceuticals, microplastics, nanomaterials, and personal care products. Recent studies have shown that snails can ingest and accumulate these pollutants, leading to oxidative stress, metabolic disturbances, immune dysfunction, and behavioural alterations. These responses provide valuable information on the environmental fate and biological effects of newly emerging pollutants that are not routinely detected through conventional monitoring methods (Panda *et al.,* 2022).

Snails are widely used in ecological risk assessment because they occupy an intermediate trophic level in terrestrial food webs. Pollutants accumulated in snail tissues may be transferred to predators such as birds, reptiles, amphibians, and small mammals through trophic interactions. Therefore, contaminant concentrations measured in snails can be used to estimate the potential risk of biomagnification and secondary poisoning in higher trophic levels (Notten *et al.,* 2018).

Recent advances have expanded the application of snails in integrated biomonitoring programmes**,** where chemical analyses are combined with biochemical, histopathological, molecular, and genomic biomarkers. This multi-disciplinary approach enables early detection of environmental stress, identification of pollution sources, and evaluation of ecosystem health with greater sensitivity than chemical monitoring alone. Consequently, snail-based biomonitoring has become an important component of environmental impact assessment, biodiversity conservation, and pollution management worldwide (Amiard-Triquet, Amiard, & Mouneyrac, 2015).

Snails have been incorporated into environmental impact assessment (EIA) programmes to evaluate the ecological effects of industrial development, mining, road construction, waste disposal, and urban expansion. Variations in snail diversity, abundance, physiological responses, and contaminant burdens provide valuable evidence of habitat degradation and ecosystem disturbance before large-scale biodiversity loss occurs (Zhang *et al.,* 2023).

Snails also play an important role in monitoring soil restoration and remediation programmes. Following remediation of contaminated sites using phytoremediation, soil amendments, or other restoration techniques, reductions in heavy metal accumulation and improvements in snail health can be used to assess the effectiveness of remediation measures.

Therefore, snails serve as practical biological indicators for evaluating ecosystem recovery after pollution control interventions (Khalil *et al.,* 2022).

Another emerging application involves the use of snails to monitor microplastic pollution in terrestrial ecosystems. Recent studies have demonstrated that land snails ingest microplastic particles together with food and soil, resulting in physiological stress, digestive disturbances, and oxidative damage. Consequently, snails are increasingly recognized as useful organisms for assessing the ecological effects of plastic pollution in agricultural and urban environments (Pan *et al.,* 2023).

Recent ecotoxicological investigations have also employed snails to evaluate the combined effects of multiple environmental stressors, including heavy metals, pesticides, temperature fluctuations, and drought. Such studies indicate that interactions among different stressors may produce synergistic or antagonistic effects, emphasizing the importance of snail-based biomonitoring for predicting ecosystem responses under changing environmental conditions (Bourgeault *et al.,* 2021).

The integration of Geographic Information Systems (GIS), remote sensing, and biomonitoring data has further enhanced the use of snails in environmental surveillance. Spatial analysis of contaminant accumulation in snail populations allows researchers to identify pollution hotspots, monitor temporal trends, and support evidence-based environmental management. These advanced applications contribute significantly to sustainable ecosystem conservation and environmental policy development (Bergey & Weis, 2021).

In conclusion, Environmental pollution continues to pose a serious threat to ecosystem stability, biodiversity, and human well-being. Rapid industrialization, urbanization, agricultural intensification, mining, and improper waste disposal have increased the release of heavy metals and other contaminants into terrestrial and aquatic environments. Therefore, effective environmental monitoring is essential for assessing ecosystem health, identifying pollution sources, and supporting sustainable environmental management. Among the various organisms used in biomonitoring, snails have emerged as valuable bioindicators because of their sedentary nature, wide distribution, intimate contact with soil and water, and remarkable ability to accumulate pollutants in their tissues and shells. Their digestive gland (hepatopancreas) serves as the primary organ for contaminant accumulation, detoxification, and storage, making it a highly sensitive biomarker for evaluating environmental pollution. Physiological, biochemical, histopathological, and molecular changes in snails provide reliable evidence of contaminant exposure and ecological stress, often before visible environmental damage becomes apparent.

This review highlights the biological and ecological characteristics that make snails suitable for environmental monitoring, including their high bioaccumulation capacity, tolerance to pollutant exposure, and measurable biological responses. It also emphasizes the mechanisms of heavy metal uptake and detoxification, the importance of the digestive gland as a biomarker, and the role of advanced analytical techniques such as Atomic Absorption Spectroscopy (AAS), Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP-OES), and Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) in accurately determining contaminant concentrations. The integration of these analytical methods with biochemical and molecular biomarkers has greatly improved the accuracy and sensitivity of environmental quality assessment. Numerous studies conducted worldwide demonstrate that terrestrial and freshwater snail species can effectively monitor heavy metals, pesticides, pharmaceuticals, microplastics, and other emerging contaminants. Because snails reflect the biologically available fraction of pollutants rather than only their environmental concentration, they provide a more realistic assessment of ecological risk. Their application in long-term biomonitoring programmes, ecological risk assessment, environmental impact assessment, and pollution surveillance further confirms their importance in modern environmental science. Despite these advantages, the interpretation of snail biomonitoring data should consider factors such as species-specific differences, age, seasonal variation, habitat characteristics, feeding behaviour, and pollutant bioavailability.

The adoption of standardized sampling protocols and integrated monitoring strategies will improve the consistency and comparability of future studies.

Overall, the available evidence strongly supports the use of snails as reliable and cost-effective bioindicators for environmental quality assessment.

Their unique biological characteristics, combined with advances in ecotoxicology, molecular biology, and analytical chemistry, make them indispensable tools for monitoring environmental contamination and protecting ecosystem health.

Future research should focus on combining conventional biomonitoring with genomic, proteomic, metabolomic, and geospatial approaches to enhance pollution assessment, strengthen ecological risk evaluation, and contribute to evidence-based environmental management and sustainable conservation of natural resources.

Author Contributions

Miriyala Leela Prasanna: Investigation, formal analysis, writing—original draft. Purushottam Sheshrao Neharkar: Validation, methodology, writing—reviewing. Milind M. Sonkamble:—Formal analysis, writing—review and editing. Anant Ganeshrao Lad: Investigation, writing—reviewing. Shraddha S. Dhurgude: Resources, investigation writing—reviewing. Faria S. Khan: Validation, formal analysis, writing—reviewing. K. Sriram: Conceptualization, methodology, data curation, supervision, writing—reviewing the final version of the manuscript.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

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