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Melanoides tuberculata as a Bioindicator of Freshwater Ecosystem: Ecological Significance, Environmental Monitoring, and Future Perspectives. A Review Paper

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ABSTRACT

Freshwater ecosystems are increasingly threatened by pollution, habitat degradation, urbanization, invasive species, and climate change, creating an urgent need for reliable biological indicators of environmental quality. This review critically evaluates the ecological significance and biomonitoring potential of *Melanoides tuberculata* as a bioindicator of freshwater ecosystem health. A structured narrative review, guided by PRISMA 2020 principles, synthesized peer-reviewed literature published between 2000 and 2026 retrieved from Scopus, Web of Science, ScienceDirect, SpringerLink, PubMed, and Google Scholar. The review examined the biology, ecological functions, pollutant bioaccumulation, responses to physicochemical stressors, biomonitoring applications, emerging contaminants, and future technological developments associated with *M. tuberculata*. Evidence demonstrates that the species is an effective indicator of environmental change owing to its broad geographical distribution, ecological adaptability, parthenogenetic reproduction, benthic lifestyle, and capacity to accumulate heavy metals, petroleum hydrocarbons, pesticides, nutrients, pharmaceuticals, and microplastics. Variations in population abundance, reproductive performance, shell morphology, physiological biomarkers, and tissue contaminant concentrations consistently reflected changes in water and sediment quality. The review further highlights the integration of environmental DNA (eDNA), molecular biomarkers, Geographic Information Systems (GIS), remote sensing, and artificial intelligence as emerging tools that can substantially improve freshwater biomonitoring. However, challenges remain, including habitat-specific responses, invasive population dynamics, seasonal variability, and the need for standardized biomonitoring protocols. Overall, *M. tuberculata* is a robust and cost-effective freshwater bioindicator whose integration with conventional ecological assessments and advanced molecular and spatial technologies will enhance environmental surveillance, ecological risk assessment, biodiversity conservation, and sustainable management of freshwater ecosystems, particularly in pollution-prone tropical regions.

Keywords: *Melanoides tuberculata*; bioindicator; ecological health; environmental monitoring; aquatic conservation.

INTRODUCTION

Freshwater ecosystems are among the most productive and biologically diverse ecosystems on Earth, providing essential services such as potable water, fisheries, irrigation, nutrient cycling, and biodiversity conservation. However, these ecosystems are increasingly threatened by anthropogenic activities, including industrial discharges, agricultural runoff, urbanization, oil exploration, habitat destruction, and

climate change, all of which have accelerated the deterioration of water quality and ecological integrity worldwide (UNEP, 2021; Dudgeon et al., 2024; Dudgeon et al., 2019). These environmental pressures have intensified the need for effective monitoring strategies capable of detecting ecological disturbances and supporting sustainable freshwater management (UNESCO, 2023).

Biological indicators (bioindicators) have become indispensable tools for environmental assessment because they integrate the cumulative effects of multiple environmental stressors over time. Unlike physicochemical parameters, which provide only instantaneous measurements of environmental conditions, bioindicators reflect the long-term biological responses of organisms to pollution and habitat alteration (Vadas et al., 2022; Ferreira-Rodríguez et al., 2023). Freshwater macroinvertebrates, particularly molluscs, are widely recognized as reliable bioindicators because of their relatively sedentary lifestyle, broad distribution, ease of sampling, and capacity to accumulate contaminants in their tissues (Lopes-Lima et al., 2025; Atkinson et al., 2023). Consequently, freshwater snails have become increasingly important in biomonitoring programmes aimed at evaluating ecological health and water quality.

Among freshwater gastropods, *Melanoides tuberculata* (Müller, 1774), a member of the family Thiaridae, has received considerable attention because of its remarkable ecological adaptability and wide geographical distribution across tropical and subtropical freshwater ecosystems (Ferreira-Rodríguez et al., 2023). The species inhabits rivers, lakes, reservoirs, wetlands, irrigation canals, and estuaries, where it functions as a benthic detritivore and grazer, contributing to nutrient cycling, sediment turnover, and trophic interactions (Pereira et al., 2020; Yap & Tan, 2021). In addition, *M. tuberculata* exhibits high tolerance to environmental stress, rapid reproduction, and the ability to bioaccumulate heavy metals, hydrocarbons, pesticides, pharmaceuticals, and other emerging contaminants, making it an excellent candidate for environmental monitoring and ecological risk assessment (Lopes et al., 2021; Ferreira-Rodríguez et al., 2023).

Recent advances in freshwater biomonitoring have further expanded the application of *M. tuberculata* through the integration of molecular biomarkers, environmental DNA (eDNA), geographic information systems (GIS), remote sensing, and artificial intelligence for environmental surveillance (Vadas et al., 2022; Clusa et al., 2017; GBIF 2024). Despite these developments, available information remains fragmented, and comprehensive syntheses integrating ecological, toxicological, and technological perspectives are still limited. This review therefore critically evaluates the ecological significance of *Melanoides tuberculata* as a bioindicator of freshwater ecosystem health by examining its biology, ecological functions, responses to environmental stressors, applications in biomonitoring, current knowledge gaps, and future research directions. The review provides an updated scientific framework to support freshwater ecosystem assessment, environmental management, and biodiversity conservation (Lopes-Lima et al., 2025; Atkinson et al., 2023; Ferreira-Rodríguez et al., 2023).

2. Review Methodology

2.1 Literature Search Strategy

This review employed a structured narrative review approach to identify, evaluate, and synthesize published literature on the ecological significance and biomonitoring potential of *Melanoides tuberculata*. To enhance transparency and reproducibility, the literature search was guided by the principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020;) for study identification, screening, and selection where applicable.

Electronic literature searches were conducted using six major scientific databases: Scopus, Web of Science, ScienceDirect, SpringerLink, PubMed, and Google Scholar. These databases were selected because they comprehensively index peer-reviewed literature in ecology, environmental science, freshwater biology, aquatic toxicology, and conservation biology.

The search included articles published between January 2000 and June 2026, with particular emphasis on studies published between 2020 and 2026 to ensure that the review reflects recent advances in freshwater biomonitoring and environmental assessment. Reference lists of selected publications were also examined

manually to identify additional relevant studies that were not retrieved during the electronic search. The search strategy combined keywords and Boolean operators to maximize retrieval of relevant literature. The principal search terms included: *Melanoides tuberculata*, *Melanoides* AND bioindicator, freshwater snail AND biomonitoring, aquatic gastropods AND environmental monitoring, freshwater molluscs AND heavy metals, ecological health assessment, water quality monitoring, freshwater pollution, bioaccumulation in freshwater snails, aquatic ecosystem health

2.2 Eligibility Criteria

Inclusion Criteria; Published in peer-reviewed scientific journals, written in the English language, published between 2000 and 2026, focused on *Melanoides tuberculata* or closely related freshwater gastropods in environmental monitoring, investigated ecological functions, pollution assessment, biomonitoring, bioaccumulation, aquatic toxicology, or freshwater ecosystem health and reported original research, review articles, or authoritative reports from recognized organizations.

Exclusion Criteria; Conference abstracts lacking full text, editorials, opinion papers, and unpublished reports, duplicate records retrieved from multiple databases, studies unrelated to freshwater ecology or environmental monitoring and articles lacking sufficient methodological or scientific information.

2.3 Data Extraction and Synthesis

Relevant information from eligible publications was extracted and organized into thematic categories. The extracted variables included publication year, geographical location, study objectives, habitat type, environmental stressors investigated, pollutants assessed, biological responses of *Melanoides tuberculata*, bioindicator applications, and principal findings. The synthesized literature was grouped under major themes including: Biology and ecological characteristics of *Melanoides tuberculata*, ecological functions in freshwater ecosystems, heavy metal bioaccumulation, responses to physicochemical stressors, applications in freshwater biomonitoring, emerging contaminants, environmental management and conservation and knowledge gaps and future research priorities. A qualitative synthesis was undertaken to compare findings across studies, identify consistent patterns, highlight contrasting evidence, and evaluate current trends in the application of *M. tuberculata* as a freshwater bioindicator (Page et al., 2021).

2.4 Quality Assessment

Priority was given to peer-reviewed articles published in internationally recognized journals indexed in Scopus, Web of Science, and PubMed. Greater emphasis was placed on recent publications (2020–2026), while seminal earlier studies were retained where they provided foundational knowledge on the taxonomy, ecology, and biomonitoring applications of *Melanoides tuberculata*. Information obtained from international organizations, including UNESCO (2023) and UNEP (2021), was incorporated where relevant to provide broader environmental context.

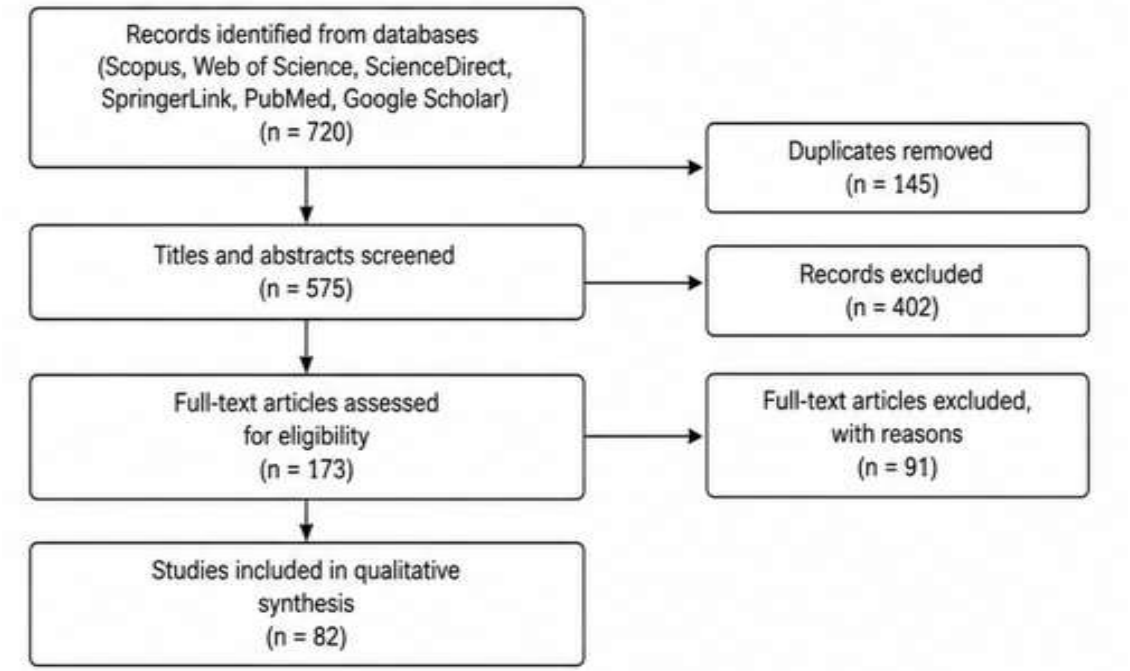

Figure 1. PRISMA 2020 flow diagram. **Source:** *Authors' illustration, developed following the PRISMA 2020 Statement (Page et al., 2021).*

3. Biology and Ecology of *Melanoides tuberculata*

3.1 Taxonomy and Geographic Distribution

Melanoides tuberculata (Müller, 1774) is a freshwater prosobranch gastropod belonging to the family Thiaridae and is one of the most widely distributed freshwater snails in tropical and subtropical regions of the world (Brusca and Giribet, 2022; Lopes-Lima et al., 2025). The species is believed to have originated in Africa and parts of Asia but has expanded its range through both natural dispersal and human-mediated introductions to Europe, the Americas, Australia, and numerous oceanic islands (Lopes-Lima et al., 2025). Its remarkable ecological plasticity has enabled it to colonize diverse freshwater habitats, including rivers, streams, lakes, reservoirs, wetlands, irrigation canals, ponds, and estuarine environments (Mahapatra et al., 2023; Lopes-Lima et al., 2025).

The successful global expansion of *M. tuberculata* has been attributed to its parthenogenetic mode of reproduction, high reproductive capacity, broad environmental tolerance, and efficient dispersal through aquaculture, the ornamental aquarium trade, and water transportation systems (Brusca and Giribet, 2022; Britton et al., 2023; Karatayev et al., 2007). Although frequently regarded as an invasive species outside its native range, *M. tuberculata* also performs important ecological functions within aquatic ecosystems and has become an increasingly valuable organism in environmental monitoring programmes.

3.2 Morphological Characteristics

Melanoides tuberculata possesses an elongated, turret-shaped shell composed of numerous whorls with distinct spiral ridges and nodules that vary considerably in colour and ornamentation depending on environmental conditions. Shell coloration ranges from light brown to dark olive with reddish or black markings, providing camouflage against benthic substrates. Adult shells generally measure between 20 and 40 mm in length, although larger individuals have been reported under favourable environmental conditions (Strong et al., 2021). The snail possesses a well-developed operculum that allows complete closure of the shell aperture during unfavourable environmental conditions such as drought, low dissolved oxygen, or pollutant exposure. This adaptation contributes significantly to its high environmental tolerance and survival under fluctuating freshwater conditions.

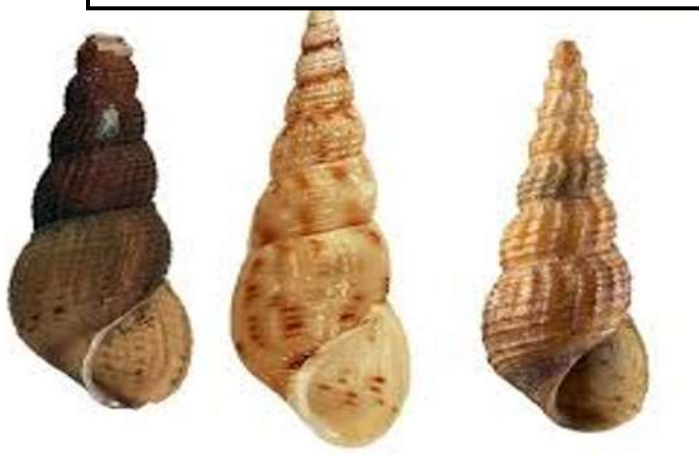

Plate 1: *Melanoides spp.* Source: Global Biodiversity Information Facility (GBIF). (2024). https://www.gbif.org (Accessed July 2026).

Table 1. Taxonomic Classification of *Melanoides tuberculata*

Taxonomic Rank	**Classification**
Kingdom	Animalia
Phylum	Mollusca
Class	Gastropoda
Subclass	Caenogastropoda
Order	Cerithioidea
Family	Thiaridae
Genus	*Melanoides*
Species	*Melanoides tuberculata* (Müller, 1774)

3.3 Habitat and Ecological Adaptation

Melanoides tuberculata inhabits a wide variety of freshwater ecosystems where it occupies benthic substrates rich in organic matter. The species is commonly found on muddy, sandy, rocky, and vegetated bottoms, often occurring in habitats characterized by slow to moderate water flow. It tolerates broad environmental gradients, including temperatures ranging from approximately 16°C to over 35°C, pH values between 6.0 and 9.0, and varying levels of dissolved oxygen and salinity (Geist et al., 2022; Mahapatra et al., 2023; Geist et al., 2022).

Its burrowing behaviour enables the snail to avoid predators, survive seasonal fluctuations, and exploit organic-rich sediments for feeding. The species also exhibits considerable tolerance to environmental contamination, allowing populations to persist in habitats affected by heavy metals, hydrocarbons, agricultural chemicals, and municipal wastewater (Preston et al., 2022). These characteristics have made *M. tuberculata* particularly useful for assessing ecological responses to anthropogenic disturbances.

3.4 Feeding Ecology and Ecological Functions

Melanoides tuberculata is primarily a benthic grazer and detritivore that feeds on algae, biofilms, bacteria, fungi, decaying plant materials, and fine organic particles deposited within sediments. Through continuous grazing and sediment bioturbation, the species contributes significantly to nutrient recycling, organic matter decomposition, and sediment oxygenation, thereby influencing ecosystem productivity and maintaining ecological balance (Hall et al., 2003).

As an important component of aquatic food webs, *M. tuberculata* serves as prey for numerous fish, crustaceans, reptiles, and water birds while simultaneously regulating microbial communities and periphyton biomass. These ecological interactions influence nutrient recycling, energy transfer across trophic levels and contribute to the resilience of freshwater ecosystems (Atkinson et al., 2023). However,

in regions where the species has become invasive, extremely dense populations may compete with native molluscs for food and habitat resources, potentially reducing local biodiversity.

3.5 Reproductive Biology and Population Dynamics

One of the most distinctive biological characteristics of *Melanoides tuberculata* is its predominantly parthenogenetic mode of reproduction, whereby females produce viable offspring without fertilization (Mahapatra et al., 2023). This reproductive strategy enables rapid population growth even when only a few individuals colonize a new habitat, facilitating successful establishment in diverse freshwater environments (Lopes-Lima et al., 2025; Preston et al., 2022).

Embryos develop within a brood pouch before being released as fully developed juveniles, resulting in relatively high survival rates compared with species exhibiting external egg development. Population density is influenced by water temperature, food availability, substrate composition, dissolved oxygen, and contaminant concentrations. Consequently, fluctuations in abundance and population structure have been widely used as biological indicators of environmental quality and ecological disturbance (Sankara et al., 2026; Mahapatra et al., 2023).

3.6 Ecological Importance in Freshwater Ecosystems

Beyond its value as a bioindicator, *M. tuberculata* performs several ecological functions essential to freshwater ecosystem stability. Its grazing activities regulate algal growth, while sediment mixing enhances nutrient availability and microbial activity (Lopes-Lima et al., 2025). The species also participates in the decomposition of organic matter, facilitating nutrient cycling and improving sediment quality.

Despite these ecological benefits, *M. tuberculata* may act as an intermediate host for several trematode parasites affecting fish, birds, livestock, and humans. This dual ecological role highlights the importance of continuous monitoring to balance its usefulness in environmental assessment with potential public health concerns (Lopes-Lima et al., 2025) Understanding these ecological interactions is fundamental for interpreting biomonitoring results and developing sustainable freshwater management strategies.

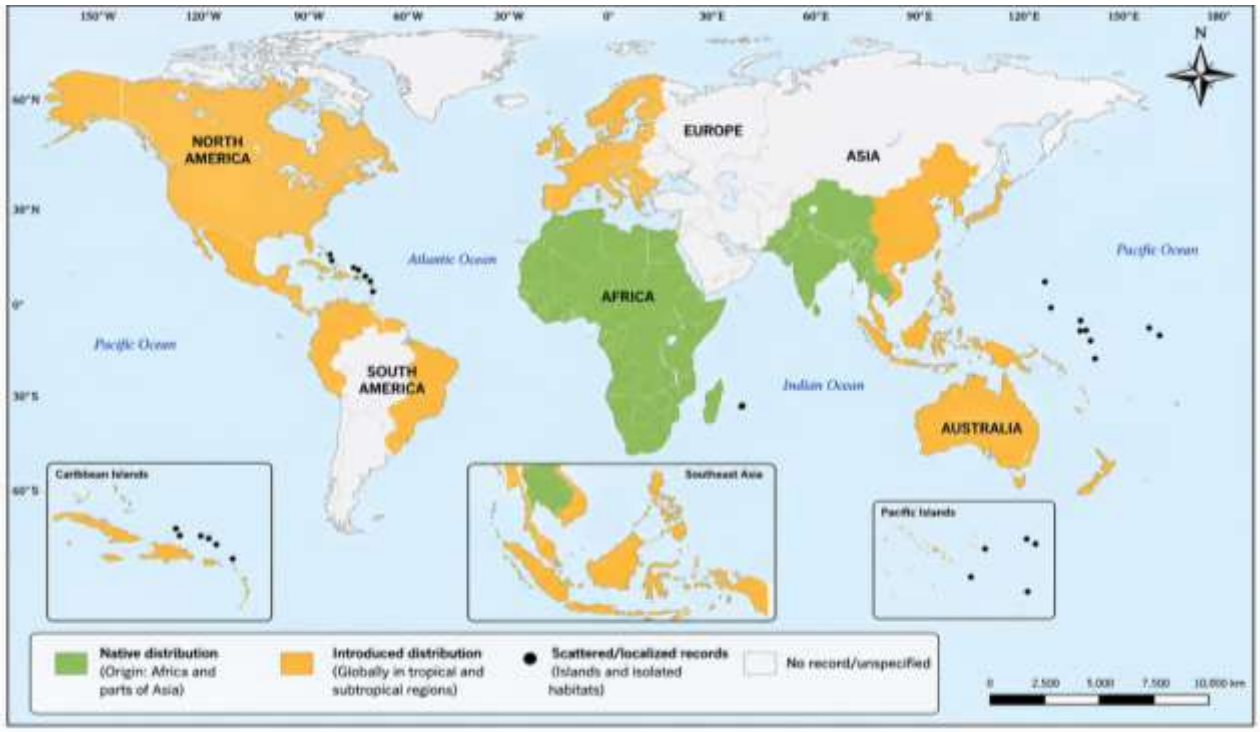

Figure 2. Global Distribution of *Melanoides tuberculata* (GIS-based world map produced in software such as QGIS or ArcGIS using verified occurrence data from repositories like the Global Biodiversity Information Facility (GBIF)**.** Source: *Authors' illustration based on published distribution records* (GBIF, 2024; Lopes-Lima et al., 2025)

4. Ecological Functions of *Melanoides tuberculata* in Freshwater Ecosystems

Freshwater gastropods perform fundamental ecological functions that contribute to ecosystem stability, nutrient cycling, and biodiversity maintenance. Among these organisms, *Melanoides tuberculata* has attracted considerable scientific attention because of its ecological versatility, broad environmental tolerance, and responsiveness to changes in aquatic habitats (Hall et al., 2003; Atkinson et al., 2023; Lopes-Lima et al., 2025; Vadas et al., 2022). Beyond its importance as a biomonitoring organism, *M. tuberculata* actively participates in several ecological processes that influence freshwater ecosystem functioning. Its interactions with sediments, microorganisms, algae, and higher trophic levels make it an important component of aquatic food webs and ecosystem dynamics (Sousa et al., 2009; Hall et al., 2006; Atkinson et al., 2023).

4.1 Role in Nutrient Cycling

One of the primary ecological functions of *Melanoides tuberculata* is its contribution to nutrient cycling within freshwater ecosystems (Hall et al., 2003; Atkinson et al., 2023; Lopes-Lima et al., 2025). The species feeds predominantly on detritus, periphyton, algae, bacteria, and decomposing organic matter deposited on sediments and submerged surfaces. During feeding, organic materials are fragmented into smaller particles that are more readily decomposed by microorganisms, thereby accelerating nutrient mineralization and recycling (Sumudumali & Jayawardana, 2021).

The continuous grazing activity of *M. tuberculata* enhances the release of nitrogen, phosphorus, and other essential nutrients back into the water column, increasing nutrient availability for primary producers. This ecological process contributes to maintaining ecosystem productivity, particularly in shallow freshwater habitats where benthic nutrient regeneration plays an important role in sustaining biological communities (Sousa et al., 2009; Hall et al., 2006; Atkinson et al., 2023). Studies have demonstrated that freshwater gastropods significantly influence microbial decomposition rates and nutrient turnover, thereby supporting ecosystem resilience under changing environmental conditions (Lopes-Lima et al., 2025).

4.2 Sediment Bioturbation and Ecosystem Engineering

Melanoides tuberculata is recognized as an important ecosystem engineer because of its burrowing activities within benthic sediments. Continuous movement through surface sediments promotes sediment mixing (bioturbation), improves sediment aeration, and facilitates oxygen penetration into deeper sediment layers. These activities stimulate microbial metabolism and enhance the decomposition of accumulated organic matter, thereby reducing anaerobic conditions that often characterize polluted aquatic environments (Ferreira-Rodríguez et al., 2023; Vadas et al., 2022).

Sediment bioturbation also modifies the physical structure of benthic habitats by redistributing fine particles and influencing sediment stability. Improved sediment oxygenation enhances nitrification and other microbial processes involved in nutrient transformation, contributing to improved ecological functioning. Consequently, variations in the abundance and activity of *M. tuberculata* populations may indirectly influence water quality and benthic habitat conditions, making the species ecologically significant beyond its role as a pollution indicator (Ladeiro et al., 2014).

4.3 Regulation of Periphyton and Algal Communities

As an efficient grazer, *Melanoides tuberculata* regulates the abundance and composition of periphyton and benthic algal communities. By feeding on attached algae and microbial biofilms, the snail prevents excessive algal accumulation on submerged substrates and helps maintain ecological balance within freshwater ecosystems. Controlled grazing reduces the likelihood of localized algal overgrowth and supports greater diversity among benthic microorganisms (Lopes-Lima et al., 2025).

However, ecological effects vary with population density. Moderate populations generally promote ecosystem stability, whereas extremely dense populations, particularly in invaded habitats, may substantially reduce periphyton biomass and alter community composition. Such changes can influence primary productivity and the availability of food resources for aquatic organisms (Strayer et al., 2019).

4.4 Contribution to Aquatic Food Webs

Melanoides tuberculata occupies an intermediate trophic position within freshwater food webs (Metz et al., 2023; Lu et al., 2018). The species functions as both a primary consumer and an important prey item

for numerous predators, including fishes, crustaceans, aquatic insects, reptiles, amphibians, and water birds. This trophic position facilitates the transfer of energy and nutrients from primary producers and detrital resources to higher trophic levels

Because *M. tuberculata* accumulates contaminants such as heavy metals and persistent organic pollutants within its tissues, predators consuming contaminated snails may experience secondary exposure through trophic transfer. Consequently, the species is increasingly used in ecological risk assessments investigating contaminant movement through aquatic food chains (Vereycken & Aldridge, 2022).

4.5 Bioaccumulation of Environmental Contaminants

The capacity of *Melanoides tuberculata* to accumulate contaminants from sediments, suspended particles, and water has made it one of the most useful freshwater biomonitoring organisms. Numerous studies have reported significant accumulation of lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), zinc (Zn), copper (Cu), nickel (Ni), arsenic (As), hydrocarbons, pesticides, and pharmaceutical residues in snail tissues (Ferreira-Rodríguez et al., 2023; Lopes-Lima et al., 2025; Sankara et al., 2026).

Unlike many aquatic organisms, *M. tuberculata* exhibits relatively high tolerance to contaminated environments, enabling long-term monitoring of chronic pollution. Tissue contaminant concentrations often correlate strongly with environmental contamination levels, allowing the species to serve as an effective biological indicator of pollution intensity and ecological risk (Ladeiro et al., 2014).

4.6 Ecological Resilience Under Environmental Stress

One of the defining ecological characteristics of *Melanoides tuberculata* is its remarkable resilience to environmental fluctuations. The species tolerates broad ranges of temperature, dissolved oxygen, salinity, pH, and nutrient availability, enabling populations to persist in habitats experiencing considerable anthropogenic disturbance. Its operculum provides protection during desiccation and oxygen depletion, while parthenogenetic reproduction facilitates rapid population recovery following environmental stress (Mahapatra et al., 2023).

Although this resilience supports its usefulness in biomonitoring, it also contributes to its invasive potential in many regions outside its native distribution. Consequently, ecological assessments should consider both the beneficial biomonitoring applications and the possible ecological impacts associated with invasive populations (Ladeiro et al., 2014).

Table 2. Ecological Functions of *Melanoides tuberculata* in Freshwater Ecosystems

Ecological Function	Ecological Importance	Environmental Significance
Nutrient cycling	Decomposition of organic matter and nutrient regeneration	Maintains ecosystem productivity
Sediment bioturbation	Mixing and aeration of sediments	Improves microbial activity and nutrient exchange
Periphyton grazing	Regulation of algal and microbial biofilms	Prevents excessive algal proliferation
Trophic interactions	Food source for aquatic vertebrates and invertebrates	Supports energy transfer within food webs
Bioaccumulation	Uptake of heavy metals and organic pollutants	Facilitates pollution monitoring
Ecosystem engineering	Modification of benthic habitat characteristics	Enhances ecosystem functioning

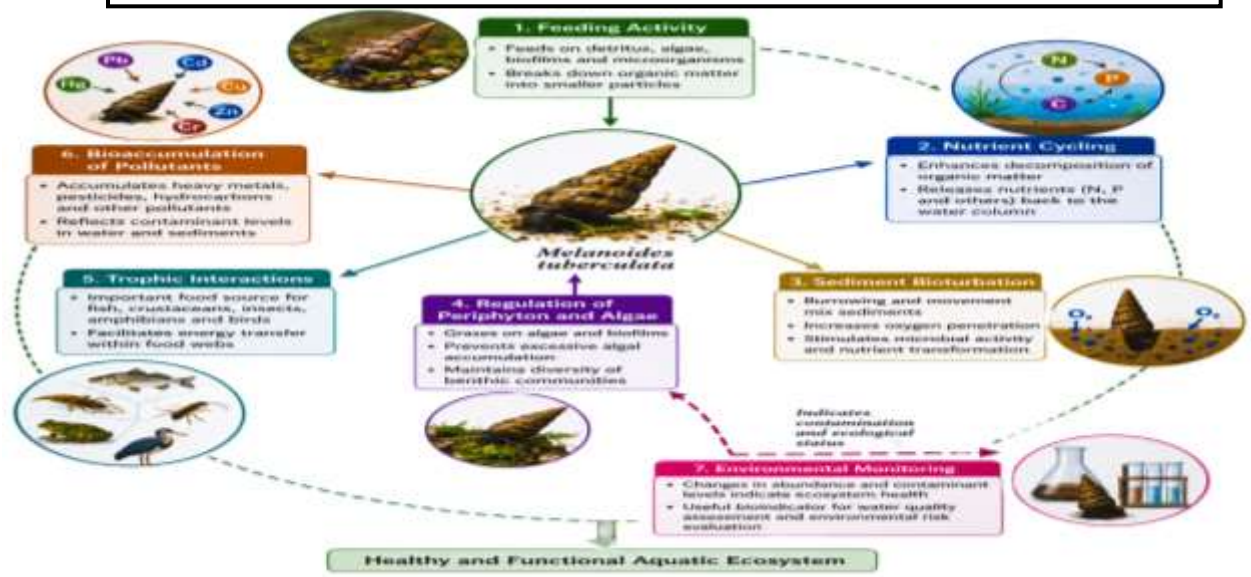

Figure 3. Ecological functions of *Melanoides tuberculata* in freshwater ecosystems, illustrating its roles in nutrient cycling, sediment bioturbation, regulation of periphyton and algal communities, trophic interactions, bioaccumulation of environmental contaminants, and environmental biomonitoring. **Source:** *Authors' illustration based on information synthesized from Sumudumali and Jayawardana (2021), Lopes-Lima et al. (2025), and Sankara et al. (2026).*

5. *Melanoides tuberculata* as a Bioindicator of Environmental Pollution

Freshwater ecosystems are increasingly exposed to diverse anthropogenic pollutants arising from industrialization, urbanization, agricultural intensification, mining, oil exploration, and domestic wastewater discharge. These contaminants alter physicochemical characteristics, disrupt aquatic food webs, and threaten biodiversity. Consequently, the use of biological indicators has become an integral component of environmental monitoring because biological responses provide more comprehensive assessments of ecosystem health than physicochemical measurements alone (Ferreira-Rodríguez et al., 2023; Atkinson et al., 2023; Sumudumali & Jayawardana, 2021). Among freshwater gastropods, *Melanoides tuberculata* has emerged as one of the most reliable bioindicator species due to its wide distribution, ecological resilience, relatively sedentary lifestyle, and exceptional ability to accumulate contaminants from both water and sediments (Preston et al., 2022; Mahapatra et al., 2023; Lopes-Lima et al., 2025).

Unlike many aquatic organisms that exhibit rapid mortality following pollutant exposure, *M. tuberculata* survives under moderate to high levels of environmental contamination while accumulating pollutants within its tissues. This unique characteristic enables the species to integrate contaminant exposure over extended periods, making it particularly useful for monitoring chronic pollution. Variations in population density, shell morphology, reproductive performance, physiological responses, and tissue contaminant concentrations have all been associated with environmental quality, allowing the species to provide valuable information on ecosystem disturbance and ecological risk (Lopes-Lima et al., 2025).

5.1 Heavy Metal Pollution

Heavy metals remain among the most persistent contaminants in freshwater ecosystems because they are non-biodegradable, toxic at relatively low concentrations, and capable of bioaccumulating within aquatic organisms. Industrial effluents, mining activities, petroleum exploration, agricultural runoff, municipal wastewater, and atmospheric deposition constitute major sources of heavy metal contamination in freshwater environments (UNEP, 2021).

Numerous investigations have demonstrated that *Melanoides tuberculata* effectively accumulates heavy metals including lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), nickel (Ni), zinc (Zn), copper (Cu), arsenic (As), manganese (Mn), and iron (Fe). Tissue concentrations generally increase with

increasing environmental contamination, making the species an effective biological monitor of metal pollution (Ferreira-Rodríguez et al., 2023; Lopes-Lima et al., 2025). Heavy metals accumulate predominantly within the digestive gland, soft tissues, and shell, where they may induce oxidative stress, enzyme inhibition, cellular damage, reproductive impairment, and reduced growth rates.

Comparative studies have reported significant positive correlations between heavy metal concentrations in *M. tuberculata* tissues and corresponding concentrations in water and sediments. Consequently, tissue analysis of *M. tuberculata* provides a time-integrated assessment of environmental contamination that complements conventional physicochemical monitoring. Recent biomonitoring programmes have increasingly utilized freshwater gastropods to evaluate ecological risks associated with industrial discharges and urban wastewater, particularly in tropical freshwater ecosystems where long-term monitoring data remain limited (Lopes-Lima et al., 2025).

5.2 Petroleum Hydrocarbons and Oil Pollution

Oil exploration, transportation, refining, and accidental spills represent major sources of hydrocarbon contamination in freshwater ecosystems, particularly within oil-producing regions such as the Niger Delta. Petroleum hydrocarbons alter sediment characteristics, reduce dissolved oxygen, impair microbial communities, and introduce toxic compounds capable of accumulating within aquatic organisms. (Atkinson et al., 2023; Ferreira-Rodríguez et al., 2023)

As a benthic detritivore, *M. tuberculata* is continuously exposed to hydrocarbon-contaminated sediments during feeding and burrowing activities. Studies have shown that chronic hydrocarbon exposure influences growth, reproduction, feeding behaviour, antioxidant enzyme activity, and survival of freshwater gastropods. Polycyclic aromatic hydrocarbons (PAHs) accumulated within snail tissues have therefore been proposed as useful biomarkers for evaluating chronic petroleum pollution and ecological recovery following oil spills (Vereycken & Aldridge, 2022).

The use of *M. tuberculata* is particularly relevant in petroleum-producing regions because sediment-associated contaminants often persist long after water quality appears to recover. Monitoring tissue contaminant concentrations alongside population dynamics provides valuable information regarding long-term ecosystem health and restoration success (Vereycken & Aldridge, 2022).

5.3 Agricultural Chemicals and Pesticides

Agricultural intensification has substantially increased the use of pesticides, herbicides, and fertilizers worldwide. Runoff from agricultural fields introduces these chemicals into freshwater ecosystems, where they may adversely affect non-target aquatic organisms. Gastropods are particularly vulnerable because they inhabit sediments where many pesticides accumulate (Vereycken & Aldridge, 2022).

Experimental studies have demonstrated that exposure to organophosphate insecticides, pyrethroids, glyphosate-based herbicides, and carbamate compounds alters feeding behaviour, reproductive performance, shell development, and antioxidant defence mechanisms in freshwater snails. Biomarker responses such as acetylcholinesterase inhibition, lipid peroxidation, and altered antioxidant enzyme activities have been proposed as sensitive indicators of pesticide exposure (Sumudumali & Jayawardana, 2021). The integration of physiological biomarkers with contaminant analyses enhances the usefulness of *M. tuberculata* as an early warning indicator of agricultural pollution (Atkinson et al., 2023).

5.4 Nutrient Enrichment and Eutrophication

Excessive nutrient inputs resulting from agricultural runoff, domestic wastewater, and industrial discharges have accelerated eutrophication in freshwater ecosystems worldwide. Elevated concentrations of nitrogen and phosphorus stimulate excessive algal growth, reduce dissolved oxygen concentrations, alter benthic habitats, and modify aquatic biodiversity (Geist et al., 2022; Vereycken & Aldridge, 2022)

Population characteristics of *M. tuberculata* often respond predictably to nutrient enrichment. Moderate increases in organic matter may initially promote population growth by increasing food availability, whereas severe eutrophication and oxygen depletion frequently reduce abundance, reproductive success, and community diversity. Consequently, changes in *M. tuberculata* populations may provide valuable indicators of trophic status and ecosystem degradation (Vadas et al., 2022).

5.5 Emerging Contaminants

Recent years have witnessed increasing concern regarding pharmaceuticals, personal care products, endocrine-disrupting chemicals, antibiotics, nanomaterials, and microplastics entering freshwater ecosystems. Although research involving *M. tuberculata* remains relatively limited compared with fish and bivalves, emerging evidence suggests that freshwater gastropods accumulate several of these contaminants and exhibit measurable physiological responses (Vereycken & Aldridge, 2022).

Exposure to pharmaceutical residues may influence reproductive biology, endocrine function, oxidative stress, and metabolic processes. Similarly, ingestion of microplastics has been associated with altered feeding behaviour, tissue inflammation, and reduced physiological performance in freshwater molluscs. These findings indicate considerable potential for expanding the application of *M. tuberculata* in monitoring emerging pollutants as analytical technologies continue to improve (Vereycken & Aldridge, 2023).

5.6 Comparative Advantages as a Bioindicator

Compared with many freshwater organisms, *Melanoides tuberculata* possesses several characteristics that enhance its suitability for environmental monitoring: wide geographical distribution, high abundance in diverse freshwater habitats, ease of collection and identification, relatively sedentary behaviour, high tolerance to environmental stress, significant bioaccumulation capacity, rapid reproductive rate, long-term integration of contaminant exposure and cost-effective field sampling. These characteristics have contributed to its widespread application in ecological monitoring programmes throughout tropical and subtropical freshwater ecosystems (Mahapatra et al., 2023; Preston et al., 2022).

Table 3. Environmental Pollutants Monitored Using *Melanoides tuberculata*

Pollutant Category	Typical Pollutants	Biological Response	Biomonitoring Application
Heavy metals	Pb, Cd, Hg, Cr, Cu, Zn, Ni	Bioaccumulation, oxidative stress	Heavy metal monitoring
Petroleum hydrocarbons	PAHs, crude oil residues	Tissue accumulation, reproductive effects	Oil pollution assessment
Agricultural pesticides	Organophosphates, carbamates, glyphosate	Enzyme inhibition, reduced reproduction	Agricultural pollution
Nutrients	Nitrogen, phosphorus	Population fluctuations	Eutrophication assessment
Pharmaceuticals	Antibiotics, hormones	Physiological alterations	Emerging contaminants
Microplastics	Plastic particles	Tissue inflammation, altered feeding	Plastic pollution monitoring

6. Applications of *Melanoides tuberculata* in Freshwater Biomonitoring

Freshwater biomonitoring integrates biological responses with physicochemical and ecological measurements to evaluate ecosystem health and detect environmental changes over time. Among freshwater molluscs, *Melanoides tuberculata* has become an important biomonitoring organism because it is widely distributed, relatively sedentary, tolerant of diverse environmental conditions, and capable of accumulating pollutants in its tissues. These characteristics enable the species to reflect both short-term and long-term environmental disturbances more effectively than many conventional water quality measurements (Vadas et al., 2022; Sumudumali & Jayawardana, 2021).

The use of *M. tuberculata* in biomonitoring has expanded considerably over the past two decades. Initially employed primarily for assessing heavy metal contamination, the species is now used to evaluate petroleum hydrocarbons, pesticides, nutrient enrichment, wastewater pollution, habitat degradation, invasive species dynamics, and the ecological effects of climate change. Recent advances in molecular biology and environmental genomics have further broadened its applications, making *M. tuberculata* an

increasingly valuable organism for integrated freshwater ecosystem assessment (Clusa et al., 2017; Thomas et al., 2020; GBIF, 2024).

6.1 Biomonitoring of Water Quality

Water quality assessment traditionally relies on measurements of physicochemical parameters such as pH, dissolved oxygen, temperature, conductivity, turbidity, biochemical oxygen demand, chemical oxygen demand, and nutrient concentrations. Although these variables provide valuable information regarding environmental conditions at the time of sampling, they often fail to capture cumulative biological effects resulting from chronic pollution (Vereycken & Aldridge, 2022; Vadas et al., 2022).

Because *Melanoides tuberculata* remains in close contact with sediments throughout its life cycle, it integrates environmental exposure over extended periods. Variations in abundance, shell morphology, reproductive success, growth rate, and tissue contaminant concentrations therefore provide valuable indicators of long-term ecological conditions. Several studies have reported significant relationships between *M. tuberculata* population characteristics and water quality parameters, supporting its application in routine freshwater monitoring programmes (Sankara et al., 2026; Vereycken & Aldridge, 2022).

6.2 Sediment Quality Assessment

Sediments function as long-term reservoirs for contaminants entering freshwater ecosystems. Heavy metals, petroleum hydrocarbons, pesticides, and organic pollutants frequently accumulate in benthic sediments where they remain biologically available to bottom-dwelling organisms (Reid et al., 2019).

Because *M. tuberculata* feeds directly on organic-rich sediments, contaminant concentrations in its tissues often reflect sediment quality more accurately than water samples alone. Consequently, freshwater monitoring programmes increasingly employ the species to evaluate sediment contamination, identify pollution hotspots, and assess ecological recovery following remediation activities. Sediment-associated monitoring is particularly valuable in wetlands, reservoirs, and oil-producing regions where pollutants persist within benthic environments long after water quality has improved **(**Vadas et al., 2022; Sankara et al., 2026).

6.3 Monitoring Heavy Metal Contamination

Heavy metal contamination remains one of the most widely investigated applications of *Melanoides tuberculata*. Tissue analyses have demonstrated significant accumulation of lead, cadmium, chromium, copper, zinc, nickel, mercury, manganese, and arsenic in populations inhabiting contaminated freshwater ecosystems (Vereycken & Aldridge, 2022)

Recent studies indicate that contaminant concentrations within *M. tuberculata* correlate strongly with metal concentrations in surrounding sediments and water, making the species an effective biological monitor of chronic pollution. In addition to measuring total metal concentrations, researchers increasingly investigate oxidative stress biomarkers, antioxidant enzyme activity, lipid peroxidation, metallothionein expression, and DNA damage to evaluate sub-lethal toxicological effects associated with heavy metal exposure (Vadas et al., 2022).

6.4 Biomonitoring in Oil-Producing Regions

Petroleum exploration and transportation frequently introduce crude oil and refined petroleum products into freshwater ecosystems. Hydrocarbon contamination alters benthic habitats, suppresses microbial activity, reduces dissolved oxygen, and affects aquatic biodiversity (Reid et al., 2019). The ecological characteristics of *M. tuberculata* make it particularly useful for assessing chronic hydrocarbon contamination. By measuring population dynamics, contaminant accumulation, and physiological responses, researchers can evaluate the ecological consequences of oil pollution and monitor ecosystem recovery following remediation programmes. This application is especially relevant in oil-producing regions such as the Niger Delta, where long-term biomonitoring remains essential for environmental management and restoration (Vereycken & Aldridge, 2022).

6.5 Ecological Risk Assessment

Ecological risk assessment integrates information on contaminant exposure, biological responses, and ecological consequences to evaluate potential environmental hazards. *Melanoides tuberculata* contributes to ecological risk assessment by providing information on contaminant bioavailability, bioaccumulation,

trophic transfer, and biological effects (Vadas et al., 2022). Population-level responses such as reduced abundance, altered reproductive success, shell abnormalities, and physiological stress may serve as early warning indicators of ecosystem degradation before more severe ecological damage becomes apparent. Consequently, *M. tuberculata* is increasingly incorporated into integrated ecological assessment frameworks that combine chemical analyses with biological monitoring (Vereycken & Aldridge, 2022).

6.6 Environmental DNA (eDNA) and Molecular Biomonitoring

Recent technological advances have transformed freshwater biomonitoring through the application of environmental DNA (eDNA), molecular biomarkers, transcriptomics, metabolomics, and environmental genomics. Environmental DNA enables the detection of aquatic organisms through genetic material released into water without requiring direct specimen collection (Clusa et al., 2017; Prié et al., 2023). Although molecular biomonitoring of *M. tuberculata* remains in its early stages, eDNA offers considerable potential for mapping species distributions, monitoring invasive populations, and detecting ecological changes across large freshwater systems. Similarly, molecular biomarkers including stress proteins, antioxidant enzymes, gene expression profiles, and DNA damage indicators may substantially improve the sensitivity of biomonitoring programmes by detecting pollutant effects before visible ecological changes occur (Clusa et al., 2017; Prié et al., 2023; Hernández Elizárraga et al., 2023).

6.7 Geographic Information Systems (GIS) and Remote Sensing

Geographic Information Systems (GIS) have become valuable tools for integrating biological monitoring with spatial environmental data. GIS enables researchers to map the distribution of *M. tuberculata*, identify pollution hotspots, evaluate habitat suitability, and examine relationships between snail populations and environmental variables (Abell et al., 2008). When combined with satellite remote sensing, GIS supports large-scale ecological assessments by linking biological observations with land use, vegetation cover, hydrology, rainfall, temperature, and watershed characteristics. These technologies are increasingly employed to prioritize conservation efforts, identify vulnerable freshwater habitats, and improve environmental management strategies under changing climatic conditions (Abell et al., 2008; Harrison et al., 2018).

6.8 Artificial Intelligence and Future Biomonitoring Technologies

Artificial intelligence (AI) and machine learning are emerging as powerful tools for freshwater ecosystem assessment. Automated image analysis can improve species identification, while predictive models integrating biological, physicochemical, and spatial datasets may enhance the prediction of pollution trends and ecological risks (Prié et al., 2023; Hernández Elizárraga et al., 2023; Sousa, 2024). Future biomonitoring programmes incorporating *M. tuberculata* are expected to combine AI-based image recognition, GIS, eDNA, remote sensing, and conventional field surveys to provide more comprehensive assessments of freshwater ecosystem health. Such integrated monitoring systems will improve early detection of environmental degradation and support evidence-based conservation planning (Prié et al., 2023; Hernández Elizárraga et al., 2023).

Table 4. Applications of *Melanoides tuberculata* in Freshwater Biomonitoring

Application	Biological Indicator	Environmental Significance
Water quality assessment	Population density, growth, reproduction	Detects long-term ecological changes
Sediment monitoring	Tissue contaminant concentrations	Indicates benthic pollution
Heavy metal monitoring	Bioaccumulation of Pb, Cd, Hg, Cr, Cu, Zn	Evaluates chronic contamination
Oil pollution assessment	Hydrocarbon accumulation and physiological responses	Monitors petroleum impacts
Ecological risk assessment	Biomarker responses and population health	Early detection of ecosystem stress
Environmental DNA (eDNA)	Species detection and distribution	Supports biodiversity monitoring
GIS and remote sensing	Spatial distribution mapping	Identifies pollution hotspots
Artificial intelligence	Automated species identification and predictive modelling	Enhances future biomonitoring

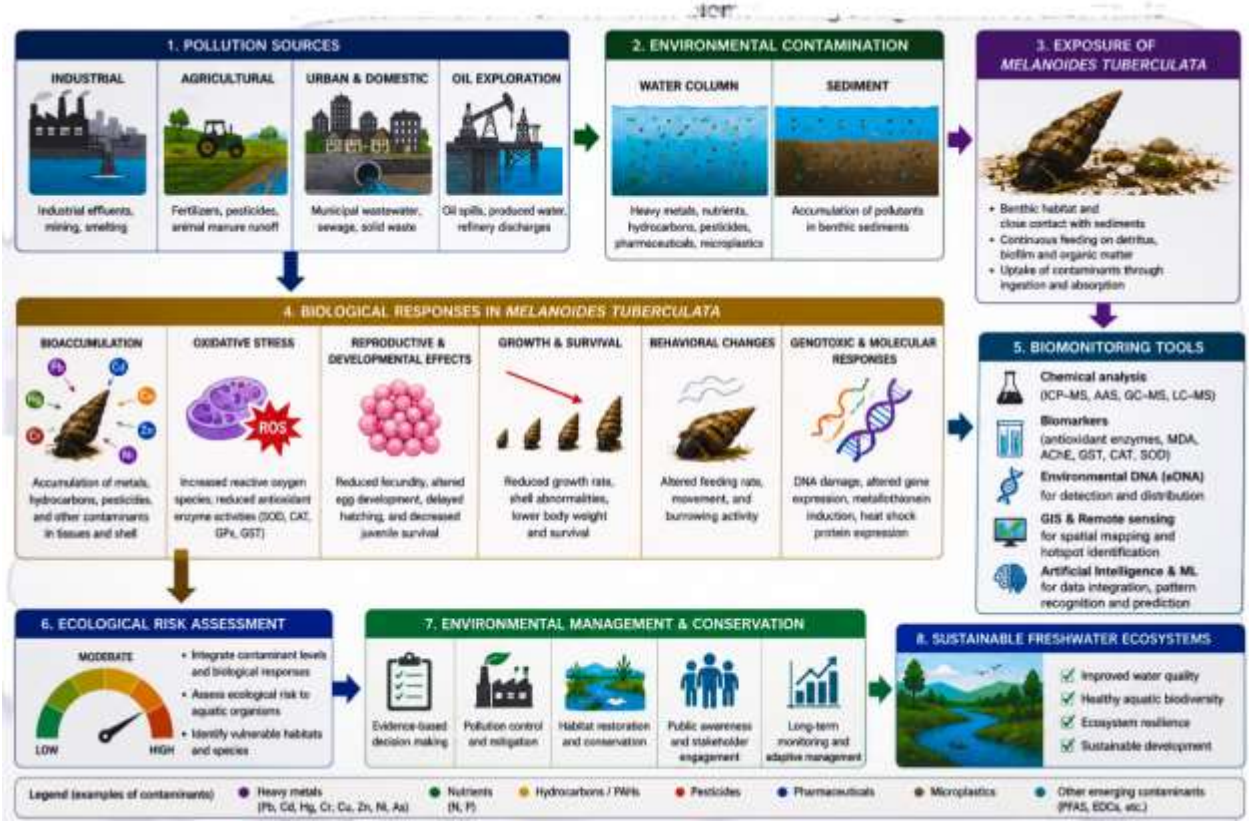

Figure 5. Integrated framework for freshwater biomonitoring using *Melanoides tuberculata*, illustrating the relationships among pollution sources, environmental contamination, biological responses, biomonitoring tools, ecological risk assessment, environmental management, and sustainable freshwater ecosystems. **Source:** Authors' illustration based on the synthesis of published literature (Sumudumali & Jayawardana, 2021; Vadas et al., 2022; UNEP, 2021; UNESCO, 2023; Lopes-Lima et al., 2025).

7. Comparative Analysis of Previous Studies on *Melanoides tuberculata* as a Bioindicator

Published studies consistently demonstrate that *Melanoides tuberculata* is an effective bioindicator of freshwater ecosystem health because of its wide distribution, ecological adaptability, and capacity to accumulate environmental contaminants (Pereira et al., 2020; Shuhaimi-Othman et al., 2022). Research has shown that changes in population abundance, tissue contaminant concentrations, and physiological responses closely reflect variations in water and sediment quality (Sankara et al., 2026; Vereycken & Aldridge, 2022).

Earlier investigations primarily focused on heavy metal bioaccumulation, while more recent studies have expanded to include petroleum hydrocarbons, pesticides, nutrient enrichment, and emerging contaminants. Recent advances have also incorporated oxidative stress biomarkers, environmental DNA (eDNA), Geographic Information Systems (GIS), and remote sensing to improve environmental monitoring (Vadas et al., 2022; Ferreira-Rodríguez et al., 2023).

Geographical differences in research priorities are evident. Studies from Asia have largely emphasized industrial pollution and heavy metals, whereas research from South America has focused on ecological distribution and biodiversity conservation (Clusa et al., 2017; Prié et al., 2023). In contrast, relatively few studies have investigated the application of *M. tuberculata* in African freshwater ecosystems, particularly in oil-producing regions such as the Niger Delta, despite the high levels of hydrocarbon contamination.

This highlights the need for increased biomonitoring studies across tropical African freshwater environments (Britton et al., 2023; Sousa, 2024).

Although available evidence confirms the suitability of *M. tuberculata* as a freshwater bioindicator, further research is needed to standardize biomonitoring protocols, integrate molecular biomarkers, and combine conventional ecological assessments with emerging technologies such as eDNA, GIS, remote sensing, and artificial intelligence. These advances will improve the accuracy of ecological assessments and support sustainable freshwater ecosystem management (Harrison et al., 2018; Reid et al., 2019).

Table 5. Comparative Summary of Selected Studies on *Melanoides tuberculata* as a Bioindicator

Authors	Country/Region	Major Focus	Key Findings
Sankara et al. (2026)	Burkina Faso	Population ecology and environmental drivers	Distribution and abundance of *Melanoides tuberculata* were strongly influenced by physicochemical characteristics, demonstrating its usefulness as an indicator of freshwater ecosystem condition.
Vereycken & Aldridge (2022)	Global Review	Molluscs as biosensors of water quality	Freshwater molluscs effectively integrate contaminant exposure over time and provide reliable indicators of water and sediment quality for biomonitoring programmes.
Ferreira-Rodríguez et al. (2023)	Global Review	Freshwater molluscs as environmental sentinels	Freshwater molluscs are valuable sentinels for monitoring contaminant bioavailability, ecosystem degradation, and long-term environmental change.
Sumudumali & Jayawardana (2021)	Global Review	Pesticide biomonitoring	Aquatic macroinvertebrates, including freshwater molluscs, effectively detect pesticide contamination through physiological and biochemical responses.
Lopes-Lima et al. (2025)	Global Review	Non-native freshwater molluscs	Highlighted the ecological importance, invasion pathways, environmental impacts, and management of freshwater molluscs as indicators of ecosystem health.

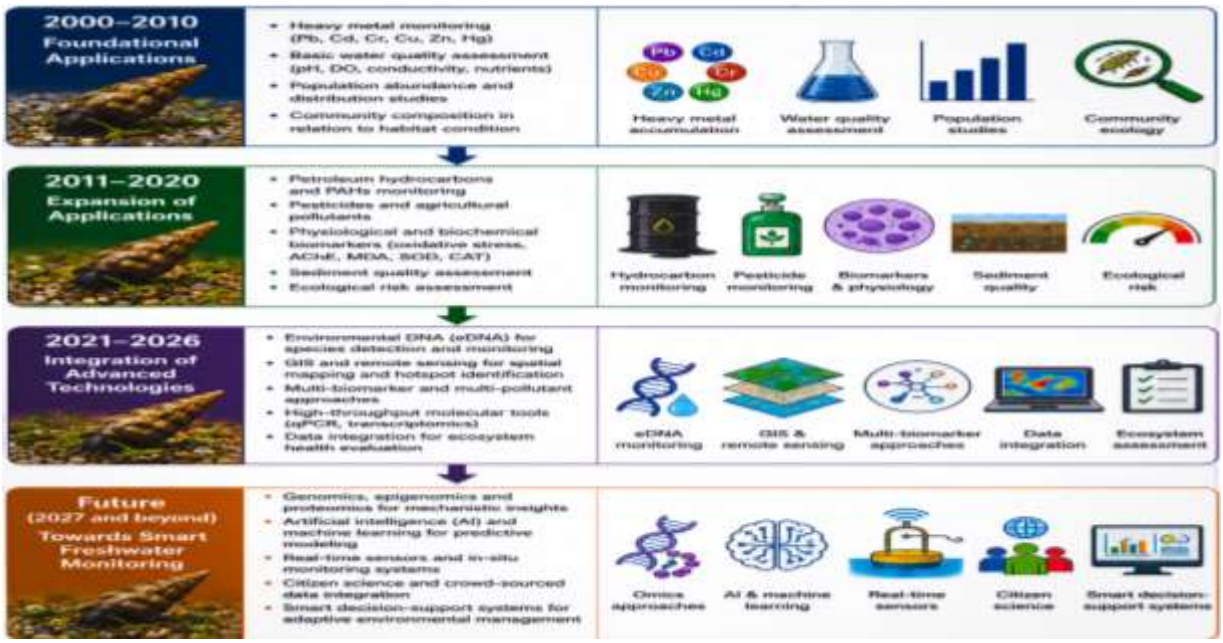

Figure 6. Evolution of biomonitoring applications of *Melanoides tuberculata* from conventional pollution assessment to integrated molecular and digital freshwater monitoring. **Source:** Authors' illustration based on the synthesis of published literature (Sumudumali & Jayawardana, 2021; Vadas et al., 2022; Page et al., 2021; UNEP, 2021; UNESCO, 2023; Lopes-Lima et al., 2025).

CONCLUSION

Melanoides tuberculata is an important freshwater bioindicator because of its ecological adaptability, wide distribution, and ability to accumulate environmental contaminants. The evidence reviewed indicates that the species is valuable for assessing water quality, monitoring pollution, and evaluating freshwater ecosystem health. Integrating *M. tuberculata* into routine biomonitoring programmes, together with emerging technologies such as environmental DNA (eDNA) and Geographic Information Systems (GIS), will enhance environmental monitoring, support informed management decisions, and contribute to the conservation and sustainable management of freshwater ecosystems.

RECOMMENDATION

Researchers and environmental agencies should incorporate *Melanoides tuberculata* into routine freshwater biomonitoring programmes and integrate conventional ecological assessments with emerging technologies such as eDNA, GIS, and artificial intelligence to improve pollution detection, ecological risk assessment, and sustainable freshwater ecosystem management.

Contribution to Knowledge

This review provides an updated synthesis of the ecological significance and biomonitoring potential of *Melanoides tuberculata* as a freshwater bioindicator. It highlights the integration of conventional ecological assessments with emerging tools such as eDNA, GIS, remote sensing, and artificial intelligence, while identifying key research gaps and future directions for improving freshwater ecosystem monitoring and management, particularly in tropical regions.

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