Int Aquat Res (2025) 17:297–311
https://doi.org/10.22034/IAR.2025.2009583.1928

REVIEW

Macrobenthic communities as sentinels of freshwater ecosystem health: a systematic review

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Received: 29 June 2025 / Accepted: 25 November 2025 / Published online: 10 December 2025

Abstract In aquatic environments, macrobenthic communities are essential. They are crucial elements of the food chain and significant markers of the ecosystem's health. The selection of sampling and reference points in inland open water bodies like rivers, streams, reservoirs, and dams significantly impacts the assessment of macrobenthic assemblages through proper methodologies. Evaluating macrobenthic communities aids in identifying possible pollutants in aquatic environments, which include heavy metal contamination, industrial waste, organic pollution, and pesticide runoff, all of which have the potential to affect the composition and operations of these communities significantly. Both biotic (living organisms) and abiotic (non-living environmental) elements affect macrobenthic populations. Their surrounding conditions influence these populations' distribution, density, diversity, and abundance. The effects of these interactions can be either beneficial or detrimental, depending on their nature. This review examines the impact of pollution and seasonal variations on macrobenthic communities in inland aquatic environments, especially rivers, dams, and reservoirs. The review emphasizes that, despite numerous studies, foundational data on freshwater macrobenthic populations remain insufficient in many areas around the globe.

Keywords Health assessment . Freshwater . Diversity . Macrobenthos . Ecological integrity

Introduction

Increasing industrialisation has a negative influence on ecosystems through a variety of interactions. Currently, human activities and natural disasters have a significant impact on all types of ecosystems, including marine, brackish, and freshwater (Neto et al. 2010; Wang et al. 2020). Furthermore, inland open water bodies are important to ecosystem health and long-term growth. Numerous studies have found that macrobenthic communities are vital for the nutrient cycle, primary production, maintaining health through interaction, bio-indicators, energy source, decomposer, transport of materials within the ecosystem, etc. (Koperski 2011; Meena et al. 2019; Sarkar et al. 2020). Macrobenthic communities are plant and animal groupings that spend part or all of their lives on bottom substrates or sediments and are little bigger than a 0.5-mm mesh screen. Macrobenthos are invertebrate species that lack a backbone and dwell in sediment or on the bottom surface (Siddig et al. 2016). Furthermore, macrobenthic communities' patterns, distribution,

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and abundance vary depending on the kind of habitat, such as a river, marsh, reservoir, or lake. Rivers have the highest biodiversity, species richness, and abundance, followed by wetlands, land, and dams (Koperski 2011). The common macrobenthos communities in inland open water bodies are polychaete, oligochaete worms, gastropods, bivalves, crustaceans, fish, and insect larvae. The taxonomically macrobenthos are more varied in size and can live in the littoral to sublittoral zone of aquatic environments. Moreover, biological, chemical, and physical factors in their environment can influence the survival and growth of macrobenthic communities (Darif et al. 2016).

In addition to being a significant source of food for animals over the whole water column, the macrobenthic community takes part in the biogeochemical cycle of elements including carbon, nitrogen, and sulphur (Li et al. 2020). In addition to providing a variety of ecological functions, including bioturbation, remineralization, and filtration, macrobenthos are an essential part of the benthic ecosystem and serve as a food source for fish, larger invertebrates, and birds (Ysebaert et al. 2003). According to Borja et al. (2012), physicochemical factors, sediment texture, organic content, and Pollution affect the variety and distribution of macrobenthos most. A more reliable option for assessing freshwater river health is the benthic communities (Borja et al. 2000). Pollution can change the species composition, assemblage pattern, and ecosystem functioning of macrobenthos in addition to environmental factors (Rosenberg 1976).

The concept of ecosystem health management originated in the early 1990s, and many researchers have focused on various elements of aquatic ecosystems, including macrobenthos. Many researchers discovered that Pollution, excessive nutrients, habitat loss, harmful components, and other variables all impact ecosystem health (Fu et al. 2021). Evaluating aquatic ecosystems through the macrobenthic community aids in understanding the degree of damage, amount of pollution, type of hazardous materials, impacts on aquatic animals, and preventative actions that may be implemented as policymakers determine. Various studies on heavy metals (Zn Cu Hg and AS), microplastics, and organic pollutants identify and characterize diatoms, planktons, and macroinvertebrates, respectively (Forio et al. 2017; Łuczyńska et al. 2018; Vanapalli et al. 2021). Moreover, the assessments of ecosystem health give information on aquatic ecosystems and provide knowledge for scientific management to improve the ecosystem's health according to UN goals that will lead to sustainable livelihoods. Maintaining ecosystem health via macrobenthic communities helps preserve and sustain the rich biodiversity for future generations and ensures the healthy functioning of ecosystems.

The abundance or richness of macrobenthic communities in freshwater ecosystems is directly controlled through predation and feeding (Hou et al. 2020). Ecology researchers are paying more attention to studies that look at the value of macrobenthic organisms as ecological indicators, because of their limited mobility, comparatively fixed habitat, and great susceptibility to environmental changes, benthic animals offer more reliable ecological indicators than fish and zooplankton. Moreover, macrobenthos, especially invertebrates, are used to track changes in freshwater ecosystems. Several ecological assessment techniques have been developed, and habitat assessments centered on benthic fauna are used in several countries' environmental monitoring (International Organisation for Standardisation, ISO 1979). Based on available literature, this review focuses on biotic and abiotic influences on the macrobenthic communities for the healthy functioning of freshwater ecosystems, the significance and advantage of bio-indicator species for species distribution, and Bibliometric analysis.

Factors influencing macrobenthic communities in inland open water bodies

The freshwater ecosystem functioning is primarily influenced by the abiotic and biotic factors that directly control the diversity, composition of species, species richness, ecological health, and water quality. Generally, the distribution of macrobenthos in freshwater ecosystems varies with depth, available dissolved oxygen, light penetration, substratum, available nutrients, and degree of stability (Hou et al. 2020). Abiotic factors such as dissolved oxygen, pH, biological oxygen demand, salinity, temperature, pollution, sedimentation, and substratum surface determine the relative abundance and pattern of distribution in aquatic ecosystems (Ge et al. 2024). Whereas biotic parameters include invasion or introduction of new species, changes in the food web or trophic level, and eutrophication can increase or decrease the macrobenthic communities via different interactions (Khim et al. 2021; Chowdhury et al. 2024). These factors are intercorrelated with freshwater ecosystem functioning and the health of macrobenthic communities. As a result, monitoring specific ecosystems and evaluating environmental health are made possible by the interplay between biotic and abiotic elements.

Temperature

In plants and animals, temperature is crucial in determining how conducive the environment is for their survival, development, reproduction, abundance, community structure, etc. (Chowdhury et al. 2024). Each microorganism has a specific temperature range for growth and reproduction. Polychaete worm (*P. popular*) females showed higher hatching with a larger size at higher temperatures (24 °C), and significant survival was shown from 21 to 24 °C, with an inverse relation with decreasing temperature and growth and survival. Similar to another worm (*B. proboscidea*), temperature did not affect brood size, but the highest survival was recorded at colder temperatures (12 °C) and the lowest at higher temperatures (24 °C) as per the study by David and Simon (2014). We can assume that each species has a specific range of physiological responses to temperature changes and modifies its functional characteristics according to the surrounding environment. Due to temperature changes, the organism's physiological response will increase or decrease, subsequently affecting the density and pattern of distribution of the benthic community. Generally, macrobenthos' highest densities were observed in warm water, but the highest biodiversity was in cold temperatures (Chowdhury et al. 2024). Das et al. (2023) studied the altitudinal and seasonal effects on the distribution of macrobenthic communities of the Yamuna River tributary. The authors reported that the abundance of macrobenthos was less during the pre-monsoon period due to high temperature, high velocity of water, and turbidity. Because the increased summer temperature will reduce the percentage of sediment, and seawater intrusion at the estuary will increase.

Sedimentation

Freshwater ecosystem structure, size, abundance, density, and diversity are intimately related to the type of sediment roughness and surface shape used in sediment sorting. Generally, macrobenthos densities are higher in coarse sediments than in clay sediments. The sediments of ecosystems can provide information about pollution and its consequences on flora and fauna. According to Dernie et al. (2003), the biotic dispersion pattern will be studied using different amounts of sand, silt, and clay. Macrobenthic communities generally thrive in sediments with diverse compositions and average organic content. Macrobenthos, such as Oregon pill bugs (*G. oregonensis*) and Baltic clams (*M. balthica*), are utilized as bioindicators because of their feeding behavior and resistance to physical-chemical changes to assess pollutants (Sizmur et al. 2019). In nature, sediments have a negative charge; therefore, sediments directly bind heavy metals and do not settle in aquatic habitats. Hess et al. (2017) discovered that increased suspended particles in water impair the gill lamellae structure of *A. melanopus*, reduce coral abundance, and become more turbid. These findings conclude that sediments impact macrobenthic populations in aquatic habitats, whether directly or indirectly. Sediments with finer-grained and less homogenized particles often exhibit greater habitat variety.

Dissolved oxygen

DO is a vital factor affecting macrobenthos communities' distribution in freshwater ecosystems, which is significantly associated with the Shannon–Wiener index, Simpson index, and Evenness index. DO is necessary for the physiological process in macrobenthic communities for metabolism and catabolism, and its concentration directly or indirectly alters the mechanisms inside the body. Typically, accessible DO in freshwater habitats was directly controlled by water temperature and depth, changing the species richness of organisms (Chowdhury et al. 2024). Water depth is exceptionally high in large wetland or pond habitats, and macrobenthic free dissolved oxygen availability is limited. As a result, density and variety are low compared to the ecosystem's coastline or edge. Martien and Benke (1977) investigated the distribution and reproduction of two crustacean macroinvertebrates. The study discovered that macroinvertebrates slow or even stop their food digestion in a hypoxic environment. Due to the accumulation of hydrogen sulfide, flooding, inadequate drainage, and low interstitial oxygen concentrations, the macrobenthic community's distribution is impacted by oxygen deficiencies in intertidal sediments (Sarkar et al. 2005).

The number of macrobenthos taxa decreased with increasing depth, leading to a deficiency of oxygen levels in the aphotic zone. Chironomid larvae, oligochaete worms, and other macrobenthos are abundant in the euphotic zone (Çelik KemaL 2002). DO availability is one of the most important factors impacting the diversity and composition of macroinvertebrate populations, and the quantity of DO varies by region. Das et al. (2023) investigated the altitudinal and seasonal influences on the distribution of macrobenthic populations in the Yamuna River tributaries. The abundance of macrobenthic communities was higher between November and January at 1150-1287 meters altitude, although Sharma and Rawat (2009) found the opposite result. The synergistic impacts of abiotic variables, such as reduced turbidity, improved transparency, low water velocity, and high DO, may lead to the increased prevalence of macrobenthic communities. Das et al. (2023) noted that the available dissolved oxygen does not influence the macrobenthic community in the upper stream of the river. In contrast, it can affect the lower stretch of the river. As per the study of Nelson et al. (2000) dissolved oxygen in wetlands plays a significant role in macroinvertebrate population composition. A higher abundance of the macrobenthic community marked at the edge of a flowing river is a favourable site due to the water quality and sufficient amount of dissolved oxygen throughout the season.

pH and BOD

Water quality parameters such as pH and biological oxygen have a negative relationship; increasing one decreases the other. The BOD requirement increases with the increasing depth of water, and the pH decreases, particularly in the large water bodies (wetlands, ponds or dams), because of the higher acidification or chemical oxygen demand at the bottom. These parameters directly influence the distribution and abundance of macrobenthos in freshwater habitats (Bendary et al. 2023). According to Walag and Canencia (2016), pH fluctuations significantly impact macroinvertebrate birth and survival rates, affecting ecosystem function and diversity. The optimal pH is ideal for macrobenthos survival and reproduction. The number and biomass of macroinvertebrates are reduced in high BOD concentrations, which may cause stress on macrobenthic ecosystems. According to Hou et al. (2020), gastropods (*Bellamya guadrata*) and oligochaetes (*Limnodrilus udekemianus*) have a low pH tolerance and a negative relationship with pH. Typically, high BOD values indicate that more organic pollutants in the water lead to high pollution of water bodies. The pH does not directly influence the macrobenthic community in the upper stream of the river, whereas it can affect the lower stretch of the river according to Das et al. (2023). The authors observed the distribution of macroinvertebrates, especially the *Epeorus* sp., *Leptocerus* sp., *Attenella* sp., *Apatania* sp., and *Leucrocuta* sp., in the river affected by river water quality. As per Tayung et al. (2022), the lacustrine zone of the reservoir contains the lowest abundance of macrobenthic community due to the sediments, low pH, and BOD at the bottom of the reservoir, which led to unfavourable conditions for the organisms. The species of Oligochaete, such as *Limnodrilus hofmeisteri*, *Tubifex tubifex*, and *Branchiura sowerbyi,* can be used as biomarkers for organic pollution in the inland aquatic ecosystem, according to Tayung et al. (2022).

Biological or invasion of species

Humans have primarily introduced invasive plants and animals, either on purpose or by mistake, which has resulted in a decline of biodiversity worldwide through adverse impacts on the ecosystem. As per Lin et al. (2015), about 9.5% of negative impacts on local environments and reduced the species in China. These species can cause habitat destruction, loss of local biodiversity, predation on native species, etc., leading to the malfunctioning of aquatic ecosystems. According to Spaulding and Elwell (2007), the introduction of *D. geminate* into water bodies in New Zealand has changed the distribution and abundance of aquatic base species, affecting ecosystem function. Additionally, his mutation may change the diet of salmonids as per Shearer et al. (2007). Gillis and Chalifour (2010) investigated the impact of *Didymosphenia geminata*, an invasive algae, on the macrobenthic ecosystem in the Matapedia River. The researchers noted that the sparse distribution of proliferations on the riverbed may have contributed to the growth in macrobenthic species. However, the ecosystem, its interactions, and favorable circumstances may be positively or negatively affected by introducing species for reclamation or other purposes.

Water pollution

In freshwater environments, water pollution is a serious issue that immediately impacts the local flora and fauna. Many types of pollutants can cause water pollution, including chemicals, pesticides, heavy metals, thermal water, and an excess load of nutrients. Many researchers have studied the effects of water pollution on water quality parameters such as pH, dissolved oxygen, alkalinity, hardness, available dissolved carbon dioxide, turbidity, heavy metals, etc., through the release of sewage and industrial water (Malik et al. 2020). Wang et al. (2022) conducted a study on the assessment of heavy metals in the Heihe River of China and their effects on macrozoobenthos in inland rivers. The authors found that the heavy metal concentration and macrobenthos correlate positively. Basommatophora densities are highly influenced by the available concentration of Pb and Cr in surface waters, and Mn was positively correlated with Araneae.

Trends of macrobenthic communities in inland open water body

Generally, a macrobenthic community in inland open water depends on various factors for habitat, such as chemical, physical, and biological factors. A freshwater ecosystem consists of many microorganisms on the bottom or substrate that help macrobenthos survive and reproduce. In the river ecosystem, macrobenthos distribution varied according to the spatial variation, and the highest diversity was found in the lower stretch of the river because of high nutrients, low velocities, and warmer temperatures, which help aquatic microorganisms grow. However, in wetland and reservoir ecosystems, the distribution of macrobenthic communities depends on the zonation, available light, water quality parameters, pollution, etc., which affect the diversity, composition, species richness, and dominance.

Various studies indicate that the majority of river ecosystems consist of Ephemeroptera, Plecoptera, Trichoptera, Diptera, Coleoptera, Amphipoda, Decapoda, Isopoda, Gastropods, Bivalves, Oligochaetes, Hirudinea, Cnidarians, fish, etc. (Koperski 2011; Das et al. 2023; Sun et al. 2024). Moreover, the abundance of crustaceans, molluscs, and annelids accounts for more than 80% found in the majority of rivers throughout the globe (Sun et al. 2024). The rain flow, water velocity, seasons, available water content, nutrients, and water quality highly influenced the trends of distribution of the macrobenthic community in the river. As per the study of Sun et al. (2024), arthropods accounted for 80% in each dry and wet season in Jingui River, but a significant difference was found in the number of species of Diptera, Odonata, Trichoptera, Decapoda, and Megastropoda across all seasons. Moreover, the study found that biomass, density, and abundance were highest in the wet season compared to the dry season. Assemblage and distribution of macrobenthos are highly variable, depending on the bottom or substrate in aquatic ecosystems (Table 1).

The river ecosystems contain more silt and clay, have higher diversity, and are richer in macrobenthos than gravel and sandy bottoms. High nutrients are available in slow-flowing rivers, which consist of high organic load and sedimentation. Yang et al. (2023) observe that the functional biodiversity, abundance, biomass, and distribution of the macrobenthic community are highly correlated with the velocity of water and sedimentation. Moreover, macrobenthos species diversity and functional diversity are directly or indirectly controlled by the available concentration of total nitrogen, ammonia nitrogen, conductivity, and hydrogen ions. Many reports indicate that water quality parameters, nutrient availability, pollution, and seasonal variation influence abundance, distribution, assembly pattern, species richness, and macrobenthic communities (Azrina et al. 2006; Dittmann et al. 2015; Feng et al. 2025).

Macrobenthic community varies in wetland and reservoir systems through zonation, light penetration, available food, temperature, and suitable environment for species richness, diversity, assembly pattern, and abundance to maintain the health of ecosystems. Generally, water depth and available substrate influence the macrobenthos. The study conducted by Meena et al. (2019) on the structure and assembly pattern of macrobenthos in the wetland of the lower Gangetic plains of India found that the diversity of macrobenthic communities is quite different. In the Akaipur wetland, the average Simpson index was 0.7. The Shanon index was 1.7, and the highest value was in the monsoon and winter season, followed by bivalvia, diptera, and oligochaeta.

In contrast, the Khalsi wetland showed the highest dominance of gastropods, which includes *Gabbia orcula*, followed by *Gyraulus convexiusculus*, *Thiara granifera*, and *Thiara lineata*. The distribution pattern, assembly pattern, species richness, and dominant species are directly controlled by the physicochemical characteristics of water as per Meena et al. (2019). The report suggested that the crustaceans, molluscs, annelids, fishes, and other invertebrates are commonly found in wetland ecosystems (Meena et al. 2019; Tayung et al. 2022). However, dry and high temperatures reduced the water level and subsequently de-

Table 1 Effects of abiotic and biotic factors influence the macrobenthic communities in different parts of the world

Water bodies	Index or analysis method	Dominant species	Effects of variable	Country	Reference
Langat River	Simpson and Shannon: significant	Ephemeroptera and chironomid dipterans in upper streams and Oligochaeta and Hirudinea in lower streams of river	Water quality parameters like pH, ammonia, DO, BOD and temperature have direct relation	Malaysia	Azrina et al. (2006)
Yuqu River	Redundancy analysis	Ephemeroptera, Plecoptera, Trichoptera, and Diptera	Dry and rainy season significantly affect the environmental factors including TDS, temperature and DO	China	Ge et al. (2025)
Nile river	Redundancy Analysis	Oligochaeta followed by Chironomidae larvae	Na, DO, SiO_4, and pH were influence the occurrence of taxa	Egypt	Bendary et al. (2023)
Tons River	Shannon and Simpson: significant	Ephemeroptera and Trichoptera	The environmental variable have positive correlation with *Attenella* sp., Baetis sp., *Apatania* sp., *Psilotreta* sp., and *Leptocerus* sp	India	Das et al. (2023)
Chishui River	Redundancy Analysis	In upper streams, middle reaches Othacladius sp., Chironomus sp. and Atyridae sp. and Chironomus sp., *L. hyalinus*, *P. liuiui* in lower reaches of river	A four variables including total dissolve gas, salinity, pH and DO were the main chemical factors affecting macrobenthic community structure	China	Feng et al. (2025)
River system	Margalef and Shannon-Wiener, Canonical correspondence analysis	Baetidae, Caenidae and Chironomidae	Turbidity has positive effects on species richness and evenness and less steep bank increase the biodiversity. Chlorophyll a can used as indictor for phytoplankton abundance and available nutrients in ecosystem.	Philippines	Forio et al. (2017)
Matapedia River	Simpson's Evenness Index	Ephemeroptera, Plecoptera, and Trichoptera	The introduction of *D. geminata* in river system decrease the following taxa Ephemeroptera, Plecoptera, and Trichoptera	Canada	Gillis and Chalifour (2010)
Jingui River	Principal Component Analysis, RDA, Friedman tests	Arthropods followed by molluscs, annelids	Dry season consist more species than the wet season and higher DO were reported in wet season. Available water temperature, rain, pH, turbidity and depth are critical parameters for macrobenthic community.	China	Sun et al. (2024)
Derjang reservoir	Shannon–Wiener, Pielou evenness, Margalef richness and Simpson dominance	Oligochaeta followed by Insecta, Gastropoda, and Bivalvia	Water quality parameters such as total alkalinity, air temperature, and water temperature were the deterministic variable infuencing the distribution, community structure, and abundance of macrozoobenthos fauna	India	Tayung et al. (2022)
Khalsi and Akaipur wetland	Shannon–Wiener, Pielou evenness, Margalef richness and Simpson dominance	Gastropod in khalsi wetland and *Tubifex tubifex* in Akaipur wetland	In Akaipur wetland, majority of the macrozoobenthos were positively influenced by DO, Alkalinity, Hardness, Electrical Conductivity and pH, whereas in khalsi wetland, macro-zoobenthos were positively influenced by Phosphorus, water depth and water temperature	India	Meena et al. (2019)
Wetland	Shannon–Wiener, Pielou evenness, Margalef richness and Simpson dominance	*Phragmites australis*	Available water depth, moisture content, organic matter, total nitrogen, and total carbon, and low salinity and hardness directly control the macrobenthic community.	China	Li et al. (2016)
Wetland	Shannon–Wiener, Pielou evenness, Margalef richness and Simpson dominance	Oligochaeta followed by branchiopod, diptera, Lymnaeidae	Restoring natural habitat and macrobenthic community in wetland local participation and continuous hydrological flow to maintain the environment.	USA	Meyer and Whiles (2008)

creased the richness, dominance, and biomass of the macrobenthic community. During high temperatures, metabolic rates are higher, and only thermophiles or Europhiles can survive in an environment. The higher incidence of Oligochaeta in wetlands and reservoirs indicates polluted water bodies, and that particular macrobenthos might be adapted to the environment. Water quality parameters highly influence the macrobenthic community in the reservoir and wetland ecosystem. Because of stagnant water bodies, many wetlands and reservoirs have higher alkalinity and pH.

We can conclude that the dominant species, assembly pattern, biomass, abundance, and distribution of macrobenthic communities do not follow any particular trends in inland open water bodies. Parameters like water quality, pollution, availability of oxygen and energy, habitat, nutrients, and suitable temperature directly or indirectly control the macrobenthos in aquatic ecosystems. However, many researchers reported that Gastropoda and Mollusca are most commonly found in all types of water bodies.

Different indices to estimate the macrobenthic communities

Macrobenthic community assessment is essential to comprehending ecological health and environmental effects. Some indices have been created to assess these communities, each with unique advantages and uses. These indices aid in evaluating the ecological quality of various habitats and tracking environmental changes.

BOPA Index

The impact of the oil spill on the macrobenthic community structure of the rocky intertidal study region was assessed using the Benthic Opportunistic Polychaetes Amphipods (BOPA) index, which was developed by Dauvin and Ruellet (2007). It is helpful when Polychaeta and Amphipoda are sufficiently represented in the community and correlate well with sediment hydrocarbons. When comparing the percentage ratios of amphipods and opportunistic polychaetes, BOPA values are high in polluted regions and low in favorable conditions.

AMBI and M-AMBI

For monitoring coastal environments and evaluating benthic quality, MBI (AZTI’s Marine Biotic Index) and M-AMBI (Multivariate AMBI) are reliable and often utilized (Borja et al. 2014). Benthic species are classified into five Ecological Groups (EGs): EGI (susceptible species), EGII (indifferent to enrichment), EGIII (tolerant to excess OME (organic matter enrichment), EGIV (second order opportunistic species), and EGV (first order opportunistic species). The AMBI index is a univariate measure that employs a “differential weighting” algorithm. On a scale of 0 to 7, the ecological quality of the estuary was divided into five classes using the AMBI index scores (0-1.2: high, 1.2-3.3: good, 3.3-4.3: moderate, 4.3-5.5: poor, and >5.5: awful). Species richness, the Shannon-Weiner diversity index, and AMBI scores are the three components that go into creating the multimeric index known as M-AMBI. On a scale of 0 to 1, the samples were classified into five classes using the M-AMBI scores (>0.77: high, 0.77–0.53: good, 0.53–0.38: moderate, 0.38–0.20: bad, and <0.20: sour).

Shannon-wiener diversity index

According to Sarkar et al. (2005), the ominance and Evenness indices show the fraction of common species and the relative number of individuals in the sample, respectively, whereas the Shannon–Wiener diversity index takes into account the richness and proportion of each species. A mathematical method used to ascertain the heterogeneity of the samples is the basis for the application of this index to biological systems. Among the several diversity indices, it is the most favoured one. The values of the index range from 0.0 to 5.0. Rarely do results surpass 4.5, usually falling between 1.5 and 3.5. The habitat structure is stable and balanced when the values are over 3.0; pollution and habitat structure degradation are indicated by values below 1.0 (Akbar et al. 2013).

Simpson index

Simpson's index can be defined in a variety of ways. However, the original and simplest definition is the likelihood that two individuals picked randomly from an assemblage belong to the same species. It is, therefore, a measure of dominance, and the likelihood of drawing two individuals from the same species will be high (near 1). This is especially true for highly dominated (i.e., extremely unequal) assemblages. Drawing two individuals from the same species in an even collection is only possible when every individual is a member of a separate species. Since more even assemblages are typically considered more diverse, this scaling seems contradictory because high values indicate low diversity. As a result, the index is frequently transformed from a dominance measure into an evenness (or equitability) measure by either taking the inverse of the dominance value or removing it from 1. Simpson's index is comparatively independent of sample size when compared to other richness and evenness metrics. Its straightforward definition also offers estimating techniques that do not necessitate in-depth taxonomic knowledge (Somerfield et al. 2008).

ISEP index

The Inverse Shannon–Wiener Evenness Proportion (ISEP) index assesses ecological quality by examining species-abundance-biomass patterns. It has shown significant correlations with environmental factors like suspended solids and applies to various sediment habitats. The ISEP index is a variation of Shannon and Wiener's evenness percentage. Based on multivariate biological data, ISEP generates a one-dimensional depiction of the state of benthic quality. However, due to the dimensionality reduction, these indices were not intended to pinpoint the impact factors that cause environmental deterioration in a given area. According to Yoo et al. (2022), these indices need to be able to reliably and consistently depict environmental state in a variety of settings and ecosystems using a simple ordered score or category unit. Yoo et al. (2010) assessed the ISEP's effectiveness over a range of coastal regions and circumstances, including habitat types, stress gradients, sample size fluctuations, and a control-impact comparison. The results demonstrate that the ISEP is an effective and robust index for the studied region during his study.

BENTIX index

This biotic index (Bentix) was created to classify the ecological quality status of soft substrate macrozoobenthic populations while fitting the benthic ecosystem. It reacts well to both human activity and environmental stressors. Depending on the idea of indicator species, Bentix employs the relative proportions of two broad ecological classes of species: "tolerant" and "sensitive," which are categorized depending on how sensitive or tolerant they are to disturbance causes (Simboura and Zenetos 2002).

Average taxonomic distinctness (Δ+)

Taxonomic distinctness (TD) measures changes in taxonomic structure by combining species richness and phylogenetic diversity (Leira et al. 2009). Clarke and Warwick established the widely used taxonomic distinctness indices, which determine the average "distance" between every pair of species in a community sample (Clarke and Warwick 1998). In the last two decades, biological conservation and assessments of the terrestrial and marine environments have used the average and variation in taxonomic distinctness. Pollution indicators or taxa may influence the effectiveness of taxonomic distinctness. When used appropriately, taxonomic distinctness indexes can help evaluate environmental degradation; however, they are not appropriate for immediately evaluating environmental quality in a new location before efficiency testing. Taxonomic diversity is evaluated, and the disturbance state is indicated by this indicator. Community structure and biodiversity in estuaries and adjacent marine environments have been assessed using it (Hu and Zhang 2016). Although these indices offer important information about the health of macrobenthic communities, they are not without limits and can produce varying outcomes based on the environmental setting. To enhance ecological evaluations, for example, genomic-based indices such as the genetics-based Marine Biotic Index (gAMBI) are being created to supplement conventional morphology-based indices.

Deficiency in ecological restoration of aquatic habitat

Healthy ecological habitat restoration is related to the resuscitation of a polluted or damaged place via ecosystem traits and functioning. However, several hurdles and concerns are involved with the ecological restoration of contaminated sites. Dam building, drought, pollution, deterioration of water quality, and other criteria can all directly impact the ecological restoration process in aquatic ecosystems. In most cases, ecological processes are restored by introducing only one or two species to the afflicted location. Because of the complexity and rigidity of understanding the healthy operation of an ecosystem for a single species, it is not easy to define the precise contribution of a particular bioindicator species. Adding a few species to a dynamic ecosystem for ecological restoration cannot meet the criteria. The oversimplification method of bioindicator species for restoration will lead to inadequate knowledge of how each species interacts with the others for their survival and physiological processes.

The free-flowing river received a large quantity of water, material, and energy during the processes, including rainfall, drainage, erosion, and biological production, which directly control the available diversity of the river ecosystem. Furthermore, industrial countries significantly impact freshwater ecosystems by dumping organic waste, fertilizers, and toxins into streams, lakes, and free-flowing rivers, which eventually reach coastal seas. Sewage treatment plants dealt with low oxygen levels, biological oxygen demand, and organic loading. The high levels of phosphate and nitrate in most surface water bodies have considerably enhanced the risk of eutrophication. As a result, there is still a scarcity of data on water quality metrics and how to reduce issues using biological, physical, or chemical methods to address the restoration process.

Experts and planners are paying close attention to sustainable urban development due to the impacts of rapid urbanization and growth, particularly in emerging economies. Achieving high-quality urban objectives and building an environment that fosters equality for present and future generations are necessary for long-term urban development (Liu et al. 2023). Other negative repercussions of human activity include the direct deposition of solid, liquid, and sand pollutants and poor agricultural practices, such as chemical fertilizers and improper waste disposal. The destruction of vegetation and soil contraction are two of the most significant effects of urbanization on coastal areas. Urbanization and impermeable surfaces significantly influence coastal habitat richness, variety, density, and biomass, as well as changes in fish populations and nutritional structure (Lundholm and Marlin 2006; Ntombela and Celliers 2015). Drought and changing hydrological conditions will significantly influence river ecology and biodiversity. Drought directly affects aquatic animals by lowering water levels and giving them less habitat (Aspin et al. 2019). Its indirect consequences include increased interspecific competition and changes to natural food sources.

Importance of macrobenthic community for assessment of ecosystem health

Assessment of aquatic ecosystem and surveillance

Generally, macrobenthic communities are sessile or slowly movable and have longer lifespans, which can offer precise information on ecology over a long time. Due to the confined life cycles and less movement, knowledge of changing environments in specific areas provides data over long periods, and long life gives data over long periods, and analyzes the combined impact of environmental stressors. The surrounding environment directly controls their life cycle. Moreover, any changes like pollution, habitat degradation, deterioration of water quality parameters, etc., reflect effects on the macrobenthic communities. The short and long-term impacts on specific species of macrobenthic community make more reliable sense for conservation and assessment of ecosystem health (Borja et al. 2000)

Evaluation of pollution and contaminants via macrobenthic community

Macrobenthic communities provide a direct means of information on the biological impacts of any anthropogenic activities on aquatic ecosystems (Sharma and Chowdhary 2011). In the past, ecological assessments frequently measured contaminant levels without considering their impact on organisms' health or ecosystems' structure. Researchers can determine the actual effects of environmental stressors by monitoring the health, population dynamics, and behavior of indicator species (Siddig et al. 2016). For instance, a study of a tropical bay system revealed that the abundance of sensitive taxa had decreased and the dominance of small-sized opportunists had increased, suggesting long-term environmental stress and anthropogenic pressure (Ormerod et al. 2010). According to Sumudumali and Jayawardana (2021), this sensitivity also makes it possible to identify minor environmental changes early on, serving as a warning system for ecological disturbances and preventative mitigation actions.

Bibliometric analysis

The Bibliometric is useful for analyzing a large number of publications, trends in publication, and authorship shared by different countries. The occurrence of common keywords across research hotspots can be clearly shown through bibliometrics. It accumulates the research data from databases (Web of Science, Scopus, Google Scholar, Microsoft Academic, Crossref, and Dimensions) used for quantitative analysis. Due to the non-availability of the research database automatically from Google Scholar, Microsoft Academic is prone to mistakes in document matching (Rathinam et al. 2022).

In order to assist researchers in determining research gaps in specific subject areas related to macrobenthos and ecosystem health management, data are collected that indicate research trends, prominent countries in the research field areas, renowned authors and their collaboration patterns across the globe. It will also help academics create productive research networks and partnerships; the productive nations, organizations, journals, and authors were examined from a management perspective.

The most productive country, authors, subject area and publication trends

The most prolific authors have been ranked based on their total number of publications. United States, China, Italy, Portugal, France, United Kingdom, India, Australia, Spain, Germany and Brazil dominate macrobenthos and ecosystem health management of aquatic ecosystems compared with other countries worldwide. Most of these publications are research articles, numbering 1152 (93%), followed by conference papers (38), book chapters (23), review articles (20), data paper (2), Letter (1), and errata (1). Figure 1 presents a graph showing the distribution of different publication types on macrobenthic comminutes in freshwater ecosystems as health assessment tools. The majority of publications on macrobenthic communities in freshwater ecosystems were published by publication house such as “Elsevier” with 278 articles (22.47%) followed by “Springer” with 126 articles (10.18%), “Academic Press” with 48 articles (3.88%), “Frontier media S, A” with 34 articles (2.74%), “MDP” I with 27 articles (2.18%), “Inter-research” with 22 articles (1.77%) and so on (Table 2).

The scientific collaboration in research area between these nations is therefore more essential. Overall, 78.65 % out of 100% of papers came from among these countries, and Chinese scholars published the highest number of papers (10.82%), followed by United States scholars (10.59). A total 1237 number of papers were published in various fields of domain, which encompasses multidisciplinary subjects. To furnish the available data on Scopus, we analyzed limited subject areas such as agricultural and biological sciences, environmental sciences, earth and planetary science and multidisciplinary. This domain covers various aspects, including macrobenthos, health, **a**nd freshwater benthic communities.

Table 2 lists the top 10 authors and countries with the highest number of publications in the field of macrobenthic communities for ecosystem health management.

Countries	No. of Publication	Authors	No. of Publication
China	134	Barnes	11
United States	131	Bertoli	9
Italy	105	Camargo	9
France	101	Thrush	9
Portugal	84	Chen	8
United Kingdom	81	Pacheco	6
Spain	81	Valdivia	6
Germany	68	Park	6
India	65	Rodil	6
Australia	62	Sivadas	5

Co-occurrence of keywords

One of the most effective techniques in scientific domain to identify, following development is co-occurrence analysis of terms. Generally, keywords are used by researcher in their titles, abstracts and titles. Moreover, the finding of particular keywords help to authors to correlated with subject area and discipline. Co-occurrence of keywords maps shows how the maturity and emphasis of research have changed throughout time. In this study, VOSviewer was utilized to create a co-occurrence network of keywords related to macrobenthic communities in freshwater ecosystem as health management tool, displaying it on a two-dimensional map. Keywords co-occur when they appear together in the same title, abstract, or citation context (Sedighi 2016). In this study, a minimum co-occurrence threshold of 10 was set, resulting in 995 keywords meeting the criteria out of 8001 total keywords, with 1,000 keywords selected by default.
They keywords such as "macrobenthos", "community structure", "biodiversity", "ecosystem" and "non-human animals" are widely occurring with highest linked. A total 9 cluster were identified in this study: Cluster I (red) with 328 items (e.g., benthos, abundance. Abiotic stress, ecosystem resilience), Cluster II (green) with 159 items (e.g., copper, metal, bioassay, community ecology), Cluster III (purple) with 131 items (e.g., agriculture, aquatic species, arthropoda), Cluster IV (light green) with 111 items (e.g., biological invasion, ecosystem health, China), Cluster V (blue) with 88 items (e.g., benthic fauna, organic matter, aquatic species), Cluster VI (sky blue) with 58 items (e.g., benthic fauna, organic matter, aquatic species), Cluster VII (golden drop) with 43 items (e.g., macro fauna, eutrophication, gastropod), Cluster VIII (light brown) with 41 items (e.g., estuaries, India, water pollutant), and Cluster IX (light blue) with 36 items (e.g., Mediterranean sea, southern Europe, lagoons). The network visualization of these keyword co-occurrences is shown in Figure 1.

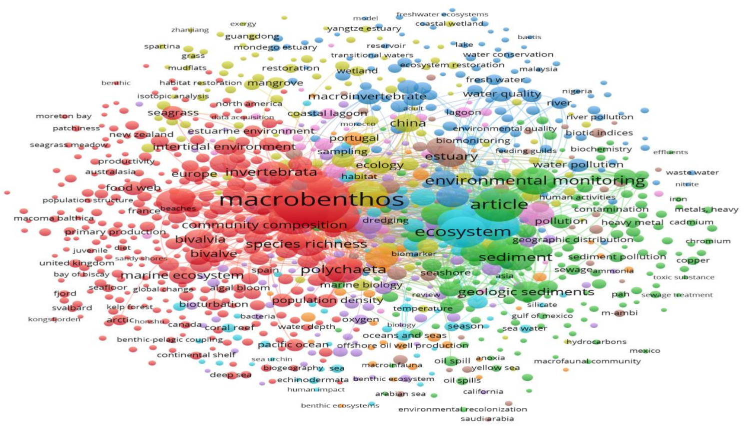

Fig. 1 Network visualization of the co-occurrence of keywords. Each node represents the number of keywords

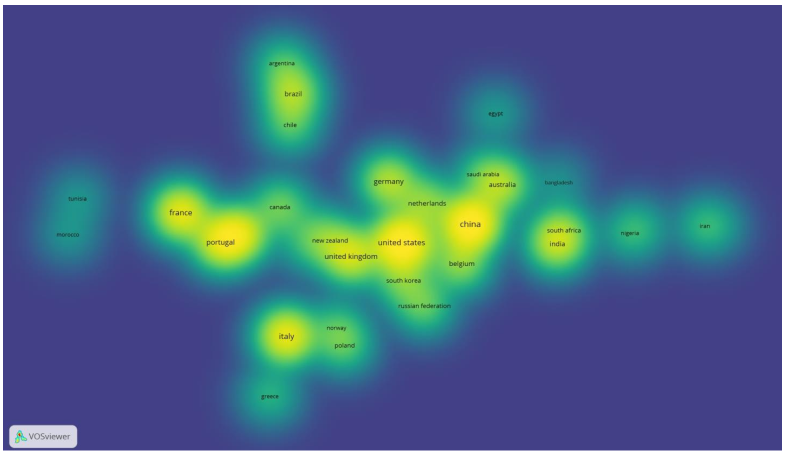

Fig. 2 Density visualization of the co-authorship shared by number countries. Each node represents the number of keywords

Future road map for the management of macrobenthic communities in the freshwater ecosystem

Freshwater ecosystems contribute significantly to the world's socio-economic development through their diversity in production. Human exploitation of freshwater ecosystems is based on the vast array of natural products and services. However, to continue using the resources, the processes and phenomena that lead to the creation of productivity and the maintenance of the biota must be maintained. The ecosystem's health for proper functioning is regarded with optimum disturbance and maximum utilization of ecological niches in environments. However, due to the various types of interaction among different kinds of benthos, communities serve as the ecosystem's primary maintainers, enhancing productivity. Biomonitoring of macrobenthic communities helps assess pollution, water quality parameters, species distribution, eutrophication, health of the ecosystem or other contaminants present in aquatic ecosystems. Various government policies and plans can be implemented through biomonitoring programs to revive freshwater ecosystems and help conserve the future. Futuristic holistic development can be achieved via genomic study and effects of abiotic or biotic factors on composition, assembling the pattern, diversity, species richness, pollution effects and so on macrobenthic communities of the freshwater ecosystem by databases. A streamlined database should be developed for a nation for each significant ecosystem for further research and enrichment programs.

Conclusion

Macrobenthic communities are essential for the health of aquatic ecosystems due to their influence on abundance, distribution, diversity, and the utilization of niches. These organisms, found across different taxonomic groups, facilitate sediment modification, nutrient cycling, and the stability of food webs through various interactions. They are commonly employed as bio-indicators in marine, brackish, and freshwater environments, as shifts in their distribution or diversity frequently indicate environmental changes. Freshwater ecosystems, in comparison to marine ones, exhibit lower species diversity and fewer abiotic resources, rendering them more susceptible to human-induced impacts. The composition and functioning of freshwater macrobenthic communities are significantly affected by the physical and chemical characteristics of the water, which in turn influence the diversity of other plant and animal species. Seasonal shifts often lead to variations in species composition, generally resulting in lower biodiversity during winter and summer compared to the rainy season. To enhance our understanding and management of ecosystem health, both theoretical and empirical studies are essential. This discussion emphasizes the value of various macrobenthic groups—including annelids, mussels, gastropods, and bivalves—as useful indicators for monitoring and managing the health of freshwater ecosystems.

Acknowledgements The authors would like to acknowledge Director, ICAR-CIFRI for providing necessary guidance and support.

Competing interests The authors declare no competing interests.

Authors' Contributions Dhamendra Kumar Meena: Visualization, Validation, Conceptualization, Writing – review & editing, Sanjaykumar Karsanbhai Rathod: Formal analysis, Methodology, Bibliometric writing, writing – review & editing, Shailendra Kumar: Writing – review & editing, Ravi Baraiya: Writing – review & editing, Soibam Ngasotter: Writing – review & editing, Basanta Kumar Das: Facilitation, Software, Writing – review & editing, Anil Verma: Writing – review & editing.

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