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Review Article

The Role of Rotifera as Sentinel Organism of Trophic Structure on Freshwater Ecosystems

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Abstract— For determining the trophic condition of freshwater ecosystems, rotifera, a phylum of tiny and near-microscopic pseudocoelomate creatures, are important sentinel or bioindicator species. For ecological monitoring and water quality evaluation, they are perfect because of their species composition, variety, and abundance, which react quickly and sensitively to changes in environmental quality and nutrient availability. Aquatic environments consist of both biotic and abiotic interactions. There is a relationship between these things. They create an ecosystem's cumulative environmental condition, which can be classified as oligotrophic, mesotrophic, or eutrophic at present. Of all the diverse types of plants and animals that live in water, zooplankton are crucial for controlling the systematic processes that keep the environment healthy. Rotifers are one of the planktonic groups of zooplanktons that perform very well in controlling the ecosystem as a whole. These large organisms are also occasionally seen as an avoidable instrument for determining the state of the environment. It is always appropriate to use these creatures as bio-indicators of the ecosystem's trophic structure and pollution level. A good bio-indicator of water quality might be the group of rotifers or a single species, depending on the many indexes and the link between various biological, chemical, and physical features such as the dynamics and diversity of the described organism. Rotifers react strongly to eutrophication, or nutrient enrichment, especially when it comes to the availability of phosphate and nitrogen.

Keywords—Freshwater ecosystem, Rotifera, Brachionus, Sentinel organism, Trophic status, Eutrophication

1. Introduction

Rotifers are mostly found in freshwater environments, and their abundance is correlated with the conditions that are best for their survival. Freshwater ecosystems can be classified as Dystrophic (abundant partially decomposed organic matter; humus marshland), Eutrophic (rich in nutrients and organic material, phytoplankton, shallow water, and seasonally fluctuating dissolved oxygen), or Oligotrophic (low organic matter, relatively deep, oxygen-rich, low calcium content). According to their shape and environment, these creatures may be divided into four categories: planktonic rotifer (found in littoral waters), sessile rotifer (attached to submerged plants), loricates rotifers (hard or semi-hard body shell), and bdelloid rotifers (soft bodies, frequently found in ponds). It has been acknowledged that rotifer species have a significant role in throphic dynamics in freshwater environments. In addition to controlling water production, the aforementioned creatures have a significant function in energy flow, nutrient cycling, and trophodynamics, which helps determine the ecological state of aquatic ecosystems. According to Sladecek (1983) [1], the aforementioned creatures are regarded as 'valuable biological indicators' that show the trophic state of the water quality of their surroundings under 'limnosaprobity'. In order to illustrate how different environmental factors interact, current literature aims to investigate the distribution and density; ecosystem role and bioindicator value in aquatic ecosystems. Rotifers may be one of the beneficial biological elements utilised to evaluate the ecological condition of a waterbody; in fact, trophic status is frequently reflected in rotifer abundance, species composition, and distribution [2]. Rotifers (Phylum Rotifera) are ubiquitous microscopic zooplankton with short generation times, wide geographic distribution, and well-developed taxonomy. Their community composition is highly responsive to changes in water quality, and therefore are excellent bioindicators of the trophic status. Different rotifer groups, feeding modes, and trophic abilities exhibit varying nutrient tolerances and the observed shifts in richness, abundance, and functional diversity directly correlate with eutrophication gradients

2. Literature Review

In freshwater ecosystems, complex biological, chemical, and physical processes sustain ecological balance. The arrangement of feeding relationships, or trophic structure, provides information about the health, energy flow, and function of these ecosystems. The significance of identifying bioindicators or sentinel organisms that can precisely signal trophic dynamics and ecological conditions has been acknowledged by researchers in recent decades. Rotifers, belonging to the phylum Rotifera, are promising sentinels for monitoring the trophic structure of freshwater ecosystems. As primary consumers that consume algae, bacteria, and detritus while preying on larger invertebrates and planktivorous fish, micrometazoans (100–500 µm) are essential to freshwater food webs [132]. Their ubiquity, high rates of reproduction, short generation times, and sensitivity to environmental changes make them valuable ecological indicators [133]. Our understanding of employing rotifers as sentinels to evaluate the trophic structure of freshwater ecosystems is covered in this review of the literature. The review discusses rotifer ecology, environmental responses, bioindicator techniques, and research challenges and directions. With 2,000 species, rotifers are divided into three classes: Monogononta, Bdelloidea, and Seisonidea [5]. Monogononta and Bdelloidea make up the majority of freshwater species; the former reproduce both sexually and asexually, while the latter do so parthenogenetically. Because of their diversity, rotifers can survive in a wide range of freshwater environments, from transient puddles to expansive lakes and rivers [134]. Many rotifer species have a cosmopolitan distribution, as reported by [135]. However, recent molecular studies have discovered cryptic diversity, indicating that biodiversity may be undervalued. Rotifers are useful as comparative indicators across freshwater ecosystems because of their abundance. As suspension feeders that link primary producers to higher trophic levels, rotifers are essential to freshwater food webs because they consume bacteria, organic particles, and phytoplankton [27]. Rotifers transfer energy to higher trophic levels by feeding planktivorous fish, larger zooplankton, and macroinvertebrates [136]. By consuming bacteria, rotifers aid in the recycling of nutrients in freshwater ecosystems [27]. Rotifer species are categorised as browser-scrapers, raptorial predators (*Asplanchna* spp.), and microphagous filter feeders (*Keratella* spp.) [137]. Because of its functional diversity, rotifer community structure allows researchers to assess several trophic pathways. The composition of freshwater rotifer communities has been linked to the trophic state in numerous studies. The rotifer trophic state index [25], based on extensive lake studies in Poland, demonstrates that trophic status can be determined by the ratio of tecta to typical *Keratella cochlearis*, total biomass, and the percentage of bacterivorous species. *Kellicottia longispina* and *Conochilus unicornis* dominate oligotrophic waters, while species such as *Brachionus angularis*, *Polyarthra* spp., and *Keratella quadrata* dominate eutrophic waters [138] These patterns provide indicators of trophic and nutrient enrichment in rotifer assemblages. Rotifer species richness decreases in highly eutrophic or dystrophic environments and peaks at mesotrophic conditions [139]. This implies that, in addition to abundance metrics, rotifer diversity may indicate trophic dynamics. Rotifers respond quickly to predator-prey interactions, making them useful markers of trophic cascades and shifts in the food web. Under high fish predation pressure, smaller rotifer species predominated due to size-selective predation on larger zooplankton competitors [140]. Invasive species can lead to cascading changes in rotifer communities [141]. By reducing phytoplankton availability, zebra mussel invasions shift rotifer assemblages to species that can benefit from alternate food sources or lower food concentrations. Rotifers are susceptible to contaminants that upset trophic relationships in addition to trophic changes brought on by nutrients. Standardizing rotifer toxicity tests for Brachionus species [142]. It is pointed out those rotifer-based bioassays can identify minor trophic disruptions before more significant organizational changes become noticeable. Quantitative trophic status evaluations are formalised from community data using the Rotifer Trophic State Index [25]. Numerous lake systems in Europe have validated this method, which can be applied to environmental monitoring initiatives. A rotifer functional diversity index including body size, feeding mode, preferred habitat, and reproductive strategy [143]. In particular, functional metrics can identify subtle trophic changes that species-based approaches fail to notice in assessments of ecosystem resilience. The potential of rotifers as trophic indicators is being expanded by recent molecular techniques. Improved trophic assessments by using DNA barcoding to identify cryptic rotifer species with unique ecological preferences [144]. Although rotifers are promising sentinels, a number of barriers prohibit their extensive application as trophic indicators. Monitoring agencies are losing the specialised knowledge needed for rotifer identification [135]. Monitoring programs cannot overlook the seasonal succession patterns of rotifer communities [145]. Habitat-specific sampling is necessary because littoral and pelagic rotifer communities respond differently to trophic changes [146]. Before being used elsewhere, indicator species and indices from one biogeographic region might require validation [138]. It is challenging to differentiate trophic responses from other environmental stressors (such as temperature, hydrology, etc.) in complex natural systems [147]. There are several promising research directions that could improve rotifers as trophic sentinels. Routine monitoring programs would benefit from standardised sampling and analysis procedures that are optimised for rotifer-based trophic assessment. Research on the complementarity of rotifer indicators with conventional trophic state metrics, such as total phosphorus and chlorophyll-a, may be useful for integrated assessment approaches. Creating easily accessible molecular tools such as environmental DNA and meta-barcoding could enhance taxonomic knowledge and surveillance. Rotifers' sentinel status would be enhanced by more experimental studies on their reactions to trophic changes. There is an urgent need for research on how rotifer communities are impacted by climate-driven changes through trophic dynamics because of the changing global environment.

3. Composition of Rotifers:

Rotifers, also called Rotatoria, are tiny, microscopic, elongated living forms that range in size from 50 µ to 2000 µ. They belong to the minor invertebrate phyla [3]. John Harris was the first to describe these soft-bodied metazoans about 200 years ago [4]. Its forward ciliated wheel, or corona, makes it easy to distinguish from other planktons. Rotifers were regarded by Dutrochet in 1812 as a separate biological category from protozoa [5]. Less than 5% of species are found in continental ocean environments, while 95% of species are native to freshwater environments [6]. About 2500 species of rotifers are distributed across 200 genera, with approximately 1400 rotifer species from waters of Europe and 620 from the waters of Australia [7]. There are roughly 59 rotifer species in the sub-Antarctic region, 50 species in the maritime Antarctic, and 13 in the continental portion. The highest numbers of rotifer species are found in the sub-Antarctic (122 species from class Monogononta,) and the continental Antarctic (32 species from class Bdelloida,). As of right now, 176 species of rotifers are known to exist in Antarctic wetland habitats [8]. Anderson (1889) [9] listed 47 species of Indian rotifers from India; however, Sharma and Michael (1980) [10] provided the first taxonomic study, listing 241 species from India. Sharma reviewed these species in depth in 1991, and Dhanapathi (2000) [11] organised the taxonomic notes. Sharma (1998) [12] listed 330 rotifer species. Tropical and sub-tropical latitudes are home to the majority of rotifers found in India, while they can also occasionally be found in temperate regions in appropriate habitats [11]. *Brachionus durgae*; Dhanapathi, 1974 from Andhra Pradesh is one of the new species depicted from India. It is also known to exist in South Africa, Japan, and South America [13] [14] and it is classified as Tropicopoliton. According to Kippen (2005) [15], rotifers are referred to be pioneer organisms since they initially appear in recently created bodies of water. Rich rotifer fauna is often found in lentic environments such as village ponds (dung water), contaminated rivers, and various stabilisation pond types [1]. Only species of rotifers that are widely distributed are planktonic, and they depend on temperature, food, and photoperiod for their life cycle [16]. Although they breathe in an aerobic manner, they can briefly withstand an anaerobic environment. The majority of plankton communities have between 50 and 500 rotifer organisms per litre, whereas highland lakes could have less than 20. The intense population in uncontaminated freshwater body reached 5800 per litre [17].

4. Function within an ecosystem:

They are some of the most significant zooplanktonic species. They are the primary eaters in aquatic habitats, devouring a range of particulate debris, free-swimming algae, and phytoplankton species. More than half of the carbon fixed by primary production can be transferred to higher trophic levels by zooplankton that feed on phytoplankton [18] [19] [20]. The rotifer community generally plays a crucial role in the aquatic food chain. They can produce up to 50% of the total plankton biomass by filling empty niches extremely quickly and transforming primary output into a form that secondary consumers can use [21]. Since rotifers are a vital source of food for fish in the early stages of their outdoor eating, they participate in several food web connections and occupy a variety of trophic levels within aquatic environments [22]. Rotifers are very nutrient-dense for planktovorous fish; their protein helps larvae and young fish grow quickly [23]. They play a part in the cycling of organic materials by acting as a bridge between carnivorous zooplankton and non-plankton [24]. Despite their diminutive size, rotifers are important to the cycling of nutrients in freshwater environments. Through a number of crucial processes, these tiny metazoans—which are normally between 100 and 500 μm—play a crucial role as intermediates in aquatic food webs, helping to recycle vital nutrients. Large volumes of dissolved nutrients, especially nitrogen and phosphorus compounds, are expelled by rotifers and are easily accessible to primary producers. In certain lake habitats, especially during their population maxima, rotifers may recover up to 30% of phosphorus and 20–40% of nitrogen [25]. Through their metabolic processes, rotifer assemblages effectively transform particulate organic matter into dissolved inorganic nutrients, releasing phosphate (PO_4^{3-}) and ammonium (NH_4^+) that bacteria and phytoplankton may use directly [26]. By feeding on bacteria and producing nutrients that promote bacterial development, rotifers improve the microbial loop's activities. Rotifer feeding activities have been shown to boost bacterial production in experimental mesocosms by as much as 40% [27]. The way the microbial loop works is that rotifers eat bacteria and tiny algae and then expel dissolved organic matter (DOM) and inorganic nutrients, which encourage more bacterial development and increase ecosystem production overall. Rotifers are efficient suspended particulate matter filters, especially in eutrophic conditions. According to calculations by Bogdan and Gilbert (1982) [28], dense rotifer populations may drastically change the distribution of particle nutrients in tiny ponds by filtering the whole water column in a matter of days. Through mechanical breakdown during intake, partial digestion and egestion as faecal pellets, and careless feeding that releases dissolved organic compounds, this filtering action reduces bigger particulate elements into smaller, more accessible forms [29]. Under ideal circumstances, rotifer populations can have a quick turnover rate, with generation periods as low as 1-2 days [21]. One important route for nutrient recovery is shown by this quick population cycling. In certain temperate lakes during spring blooms, rotifer biomass turnover may account for up to 15% of the total phosphorus cycle [27]. Their short life cycles and high rates of reproduction allow ongoing recycling of nutrients. Rotifers improve the effectiveness of energy and nutrient transmission between trophic levels because they are intermediate consumers. In order to make nutrients accessible to higher trophic levels, rotifers convert bacterial and algal biomass to animal tissue with a comparatively high efficiency (20–30%) [130]. Rotifers become the principal connection between primary producers and planktivorous fish, especially in freshwater settings where bigger zooplankton, such as

Daphnia, has disappeared or decreased [30]. In different freshwater environments, rotifers contribute differently to the cycling of nutrients: *Brachionus* species may consume up to 40% of primary output and are frequently dominant in shallow eutrophic lakes [25]. Smaller rotifers like *Keratella* and *Polyarthra* are essential for recycling limited nutrients in oligotrophic environments, increasing system productivity above and beyond what would be achievable with only external inputs [26]. In river ecosystems, rotifers are essential to the downstream nutrient cycling process because they transform particulate nutrients into dissolved forms [31]. Because of their exceptionally fast rate of reproduction, which is characterised by parthenogenetic production, rotifers are important for trophodynamics, ecological energy, material cycle, and aquaculture productivity [32]. Rotifers react quickly to ecological changes [33]. The shift in zooplankton distribution is caused by biotic (food limitation, predation, and competition), abiotic (temperature, salinity, stratification, and advection), or a combination of the two [34] [35] [36]. A higher degree of adaptation, evolution, and tolerance of the organisms in a progressively contaminated habitat is shown by the rotifers' growth, survival, and efficiency in digesting heavy metals [37]. With around 160 genuine species, The Lecanidae family is the second largest among rotifers [38]. Rotifers may inhabit a range of environments in freshwater bodies, such as planktonic, benthic, epiphytic, and littoral zones. Meanwhile, a common toxicity test organism is the planktonic rotifer-like genus Brachionus [39].

5. Rotifer as an indicator of saprobity:

Using both biological and physico-chemical approaches, a comprehensive bio-monitoring strategy reveals the exact status of the aquatic environment [40]. As characteristically aerobic invertebrates, rotifers are good indicators of saprobity; they only show signs of limnosaprobity, not eusaprobity [1]. In 1902 and 1909, Kolkwitz and Marsson [41] were the first to employ rotifers as an indication. Indicator species in India were initially observed by Arora in 1961 [42] and 1966 [43]. As a bio-indicator of water quality's trophic state, rotifers are regarded as crucial [44] [45] [46] [47] [1] [48] [49]. While some species thrive in extremely eutrophic environments, others are more vulnerable to chemical and organic wastes [50]. For instance, the saprobic valences of *Brachionus urceolaris*, *Pompholyx sulcata*, *Polyarthra vulgaris*, and *Keratella cochlearis* are known to signal eutrophic environments [51]. Elevated phosphorus and nitrogen concentrations are strongly associated with the abundance of *Brachionus* species, *Keratella cochlearis*, and *Filinia* species, which thrive under eutrophic conditions. For instance, nutrient-rich streams saw a large rise in *Brachionus plicatilis* populations [52]. According to Saksena (1978) [53], Certain species are used to assess environmental pollution due to their adaptability to extreme situations and their ability to indicate the ecological quality via their responses. These species are referred to as bioindicators. A biological indicator is meant to provide a useful biological measure that is sensitive enough to be used for diagnosis, control, prevention, and reclamation [54]. Various studies have done in productive and tropical ponds fed with manure, indicate the nature of water bodies [55] [56] [57]. In polluted water that has been culturally eutrophied, Brachionus species are [58]. Some species flourish in highly eutrophied water, whereas others are very sensitive to organic and chemical waste. Eutrophic water is home to *Trichocerca cylindrical*, *F. terminalis*, *B. angularis f. bidens*, *B. calyciflorus*, and *B. calyciflorus f. amphicerus* [59]. While *B. quadridentatus*, *B. urcens*, *Keratella quadrata*, *Trichocerca capucina*, *Filina longiseta*, and *F. terminalis* are found in eutrophic water [60] states that B. angularis, *Trichocerca cylindrical*, and *Polyarthra euryptera* are the indicator species of eutrophy [61]. *Brachionus* species, *Keratella cochlearis*, *K. quadrata*, *Trichocerca cylindrical*, *Polyarthra euryptera*, and *Filinia longiseta* were all found in mesotrophic to eutrophic streams [62]. *Rotaria rotatoria* were found in contaminated water [42]. The presence of Brachionus indicates that the waters are eutrophic [63]. *Brachions* species, *Anuraeopsis fissa*, *Keratella quadrata*, *Filinia longiseta*, and *Trichocerca pusilla* [64]. Presence of *B. calyciflorus* is a sign of eutrophication [65]. The larger numbers in downstream areas would imply that *B. calyciflrous* is a species that can tolerate pollution [66]. Other Brachionus species found at the downstream site fed waste water include *B. angularis*, *B. bidentata*, *B. budapestenesis*, *B. caudatus*, *B. diversicornis*, *B. plicatilis*, *B. quadricornis*, and *B. quadridentatis*. According to Dhanapathi (2000) [11], they grow significantly in number very quickly under certain environmental circumstances. A significant rotifer population in lake water indicates pollution from untreated domestic sewage entering directly [43]. Rotifers and copepods predominate due to eutrophication [67]. It is not possible to draw broad conclusions about rotifer indicators from water bodies with different trophic levels due to the limited knowledge from India. However, it is frequently recorded that eutrophic to hypereutrophic conditions are present for the following species: *Philodina*, *Rotaria neptunia*, *Fillinia longiseta*, *F. opalionisis*, *Brachionus rubens*, *B. angularies*, *B. urseolaris*, and *Rotaria neptunia*. Alkaline eutrhophic waters are frequently home to *Brachionus caudatus*, *B. calyciflorus*, *Anuraeopsis fissa*, *Keratella tropica*, *Asplanchna brightwelli*, *Phompholyx sulcata*, *Polyarthra vulgaris*, *Conochilus unicornis*, and *Sinantherina sociolis* [6]. Eutrophication was shown by Brachionus and Keratella) [65]. Rotifers in water bodies grew enormously suggesting eutrophic conditions [68]. A high density of Brachionus species is believed to be the source of phytoplankton control, whereas rotifers acted as a limiting factor for phytoplankton density [69]. At a depth of one meter, rotifer populations in eutrophied and contaminated lentic water bodies reached 33900 individuals per litre. The predominant food sources in polluted streams are suspended particles and colloids from wastewater, which harbour bacteria that decompose organic matter. Other typical food sources include bacteria, tiny algae, flagellates, and detritus filtered from the water. Waste water concentration increases the density of *B. calyciflorous* [70] [71]. There are no known indicator species of rotifers for polysaprobic among the 29 reported species from the unpolluted Omi River, despite the dominance of the Brachionidae family [72]. The enormous number of rotifer species that occur in water with significant eutrophication is directly proportionate to the limited copepod population [73]. Rotifer species predominance suggests organic contamination brought on by untreated sewage entering directly from the catchment region [43]. Oligotrophic water is home to *B. patulus, K. quadrata, and K. cochlearis,* as well as *Lacane bulla, L. hamata, L. lunaris, Ascomorpha ovalis,* and *Mytilina ventralis* [74]. Trichocerca is a sign of water that is just oligotrophic. *Ascomorpha ovalis, Conochilus unicornis*, and *Synchaeta stylata* are oligotrophic species; many species in mesotrophic water are clearly transitional species. In eutrophic water the main species include *Trichocerca cylindrica*, *T. pusilla*, *Filinia longiseta*, *K. cochlearis*, *K. quadrata*, Brachionus species, *Anuraeopsis fissa*, *Pompholyx sulcata*, *P. complanata*, and *Polyarthra euryptera*. Various rotifer species may be found in water with various nutritional contents [75]. For instance, although *B. calyciflorus* and *F. longiseta* are eutrophic, Polyarthra species thrive in oligotrophic water. Small rotifers have a lower essential food concentration and maximal development rate than bigger species [76]. Common oligotrophic indicators like *Lecane ludwigii, L. arcula, Notholca labis, Monostyla hamata, M. furcata, Monomata longiseta, Cephalodella exigua, Scaridium longicaudum, Metadiaschiza trigona, Ascomorpha saltans,* and *Conochilus hippocrepis*, as well as mesosaprobity species like *B. calyciflorus*, *B. angularis*, and *F. longiseta*, made up the majority. *Trichocerca* species suck the cell contents of filamentous algae [77] [78], *Synchaeta oblonga* and *K. cochlearis* devour algae, while *Anuraeopsis fissa* mostly consume detritus [79]. Rotifers showed increased abundance in response to edible phytoplankton [80]. When found in eutrophic and highly polluted waters, species like as *B. quadridentatus, Lapedella, Platias quadricornis, epiphanus,* and *R. rotatoria* exhibit superior tolerance to alkanities [81]. Additionally, *Anuraeopsis fissa*, *B. forficula*, *Dipleuchlanis propatula*, and *Lacane stenroosi* exhibit the warm stenothermal feature [82]. Rotifers have a reasonably high output at low temperatures and can withstand the harsh Antarctic climate. Rotifer is a crucial element of freshwater in the Antarctic and may be a sign of climate change. There is a significant capacity for reproduction and anhydrobiosis (Poceiacha, 2010) [83]. In aquatic ecosystems, rotifers are essential for the movement of energy and the cycling of nutrients, especially when large zooplankton, such crustaceans are limited [84]. The majority of rotifers are suspension feeders [85], which filter or sediment the tiny particles into the mouth by a water stream produced by the cirri. They are responsible for the transport of carbon among the microbial food web, which consists of bacteria, fish, algae, crustacean zooplankton, and heterotrophic and mixotrophic flagellates and ciliates [86]. Therefore, the structure of rotifer communities, which varies from lake to lake, may be used to illustrate the present condition of environmental health [87]. Rotifers may convert a large portion of their food into biomass, which is subsequently available to higher trophic levels, thanks to their high assimilation efficiencies [88]. The number and species composition of rotifers are thought to be closely related to the health of the ecosystem, and the degree of eutrophication may be reflected in the species [89]. Increased abundance of tolerant rotifer species and changes in species composition can result from eutrophication [90]. Because of the high composition rate of accumulated dead phytoplankton biomass, increased bacterial production may be the cause of increased rotifer abundance in eutrophic circumstances [64]. *Brachionus* is known to have a high tolerance to cynobacterial toxins [91], make use of colonial blue green algae as food, and show a high tolerance to their blooms [92]. High trophic conditions are linked to high abundances of blue green algae. It is possible that certain rotifers and small cladocerans are competing for the same resources at the same time, and that giant cladocerans are preying on rotifers [93]. Since planktovorous fish are often found in eutrophic environments, it is possible that their depletion of cladocerans is the cause of the higher rotifer survival rate in eutrophic water [94]. When beneficial micro-algal species decline and inedible blue-green algae increase, the amount of zooplankton may decrease [95]. The presence of more than five *Brachionus* species suggests that the water body has become eutrophic [96]. Reduced energy transfer efficiency between phytoplankton and zooplankton may be the cause of lower rotifer density [97]. Rotifers' density and biomass rose as their trophic status climbed. While the number of rotifer species in eutrophic locations rises from 1000 to 2000/L, in oligotrophic locales, the number does not surpass 200/L. In eutrophic water, Monogonaont rotifer can attain remarkable densities [88]. Rotifer populations have a high turnover rate, which enables them to play a major role in aquatic environment nutrient recycling [98] [99]. Rotifers, such as *Asplanchna* [94], cyclopoid and calnoid copepods [100], insect larvae [101], and fish [102], occasionally face severe competition for food from microcrustacens and zooplankters [103].

6. Water Quality Indicator

A variety of physical, chemical, and biological variables may impact the species composition and abundance of rotifers, including temperature, dissolved oxygen, turbidity, pH, nutrient availability, food quantity and quality, predation, and habitat quality [104] [105] [106]. Rotifer communities' occurrence and abundance are also significantly influenced by dissolved oxygen. Cold stenothermal forms are more tolerant of low oxygen levels in the water than eurythermal species [62] [107]. Hypoxia (low oxygen concentration) may have a detrimental physiological effect on rotifer species and lead to a decline in population size [108]. Aquatic species require hardness for proper growth and development [109]. Large amounts of carbon dioxide harbour a relatively small population [110]. Many rotifer species prefer more alkaline water; Brachionus, for example, has a higher population during high alkalinity periods [11]. Few species can be found in alkaline water, but many individuals and diversity can be found in acidic water [17]. More alkaline waters are preferred by several rotifer species. Rotifer has exceptional population density increase throughout the summer, when macrophyte abundance is [111]. The greatest diversity is available in the summer, when species like *B. diversicornis, B. forficula*, and *K. Tropica* are more abundant, diverse, and even [112] [113] noted a high level of variety. *B. forficula* and *B. calyciflorus* are warm stenothermal forms [114] [115]. High alkalinity values affect the growth and abundance of loricate forms, but they cannot be a limiting factor for other species [11]. Species with well-developed lorica, such as *Brachionus, Keratella, Mytilina, Platyas*, and *Asplanchana* species, expand their populations when alkalinity is also high. The alkaline hard waters were abundant in *K. tropica* and Brachionus species [6]. Density, species richness, evenness, and variety were all reduced by the high electrical conductivity and low temperature [112]. Some researchers have noted that late summer and early fall are when populations peak [116] [115] [118]. High temperatures, extended photoperiods, and increased light intensity [119] as the reasons for the high rotifer peak during the summer. Eurytopic species are those that can endure a wide variety of biotopes, whereas stenotopic species are those that can tolerate a narrow range [120] noted that since most rotifers are detritus eaters, they do well in low oxygen environments. Rotifers continued to have unfavourable relationships with both total hardness and dissolved oxygen [121]. Chemical ions like calcium and magnesium have little effect on rotifer density [122]. Rotifers were more prevalent in warm climates and less prevalent in cooler climates [123]. They were also more prevalent in areas with high levels of human pressure. Water temperature has long been thought to be the primary factor influencing rotifer occurrence and seasonal succession [48]. Even within a single species, rotifers differ in their thermal tolerance, and their maximum growth rate happens when the water temperature reaches its ideal level [124]. In fresh water, rotifer species abundance and occurrence are strongly correlated with pH. Rotifers can be categorised as alkaliphilic, euryionic, or acidophilic based on their preferred pH. Species are often plentiful yet uncommon in acidic water, whereas the contrary occurs in alkaline environments [125]. Rotifer assemblages are most diverse in soft, slightly acidic, oligo- to mesotrophic environments [126]. Rotifer population density and nitrogen and phosphorus were shown to be positively correlated [127]. Rotifers responded most strongly to elevated phosphorus levels based on densities. The existence of species and the dynamics of rotifer assemblages may be partially determined by total phosphorus, one of the most significant nutrients that reveals the trophic condition of the ecosystem [128] [129]. Because they frequently have a significant impact on the dynamics of freshwater and coastal marine ecosystems, rotifers are valuable models in eco-toxicology [130]. Heavy metal toxicity has been evaluated by a rotifer toxicity test. Using *Philodina* species [131] demonstrated that a short-term mortality test may be used to evaluate the toxicity of heavy metals. Peak population densities and daily population growth rates were two population level indicators that declined as heavy metal concentrations increased; peak population density was also impacted by metal stress.

7. Results and Discussion:

Freshwater rotifer communities vary along trophic gradients, according to the literature. Some studies show that rotifer assemblages differ by trophic state. *Brachionus, Keratella,* and *Trichocerca* species predominate in enriched systems and *Notholca* and *Kellicottia* species predominate in nutrient-poor waters ranged from oligotrophic to hypertrophic [25]. Rotifer-trophic relationships can transcend biogeographic boundaries despite species pool variations [138]. Rotifer communities' consistency makes them valuable comparative indicators across a range of freshwater ecosystems. Discovered a unimodal correlation between rotifer species richness and trophic state, with mesotrophic conditions showing the highest diversity [146] [148]. Since moderate nutrient levels may maximise resource diversity without a few competitive species predominating under highly enriched conditions, this pattern lends credence to the intermediate disturbance hypothesis. From oligotrophic to hypertrophic waters, trophies increase the overall abundance of rotifers by one to two orders of magnitude. This abundance relationship may become non-linear in highly enriched or polluted systems where environmental conditions surpass the physiological tolerances of the majority of rotifer species [149]. A review of the literature indicates that a number of rotifer taxa consistently indicate particular trophic conditions: In Europe [25], North America [150], and Asia [31], oligotrophic indicators such as *Kellicottia longispina*, *Conochilus unicornis*, *Gastropus stylifer*, and some *Polyarthra* species are consistently associated with nutrient-poor waters. In contrast, mesotrophic indicators such as *Polyarthra dolichoptera*, *Synchaeta pectinata*, *Gastropus hyptopus*, and *Ascomorpha ovalis* are consistently linked to moderate nutrient conditions [138]. Eutrophic indicators: nutrient-rich conditions are consistently indicated by *Keratella cochlearis, K. quadrata*, *Brachionus angularis, B. calyciflorus*, *Filinia longiseta*, and *Polyarthra vulgaris*. *Brachionus budapestinensis, B. urceolaris*, *Anuraeopsis fissa*, and some species of *Filinia* predominate in highly enriched waters [148] [151]. Composite metrics and indices for rotifer communities that go beyond individual indicator species have been developed in a number of studies. Rotifer Trophic State Index [25], which takes into account bacterivorous species, biomass, abundance, and tecta forms in populations of *Keratella cochlearis*. In European lake systems, there is a strong correlation ($r > 0.8$) between this index and chemical-based trophic state indices. Many researchers have successfully modified [1] rotifer saprobic index for trophic assessment, and in a variety of aquatic systems, these modified versions show notable correlations with nutrient loading [2] [151]. Ecological mechanisms are revealed by the consistent patterns of rotifer functional traits across trophic gradients. Numerous studies demonstrate that while raptorial species decline with trophic state, microphagous filter-feeders, mainly Brachionidae, increase proportionately. While eutrophic systems favour filter-feeding strategies with a wealth of bacteria, detritus, and colonial algae, oligotrophic systems typically support raptorial feeders with nanoflagellates and small algae [27] [143]. Across trophic gradients, the average rotifer size decreases as trophy size increases [152][31]. This size shift was probably caused by several mechanisms, In habitats with abundant resources, smaller species with quicker growth rates are more advantageous [137]. More planktivorous organisms raise the pressure of size-selective predation in productive systems [140]. Because of physiological limitations, smaller species with higher surface area-to-volume ratios flourish in oxygen-depleted eutrophic waters [148]. The efficiency of energy transfer and predator-prey dynamics in food webs are impacted by size-structured community reorganisations [136]. The species those with small bodies, high rates of reproduction, and short generation times, dominate in enriched environments [148]. This pattern is consistent with ecological theory regarding adaptation to eutrophic systems that are productive but unstable or stressful.

The physiological reactions of rotifers to trophic conditions are being revealed by recently developed molecular techniques. Rotifers from nutrient-enriched environments exhibited higher levels of detoxification, oxidative stress, and protein turnover genes compared to those from oligotrophic conditions [153]. Different trophic states were indicated by the different protein expression patterns that observed in *Brachionus calyciflorus* exposed to various algal food sources [142]. Before community-level changes occur, these molecular signatures might offer mechanistic biomarkers to identify subtle trophic shifts. Rotifers from eutrophic environments have higher metabolic rates, faster development, and greater tolerance to low oxygen, according to comparative physiological studies [154]. They may be able to survive in stressful, nutrient-rich environments with higher biological oxygen demands thanks to these adaptations.

Using rotifer dynamics in food web studies helps explain their role as trophic indicators. Rotifer responses to predation reveal trophic cascades and food web structure. Smaller rotifer species became dominant under increased fish predation due to size-selective feeding on larger zooplankton competitors, according to [141]. Under high invertebrate predator abundance, predator-resistant forms (e.g., loricated species, colonial forms) became more prevalent in rotifer communities, according to [140]. Rotifers are sensitive to higher trophic level changes and Cascade effects due to their response patterns. Microbial food web studies show rotifers' integrative role as trophic indicators. Bacteriovorous rotifers control bacterial dynamics more in eutrophic environments where bacterial production is high, Rotifers mediate nutrient cycling, especially in systems with high organic loading [27].

A review of the literature demonstrates the following benefits of employing rotifers as sentinel organisms for trophic assessment: Rotifer communities react swiftly to trophic changes, frequently ahead of conventional metrics, according to research [148] [117]. Early ecological change detection is made possible by this sensitivity. Although cross-system comparisons are possible due to the global distribution of rotifer genera, species-level variations may require regional calibration of indicator values [5] [135]. Because of their intermediate position in food webs, which links microbial components and primary producers to higher trophic levels, rotifers are important indicators of ecosystem function [132] [27]. Taxonomic and Functional Diversity: Rotifer taxa offer a variety of ecological assessment dimensions due to their varied feeding habits, habitat preferences, and life histories [137] [143]. Rotifer-based indices are simple to incorporate into current monitoring frameworks due to their strong correlation with conventional trophic state parameters [25] [138]. Although rotifers are helpful trophic indicators, their application is restricted by a number of issues: Taxonomic Knowledge Required: The ability of monitoring organisations to identify species at the species level is becoming less and less proficient [132] [135]. This problem is faced by cryptic-diverse organisms like *Brachionus* and *Keratella*. Season-specific reference conditions or standardised sampling are required to properly evaluate seasonal succession patterns in rotifer communities. Habitat Specificity: Littoral and pelagic rotifer communities require habitat-specific sampling and interpretation due to various trophic changes [145] [146]. Certain indicator species may differ between biogeographic provinces, necessitating regional validation even though rotifer-trophic patterns are consistent across regions [5] [31]. It can be challenging to differentiate trophic responses in complex natural systems from other environmental stressors, such as contaminants, hydrological changes, and extreme temperatures [147] [154].

8. Conclusion and Future Scope

In freshwater habitats, rotifers are essential markers of ecological health. Their established ecological indicator values, distinct distribution patterns, and quick and sensitive reactions to trophic alterations make them essential for water quality monitoring. Rotifers have several bioindicator qualities: Rotifers inhabit most freshwater ecosystems, from lakes and ponds to rivers and transient waterbody. Rotifers detect ecological disturbances shortly after environmental changes. Rotifers' community structure reflects site circumstances because they cannot avoid local contaminants. Rotifers have 2,000 species and vary in environmental stress sensitivity. Rotifer communities and water quality are strongly correlated. If *Brachionus calyciflorus* and *Keratella quadrata* are absent, nutrient-enriched waters may be oligotrophic. *Lecane lunaris* and *Keratella serrulata* have acid tolerance, whereas others perish at lower pH. In heavy metal-contaminated streams, rotifer diversity declines considerably, with species-specific responses. Diversity in rotifer assemblages indicates healthy waterways, whereas Brachionus dominates organically damaged environments. Microscopic size enables for easy collection with minimum equipment. Lab culture makes toxicity assessment of many rotifer species easy. Fish and crustacean bioassays cost more than rotifer ones. Rotifer sampling disturbs ecosystems less than larger organisms. In standardised toxicity tests, *Brachionus calyciflorus* assesses pollutants' effects on aquatic environments. Rotifer community composition can reflect climate changes like temperature shifts. Ecosystem restoration is assessed by diverse rotifer community survival.

Stakeholders may conserve and improve aquatic ecosystems by incorporating rotifer-based evaluations into lake management and restoration plans. This allows them to make better informed choices more quickly. There is a lot of potential for improving freshwater ecosystem monitoring through future studies on rotifers as bioindicators. More accurate bioassessment is made possible by the improved species-level identification of rotifers made possible by the growing availability of molecular techniques. Deeper understanding of ecosystem resilience and stress responses may be possible through extensive, long-term research that integrates rotifer population dynamics with other biotic and abiotic components. Furthermore, extending rotifer-based indicators to a variety of freshwater systems, such as urban water bodies, reservoirs, and wetlands, may enhance regional frameworks for monitoring water quality. Early identification of pollution, eutrophication, and climate-driven changes may also be facilitated by the creation of standardised rotifer-based indicators and real-time monitoring procedures. All things considered, rotifers offer a neglected but effective tool for integrated lake management, ecological forecasting, and international freshwater conservation initiatives.

Data Availability

The text includes citations to previously published data that served as the basis for this investigation. The current study did not create or analyse any new datasets.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Authors' Contributions

Sudhir Bhandarkar: Researched literature and conceived the study and manuscript preparation.
Sonam Bansod: Literature survey, wrote the first draft of the manuscript

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