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Environmental drivers of zooplankton community structure and bacterial load in Rajasthan's freshwater ecosystems: A global perspective

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Abstract

Freshwater ecosystems face numerous environmental challenges, including climate change, eutrophication, and pollution. These factors can significantly influence zooplankton community structure and bacterial loads. This review highlights the ecological factors influencing zooplankton community structure and bacterial loads in Rajasthan's freshwater ecosystems, offering a global perspective. Zooplanktons are essential components of aquatic food chains and serve as effective bioindicators of environmental health. They are sensitive to changes in physical-chemical conditions and climatic variations. Eutrophic conditions often reflect species composition that indicates pollution levels and anthropogenic impacts. Various studies reported high levels of bacterial content during the rainy season, particularly coliforms, fecal coliforms, and *Escherichia coli*. This condition is due to poor sanitation and surface runoff. Various researchers identified that *Salmonella, Shigella, Vibrio cholerae*, and *Pseudomonas aeruginosa* often coincided with water-borne diseases such as diarrhea and typhoid. The increased bacterial loads in water bodies during the monsoon season intensify public health risks. Our analysis reveals that environmental factors such as temperature, pH, nutrient levels, and land use patterns can significantly impact zooplankton community composition and bacterial loads. We also explore global patterns and trends related to these communities and discuss the implications for freshwater management and conservation efforts. This review highlights the need for more comprehensive integrated management strategies that include zooplankton analysis alongside measurements of bacterial abundance. Such approaches are essential for developing effective protection measures and health policies.

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Introduction

Freshwater ecosystems, including lakes, reservoirs, and wetlands are vital components of the environment, providing numerous ecological and economic benefits. Approximately 97% of the Earth's surface is covered by seawater, leaving only a small percentage available as freshwater for drinking (Tahir *et al.,* 2016). However, these ecosystems face numerous threats, including bacterial contamination, which can have far-reaching consequences for aquatic life and human health. Zooplanktons are vital in aquatic food webs, providing an essential link for energy transformation due to their migratory behavior, high density, diverse species, and adaptability to various stressors. They are morphologically and taxonomically diverse and include unicellular, colonial, and multicellular organisms such as protozoa, protists, invertebrates, and vertebrates (Kiørboe, 2011). Their size ranges from microscopic flagellates to meter-sized gelatinous forms. They also form a vital connection between autotrophs and heterotrophs and contribute significantly to biological productivity in freshwater ecosystems (Bhat*et al.,* 2014; Nimbalkar *et al.,* 2013). Their diversity and community structure are highly sensitive to changes in physicochemical parameters such as temperature, dissolved oxygen (DO), pH, salinity, and nutrient levels.

Rajasthan, the largest state of India, spans the area of 342,226 km² and is predominantly agrarian, with 70% of its population dependent on agriculture. Although Rajasthan covers 10.5% of India's geographical area, it accounts for only 1.15% of water resources. Western Rajasthan experiences arid to semi-arid conditions, characterized by low and erratic rainfall, high summer temperatures, low humidity, and high-velocity winds, resulting in an average potential evapotranspiration of 2,000 mm, a negative water balance, and acute water deficit.

In contrast, eastern Rajasthan has a semi-arid to sub-humid climate; characterized by relatively better rainfall, lower wind velocity, and higher humidity, as reported by Narain *et al.* (2005). Rajasthan states is home to numerous freshwater bodies including lakes, reservoirs, and wetlands that support a rich diversity of aquatic life. However, these water bodies face increasing pressure from human activities, including agriculture runoff, sewage disposal, and industrial effluent, leading to bacterial contamination and degradation of water quality.

The highest bacterial risks arise from drinking water contaminated by human and animal excreta. Coliform bacteria, which include *Escherichia coli, Enterobacter aerogenes, Salmonella,* and *Klebsiella,* indicate fecal contamination in water and are responsible for diseases such as cholera, typhoid, and dysenteries (Ashbolt, 2004). Bacterial hazards remain the primary cause of waterborne diseases globally, although chemicals in water supplies can also pose serious health risks, whether naturally occurring or pollution-derived (WHO, 2007).

Limnological parameters within optimal ranges in aquatic ecosystems can reveal ecological diversity and water quality. The portability of water in reservoirs is often indicated by zooplankton abundance, while physical, chemical, and biological characteristics define water quality standards (Gothwal, 2023). This review aims to provide a comprehensive analysis of zooplankton diversity and bacterial contamination in Rajasthan's aquatic ecosystems while contextualizing these findings within global environmental influences on zooplankton communities. By integrating insights into biological diversity with bacterial health risks, this study underscores the importance of biomonitoring for sustainable management of aquatic ecosystems and public health interventions.

Zooplankton diversity as bioindicators in Rajasthan's aquatic ecosystems

Plankton, which includes a diverse group of microscopic plants and animals, inhabit aquatic systems and are important indicators of water quality and ecosystem health. The diversity and composition of plankton in this environment reflect pollution levels and play a crucial role in biomonitoring (Venkateshwarlu, 1981). Planktonic diversity, divided into phytoplankton and zooplankton, is vital for limnological studies, with phytoplankton acting as primary producers and zooplankton forming a critical link between autotrophs and heterotrophs in aquatic trophic systems (Khanna and Yadav, 2009). Zooplanktons are excellent bioindicators of environmental conditions because they are sensitive to changes in water quality, and are vital in terms of nutritional levels, temperature, and pollution. They are used to determine the health of an ecosystem (Purushothama *et al.,* 2011) (Table 1).

Table 1. Zooplankton diversity across Rajasthan water bodies

Water body	Zooplankton diversity	Dominant groups	Key observations	References
Pushkar Lake, Ajmer	16 genera	Moderate pollution; density peaked in summer	48 phytoplankton, 16 zooplankton genera; moderate pollution	(Khanna and Yadav, 2009)
Gulab Sagar, Jodhpur	41 species (dominated by Rotifers)	Rotifers peaked in winter; followed by Ostracods, Cladocerans, Copepoda	Rotifers dominant across 2 years; favorable winter conditions	(Vyas and Chouhan, 2017)
Guda Bishnoiyan Pond, Jodhpur	Correlated with salinity, turbidity; dominated by Rotifers	Rotifers dominated; eutrophic conditions	Heavy pollution and eutrophic conditions	(Saraswat and Mathur,2021)
Jaisamand Lake, Udaipur	51 species (dominated by Rotifers)	Rotifers with peak density in summer	51 species; seasonal influence of physico-chemical parameters	(Balai *et al.*, 2014)
Gang Canal, Ganganagar	6 genera (dominated by Rotifers)	Rotifers, Cladocerans, Protozoans	Dominance of Rotifers; influenced by water quality	(Bishnoi and Sharma, 2016)
Lake Pichhola, Udaipur	104 zooplankton forms	Eutrophic conditions; rich biodiversity	104 zooplankton forms; high primary production	(Mishra *et al.*, 2019)
Madar Tank, Udaipur	Linked to trophic environments; oligotrophic to eutrophic	Trophic linkages; oligotrophic to eutrophic	Diversity linked to trophic environments	(Sharma *et al.*, 2012)
Barali Lake, Bhilwara	Rotifera, Cladocera; high Shannon-Weaver indices	Rotifera, Cladocera; suitable for fish culture	Eutrophication; suitable for fish culture	(Vijayvergiya *et al.*, 2020)
Raipur Water Reservoir, Pali	20 species; Cladocerans dominant	Cladocerans dominated	Rich diversity; Cladocerans dominant	(Siroya and Siroya, 2019)
Bisalpur Reservoir, Thadoli	Seasonal peaks; Protozoa, Rotifera, Cladocera, Copepoda	Paramecium prevalent, Rotifers peaked in summer	Seasonal peaks; Protozoa, Rotifera dominant	(Summarwar, 2012)
Kishore Sagar Tank, Kota	36 species of zooplankton from 7 groups	Seasonal variations; plankton linked to water quality	36 zooplankton species; seasonal variations in diversity	(Dube *et al.*, 2010)

Gozdziejewska (2024) states that zooplankton are significant indicators of pressures impacting freshwater ecosystems. Community diversity is influenced by species richness and evenness, together known as heterogeneity, as observed by Lloyd and Gheraldi (1964). Table 1 illustrates the zooplankton diversity across various water bodies in Rajasthan and highlights the dominant groups, key observations, and corresponding references for each study. Different research revealed significant insights into plankton diversity. Khanna and Yadav (2009) identified 48 phytoplankton and 16 genera of zooplankton, with maximum density in summer and minimum in monsoon, indicating moderate pollution in the holy lake of Pushkar.

A study conducted by Vyas and Chouhan (2017) on Gulab Sagar, Jodhpur, found that rotifers were the dominant zooplankton, followed by Ostracods, Cladocerans, and copepods. The highest population of rotifers was recorded in winter, as the conditions during this season were particularly favorable. Similarly, zooplankton diversity was influenced by seasonal changes in water quality, with the highest population recorded in summer. This increase showed positive correlations with total dissolved solids (TDS), biochemical oxygen demand (BOD), and chloride levels. The study identified 70 species across five groups: Protozoa, Rotifers, Cladocera, Ostracoda, and Copepoda (Sharma and Sharma, 2017). The size of the zooplankton population is generally associated with biotic and abiotic factors. Species variation in aquatic environments often decreases in polluted waters. While some species showed high tolerance to pollution, others were missing from heavily contaminated areas (Zannatul and Muktadir, 2009).

Further research work has revealed rich zooplankton diversity in various water bodies. In Guda Bishnoiyan pond in Jodhpur, zooplankton populations correlated positively with free carbon dioxide, salinity, and turbidity. Saraswat and Mathur (2021) found that rotifers were the dominant group, indicating eutrophic conditions and significant pollution. In Jaisamand Lake, Udaipur, rotifers dominated during the summer, with their highest density influenced by physicochemical parameters, comprising 51 zooplankton species (Balai *et al.,* 2014). The Gang Canal zooplankton encompasses six genera, dominated by rotifers, followed by Cladocerans and Protozoans (Bishnoi and Sharma, 2016). Mishra *et al.* (2019) observed a eutrophic condition with high primary production and rich biodiversity, including 104 zooplankton in Lake Pichhola, Udaipur. Various studies have made a consistent and crucial realization that zooplankton taxa are rapid responders to many environmental stressors, such as hydrological changes, climate changes, and anthropogenic activity-induced water pollution (Duggan *et al.,* 2001; Pawlowski *et al.,* 2016).

Sharma *et al.* (2012) found that zooplankton communities were associated with trophic environments, ranging from oligotrophic to eutrophic in Madar Tank, Udaipur. In Barali Lake, Bhilwara, Rotifera, and Cladocera were dominant, with high Shannon-Weaver diversity indices indicating eutrophication conditions suitable for fish culture (Vijayvergiya *et al.,* 2020). Siroya and Siroya (2019) conducted studies on the Raipur water reservoir that showed dominance of Cladocerans among 20 identified zooplankton species, suggesting rich zooplankton diversity. Similarly, in the Thadoli area of Bisalpur reservoir, seasonal peaks of zooplankton groups such as Protozoa, Rotifera, Cladocera, and Copepoda were observed, with *Paramecium* prevalent throughout and Rotifers peaking in summer (Summarwar, 2012).

Additionally, a study on the community structure of zooplankton in Kishore Sagar Tank recorded 36 species belonging to seven different groups (Dube *et al.,* 2010a). The occurrence and seasonal variation of plankton in Kishore Sagar Tank, Kota, Rajasthan, and a total of 60 species of planktons (twenty-four species of phytoplankton and thirty-six species of zooplanktons) were recorded (Dube *et al.,* 2010b). Azevedo *et al.* (2015) found that zooplankton communities complement macroinvertebrates in indicating variations in the trophic status of water bodies. Therefore, bio-monitoring zooplankton communities have become a widely accepted and impeccable aspect of ecological conservation and the management of aquatic ecosystems.

Bacterial contamination in Rajasthan's water: Seasonal and health insights

Contamination of drinking water is a major health threat in developing countries. According to the WHO, over one billion people rely on limited water sources, and 88% fall ill due to inadequate health, sanitation, or hygiene. Bacterial contaminants in water pose serious health risks, including diarrheal diseases, cholera, and hepatitis A (Butt and Iqbal 2007). These microorganisms primarily inhabit surface water and are seldom found naturally in groundwater unless influenced by surface water bodies (Ottawa, 2006). It is challenging to sample all types of pathogens in water, so bacterial indicators like coliforms are used to assess bacterial pollution. While steadily not threatening, the coliforms mentioned above point to the probable presence of serious pathogens (Emmanuel *et al.,* 2009).

Coliforms are rod-shaped bacteria that are gram-negative, non-spore-forming, and facultative anaerobes, primarily originating from the intestines. When assessing water quality, the primary focus is on total coliform (TC), fecal coliform (FC), and *Escherichia coli* (United States. Environmental Protection Agency, 1997). While *E. coli* is generally harmless, some strains like *E. coli* O157:H7 can cause severe illness. *E. coli* is native to warm-blooded animals and an effective indicator for assessing fecal pollution and identifying potential pathogens in water (Odonkor and Ampofo, 2013). Bacteria such as *Campylobacter, Salmonella typhi,* and *Vibrio cholerae*, derived from human and animal feces, pose significant health risks (WHO, 1993; WHO, 2004). Data includes general indicators of water sanitation and total coliforms, derived from soil and water affected by surface water and waste. While total coliforms have limited predictive ability in identifying the source of water pollution, higher concentrations of fecal coliforms, which are commonly present in the intestines and feces of warm-blooded animals, give a general picture of the fecal contamination of a water sample (New Hampshire Department of Environmental Services, 2010).

In developed regions, significant enteric bacteria such as *Salmonella enterica, Campylobacter jejuni,* and *E. coli O157:H7*, exhibit different pathogenic strains based on their fecal source (Angulo *et al.,* 1997; Hrudey *et al.,* 2002). The main agents that cause diarrhea include *rotavirus, Cryptosporidium parvum, Campylobacter jejuni,* enterotoxigenic *E. coli* (ETEC),enteropathogenic *E. coli* (EPEC), *shigella* sp., and *Vibrio cholerae* serotype O1 or O139. There are also less common contributors, such as *Aeromonas sp. Bacteroids fragilis* and *Clostridium difficile* strains of EPEC are significant causes of infant diarrhea in developing countries, while atypical EPEC is more frequently associated with diarrhea in developed countries (Trabulsi *et al.,* 2002). In a study conducted by Suthar *et al.* (2009) in rural northern Rajasthan, India, they isolated ten bacterial strains from drinking water, with *Escherichia coli, Pseudomonas aeruginosa*, and coliforms being the most predominant. The level of bacterial pollution in various samples was high in four villages, attributed to poor sanitation and a lack of hygiene awareness. Total coliform counts ranged between 25 and 41 TTC(m) of water. Pathogenic bacteria are harmful to health and contribute to waterborne diseases, negatively affecting the health of the region's inhabitants.

The bacterial colonies isolated from water samples of Lake Pichhola, Fatehsagar, and Swaroop Sagar by Bhumbla *et al.* (2020) include circular ones, irregular ones, rhizoidal ones, and filamentous ones. Cultural examination using Gram staining revealed various forms: cocci, bacilli, and coccobacilli, with gram-negative organisms predominating over gram-positive ones; specifically, gram-negative bacilli were more numerous than gram-positive cocci and bacilli. The standard plate count (SPC) and total viable count (TVC) were relatively high, with average values of 4,560 and 4,030, respectively, in May. The most probable number (MPN) count from the bacteriological tests was also extremely high, ranging from 810 to over 1,600. The water quality was mediocre because coliform count and *Escherichia coli* were above 1 for 100 milliliters, showing severe pollution.

Ninama (2023) highlighted the seasonal variation in coliform counts observed in three water bodies of Dungarpur. During winter, coliform counts exceeded 200 MPN/100 ml of water, while in the rainy season, they rose to 1600 and above, levels considered beyond measurable limits. The MPN/100ml also rose from 17 for total coliform to 500 for fecal coliform to 500 and *E. coli* at one station. Total coliform, fecal coliform, and *E. coli* fluctuated with the rainy season. Five groups of enteric bacteria were identified in most water bodies, except for Margia Dam, during the rainy season through IMViC tests. As noted earlier, this period saw an increase in disease-causing agents, which corresponded with a high incidence of waterborne diseases, particularly during the late summer months and throughout the rainy season. Coliform counts varied by season and location. Adward Samand recorded over 1,600 counts during the rainy season, 500 in winter, and 900 in summer.

Dimia Talab had counts of 900 in the rainy season, 280 in winter, and 300 in summer. Gapsagar accrued 1,600, 900, and 900 counts for the respective seasons. Sabela Pond reported counts of over 1,600 in the rainy season, 900 in winter, and 1,600 in summer. Margia Dam had counts of 900 in the rainy season, 220 in winter, and 900 in summer. Cyclicality was affected by the location of the reservoir, the waste inlet, the sewer systems, and the rates of rainwater input. Samples showing bacterial counts exceeding 1,600 per 100 ml indicate severe contamination. The high bacterial counts observed may also reveal slight variations in contamination levels between Sabela Pond and Adward Samand during the rainy season. Overall, these locations experienced different degrees of contamination.

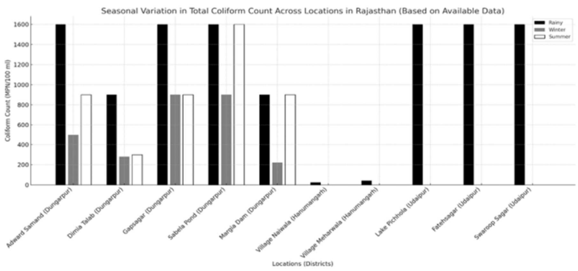

Fig. 1. Seasonal variation in total coliform count across locations in Rajasthan

A detailed study conducted in the Bikaner district of Rajasthan by Ur Rehman *et al.* (2024) assessed the microbiological and physicochemical quality of different drinking water sources. The findings indicate significant fecal bacterial contamination and a variety of waterborne enteric pathogens. These included pathogenic *E. coli, Shigella, Salmonella, Vibrio cholerae, Klebsiella, Pseudomonas,* and *Aeromonas* species, further underlining the health risks associated with contaminated drinking water in the region. Seasonal variation in total coliform counts of various locations in Rajasthan is illustrated in Fig. 1.

Environmental factors shaping zooplankton communities

Zooplankton refers to specific community structures that can be influenced by climatic, physicochemical, and biological factors. Some species are well adapted to the prevailing environmental conditions, while others are constrained by various physicochemical factors, as reported by Gannon and Stemburger (1978) and Neves *et al.* (2003). Additionally, they found a significant relationship between temperature and the quantity and distribution of zooplankton. Zooplanktons are small organisms that play an essential role in the aquatic food chain. Chemical factors can influence metabolic processes, development, fertility, and the ability of organisms to survive. These factors can enhance metabolic rates related to growth and reproduction; however, they can also increase thermal stress and mortality rates at higher temperatures throughout the seasons. As ectothermic organisms, zooplankton's physiological processes, including ingestion, respirations, and reproduction, are dependent on temperature.

A temperature increase of 10°C may cause these processes to double or triple (Mauchline, 1998). Ishaq and Khan (2013) found that the Rotifera and Copepoda populations in the River Tons of India decreased as water temperature increased, indicating a negative relationship. The average body size of cladocerans and cyclopoid fry decreased as water temperature increased, while little evidence supported a similar trend for calanoids (Havens *et al.*, 2015). Moreover, the fatty acid composition indicated that as water temperature decreases, fatty acid levels in Copepoda increase (Gladyshev *et al.,* 2013).

Adequate DO levels are essential for supporting vital metabolic activities. When oxygen levels are low, zooplankton can experience stress, reduced activity, or even death. Low DO concentrations can also affect the spatial distribution of zooplankton, prompting them to migrate to areas with higher oxygen levels. This migration can impact predator-prey relationships and the overall food chain. For example, research conducted by Ekpo (2013) in a tropical rainforest river in Nigeria found a significantly positive relationship between zooplankton species seasonality and dissolved oxygen levels. The cladocerans *Daphnia magna* and *D. pulex* were particularly affected, showing adverse effects at DO concentrations of 0.6 mg/l and 1.6 mg/l, respectively (Nebeker *et al.,* 1992).

pH is a crucial factor that affects zooplankton, as it determines the acidity or alkalinity of their environment, which in turn impacts their physiology and survival. Most zooplankton species thrive within a narrow pH range. Extremely acidic (low pH) or alkaline (high pH) conditions can disrupt their metabolic processes, impair reproduction, and increase mortality rates. Additionally, changes in pH can affect nutrient availability and toxicity, further impacting zooplankton populations. For example, zooplankton composition in the Betwa River decreased with reduced pH levels resulting from industrial effluent discharge (Vishwakarma *et al.,* 2013). Suárez-Morales (2015) categorized copepod species into three groups based on their pH tolerance; euryionic species like *Macrocyclops albidus, Tropocyclops prasinus*, and *Paracyclops fimbriatus* tolerate a wide pH range (4.0–10.5, 4.0–10.5, and 3.5–9, respectively; acidic species like *Diacyclops languidus* and *D. nanus* thrive in acidic conditions but cannot exceed a pH of 8.0; and mesoionic or neutral species like *Cyclops furcifer, C. vicinus, Metacyclops minutus*, and *M. gracilis* inhabit neutral freshwater systems with a pH range of 6.5-8.

High levels of BOD deplete dissolved oxygen, leading to hypoxic conditions that stress zooplankton. This stress negatively impacts their survival, growth, and reproduction. Elevated BOD often favors species tolerant to low oxygen, altering community composition. Rotifer density in the Tigris River decreased as BOD levels increased, which is linked to the direct dumping of domestic sewage into the river, as discussed by Abed *et al.* (2022). Salinity influences zooplankton distribution and physiology, with species thriving within specific tolerance ranges. Changes in salinity, such as from freshwater influx or seawater intrusion, can cause osmotic stress and shift community composition, impacting ecosystem dynamics. Copepoda density increases with rising salinity, while Rotifera density decreases as salinity increases (Nguyen *et al.,* 2020; Majeed *et al.,* 2021). Kaya *et al.* (2010) reported that the zooplankton composition in the Zamanti River is significantly affected by salinity.

Total Dissolved Solids (TDS), comprising salts, minerals, and organic matter in water, significantly affect zooplankton. Elevated TDS levels can cause osmotic stress, impairing zooplankton's physiological processes like growth and reproduction. Excessive TDS may reduce species diversity by favoring more tolerant organisms, while low TDS might limit essential nutrient availability. Scannell and Jacobs (2001) found that higher TDS concentrations in river water typically harm zooplankton, such as *Daphnia magna, Ceriodaphnia dubia*, and *Cyclops abyssorum* prealpinus, along with other aquatic organisms, including algae, fish, insects, and worms. Zooplankton species showed a negative correlation with total dissolved solids (TDS) in the Tropical Rainforest River in Niger (Ekpo, 2013).

Abed *et al.* (2022) observed an inverse relationship between TDS concentrations and Rotifera density in the Tigris River in northern Baghdad City. Increased value of total suspended solids in the Tigris River decreased zooplankton diversity (Abdulwahab and Rabee, 2015). Copepoda negatively correlated with TSS concentrations in the Asan River in India (Ishaq and Khan, 2013). Majeed *et al.* (2022) found that an increase in suspended solids in the Tigris River during the winter season leads to higher Rotifera diversity.

Alkalinity measures the ability of water to neutralize acids, which is essential for maintaining stable pH levels in aquatic ecosystems. Proper alkalinity is vital for zooplankton to sustain physiological processes and mitigate stress caused by fluctuations in pH. In the Haraz River, alkalinity is considered one of the most important factors limiting the growth, composition, and abundance of zooplankton assemblages. This is directly influenced by calcium and magnesium ions, as observed by Jafari *et al.* (2011). Rotifera and Copepoda were positively correlated with total alkalinity in the Tons River (Ishaq and Khan, 2013). Ions, such as calcium, magnesium, sodium, potassium, and chloride, are critical components of water chemistry that influence zooplankton physiology and survival. These ions help maintain osmotic balance, which is essential for processes such as respiration, reproduction, and growth. Essien-Ibok and Ekpo (2015) discovered that the highest zooplankton density coincides with the high values of phosphate and nitrates. Increasing phosphates and nitrates stimulate the growth of rotifera and cladocera in the Ob River in western Siberia (Yermolaeva *et al.,* 2021). The cladoceran population positively correlated with calcium ions in the Tigris River (Abdulwahab and Rabee, 2015).

Some rotifer species and some harpactacoid copepod species prevailed in lakes with Cl-dominated water. In contrast, certain calanoid copepods were dominant in the SO_4^{2-}/CO_3^{2-} dominated lake water (Derry *et al.,* 2003). The acceptable water conductivity value for aquatic organisms is between 250 and 500 µmhos/cm (maximum: 2000 µmhos/cm). Electrical conductivity values showed a positive correlation with zooplankton production, as documented by Bozkurt and Sagat (2008). Williams (1998) noted that variations in conductivity can significantly regulate the structure of zooplankton assemblages, particularly affecting species diversity and richness.

Conclusion

The current review emphasizes the importance of zooplankton diversity and bacterial analysis for assessing the aquatic status of Rajasthan. Zooplankton provides an index of the quality of water primarily due to its susceptibility to hydro metrics such as temperature, dissolved oxygen, pH, and salinity. The density fluctuations of zooplankton are closely related to pollution and eutrophic conditions resulting from human activities. In addition, bacterial pollution presents a significant issue, as waterborne illnesses are caused by pathogens such as *E. coli, Salmonella*, and *Vibrio cholerae*. Bacterial loads are particularly high during the rainy season due to inadequate sanitation and runoff, which exacerbate the issue. Analyzing zooplankton diversity alongside bacterial surveys is essential for sustainable water management and health-related interventions in the water habitats of Rajasthan.

Future research directions

Although recent studies analyzed the diverse zooplankton species and bacterial pollution in the aquatic environment of Rajasthan, there are key gaps that hamper further synoptic assessment and management approaches to public health. One of these gaps is the absence of combined analyses of the relationships in a body of water between the zooplankton communities and bacterial concentrations that could give information about the health state of the tested ecosystem. Moreover, the variations in these factors by season are well established, but the spatial differences within the different water bodies of Rajasthan are relatively unknown. Such cross-system comparisons might reveal more details about the patterns and causative factors of biological diversity fluctuations in the various aquatic habitats in the regions. Another research gap is the effects of global climate change on the composition of zooplankton communities in Rajasthan and quantifying the changes prompted by fluctuations in temperature and severe weather conditions requires long-term assessment.

Documented evidence shows significant relationships between environmental factors and zooplankton species richness; however, the mechanisms influencing zooplankton physiology remain unclear. Previous water quality assessments have primarily focused on bacterial samples using indicator organisms, such as coliform bacteria, and there are relatively few comprehensive studies on pathogenic microorganisms. There is limited knowledge about how microorganisms transfer and behave in infected waters, particularly regarding the role of zooplankton as carriers of pathogens. To fill these gaps, future studies should focus on the interactions between zooplankton and microbes. They should cover larger geographic areas, examine the impacts of climate change, explore various pathways, investigate a diverse range of microbes, assess the role of zooplankton as vectors, and utilize advanced monitoring technologies. These efforts will enhance biomonitoring approaches and support the organization of effective biomonitoring, conservation measures, and public health initiatives in the water ecosystems of the Rajasthan region.

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