Rotifers: general biology, ecological roles and applied importance

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ABSTRACT:

Rotifers are microscopic, multicellular animals belonging to the phylum Rotifera and are widely found in freshwater, marine, and most terrestrial habitats.They are an important part of aquatic ecosystems due to their small size, fast reproduction, and quick response to environmental changes. Rotifers play a key role in aquatic food chains by feeding on algae and bacteria and serving as food for fish larvae and other zooplankton.

This review summarizes the basic biology of rotifers, including their classification, body structure, feeding habits, reproduction, and distribution. It also highlights their ecological importance at practical use. Rotifers are widely used in aquaculture as live feed for fish larvae and are commonly applied as bio indicators to assess water quality. Recent molecular studies have shown that some rotifers, especially bdalloid rotifers, possess genes Obtained from bacteria that are similar to antibiotic producing genes. These genes become active when rotifers face microbial infection, suggesting a natural antimicrobial defense system.

Keywords: Rotifers, Ecotoxicological study, Genomics and Adaptation, Bioindicators, Aquaculture, Waste water treatment, Bioremediation.

INTRODUCTION :

Rotifers are microscopic, multicellular aquatic invertebrates belonging to the phylum Rotifera and are widely distributed in freshwater, brackish, and marine environments. They occur in a broad range of habitats, including permanent water bodies as well as temporary and extreme environments such as ephemeral ponds, mosses, and soil films. Their short life cycles, high reproductive rates, and ability to rapidly exploit available resources make rotifers important components of aquatic food webs and sensitive responders to environmental change (Ricci & Fontaneto, 2009).

Beyond their ecological importance, rotifers have gained attention due to their unusual biological traits and applied relevance. They exhibit diverse reproductive strategies, including cyclical parthenogenesis and obligate asexuality, and show remarkable tolerance to environmental stress . In addition, rotifers are increasingly used in aquaculture, wastewater treatment, and environmental monitoring, highlighting their value as both model organisms and practical tools in applied biological research (Dahms et al., 2011;

Hagiwara et al., 2017). This review provides an integrated overview of rotifer biology, ecology, genetics and genomics, adaptations to extreme habitats, and major applications, while also addressing limitations associated with their use.

Fig 1: Microscopic Image of Rotifers at 100X magnification

CONTEXT :

1.Taxonomic position and phylogenetic placement of rotifers

Rotifers are microscopic multicellular acquisitive animals classified under the phylum Rotifera. For a long time, rotifers were treated as independent phylums. However, molecular and morphological studies have now placed them with the clade Syndermata,Together with Acanthocephala(thorny-headed worms)(Witek et al., 2008; Paps et al., 2009).This taxonomic placement is supported by shared characteristics such as syncytial epidermis and similarities in reproductive and developmental features,As well as evidence from ribosomal RNA and genome based phylogenetic analysis(Wallace et al., 2006). The phylum Rotiferra is taxonomically divided into 3 major classes: Monogonota, Bdelloidea and Seisonidea (Segers, 2007).Monogononts represent the most diverse group and reproduce mainly through cyclical parthenogenesis, Alternating between asexual and sexual phases, Bdelloid rotifers are Entirely asexual and are well known for their ability to survive extreme environmental conditions such as desiccation(Mark Welch & Meselson, 2000).Seisonids are rare, mostly marine rotifers, and are considered important for understanding early diversification of the group.Phylogenetic studies further indicate that acanthocephalans likely evolved from free living rotifer-like ancestors, strengthening the close evolutionary and taxonomic relationship between these groups(Witek et al., 2008)

2.External Morphology and Body Organization

Rotifers are microscopic aquatic invertebrates with a characteristic external body organization that shows clear adaptation to their lifestyle. The bodies typically divided into 3 regions, the head, trunk, and foot, although the degree of separation between these regions varies among species(Wallace et al., 2006).The basic body plan is defining feature of the phylum Rotifera and is widely used in morphological identification(Segers, 2007)

The head region bears the corona a ciliated structure that appears wheel-like in motion. The corona plays an important role in both locomotion and feeding by creating water currents that direct food particles towards the mouth(Nogrady et al., 1993).The structure of the corona differs among the rotifer groups and is often related to habitat and feeding mode, with planktonic forms generally having more prominent corona than benthic species(Wallace et al., 2006).

The trunk region forms the main body and contains most internal organs. In many monogonont rotifers the trunk is enclosed by a rigid or semi rigid covering called the lorica which provides protection and structural support(Koste, 1978). Lorica shape and ornamentation are important taxonomic characters at the species level. In contrast, bdelloid rotifers lack a rigid locaria and possess a flexible body wall that allows extensive contraction and extension, an adaption linked to creeping movement and desiccation tolerance (Ricci, 1998).

The posterior foot region is usually segmented and ends in one or more toes that secrete adhesive substances, allowing rotifers to attach temporarily to substrates such as plants or sediments(Wallace et al., 2006). In some free-swimming species, the foot is reduced or absent, reflecting differences in habitat preference and mode of life (Segers, 2007).

3.Internal Anatomy and Physiology of Rotifers

Rotifers possess a well developed internal anatomy despite their microscopic size with organ systems adapted for efficient feeding, metabolism and reproduction. The internal organization is relatively consistent across phylum. Although structural details vary among different taxonomic groups (Wallace et al., 2006). Most internal organs are located within the trunk region, which is enclosed by the body wall or lorica.

The digestive system of rotifers is complete and consists of a mouth, pharynx, esophagus, stomach, intestine and anus. A distinctive feature of rotifer anatomy is the mastax, A muscular pharyngeal structure containing hardened jaw elements known as trophy(Nogrady et al., 1993).The mastax plays a crucial role in food processing the shape and arrangement of the trophy vary according to the feeding habits such as filter feeding, scraping or predation.Digestive enzymes secreted in the stomach aid in extracellular digestion, followed by nutrient absorption in the intestine (Wallace et al., 2006).

The excretory and osmoregulatory system is composed of pair protonephridia with terminal flame bulbs.These structures function in the removal of metabolic waste and help maintain ionic and osmotic balance, a critical adaptation for survival in hypotonic freshwater environments(Clément & Wurdak, 1991). The activity of the flame bulbs is closely linked to the regulation of body fluid volume and overall physiological stability.

Rotifers possess a relatively simple but functional nervous system, typically consisting of cerebral ganglion located near the anterior region, longitudinal nerve chords, and peripheral sensory structures (Nogrady et al., 1993). Sensory organs such as tactile bristles, photoreceptors and chemoreceptors allow rotifers to respond effectively to environment stimuli, aiding in feeding, movement and predator avoidance(Wallace et al., 2006).

The reproductive organs are also part of internal anatomy and show considerable variation between classes. In monogonont rotifers, females usually possess a single ovary that also functions as vitellarium, whereas male are often reduced in size and lack a digestive system. In contrast, bdelloid rotifers possess paired ovaries and reproduce exclusively by parthenogenesis, a unique evolutionary strategy where females produce offsprings without genetic contribution from males (Mark Welch & Meselson, 2000).

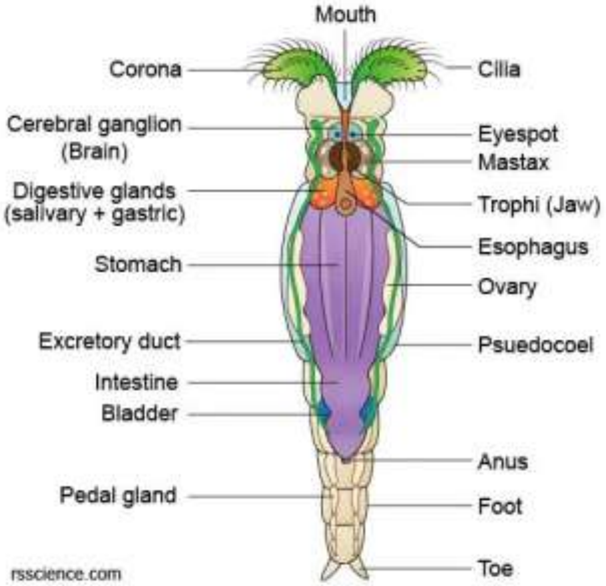

Fig 2: The anatomy of a female Bdelloid Rotifer

4.Reproductive Biology and Development of Rotifers

Rotifers exhibit diverse and highly specialized reproductive strategies that contribute to their rapid population growth and ecological success.Reproductive biology varies significantly among major rotifer groups, particularly between monogonant and bdelloid rotifers, and is closely linked to environmental conditions (Wallace et al., 2006).

In monogonont, rotifer's reproduction typically occurs through cyclic parthenogenesis, in which females reproduce sexually for several generations by producing diploid eggs that develop directly into females(Nogrady et al., 1993). Under unfavorable environmental conditions such as changes in population density, food availability, or temperature, sexual reproduction is induced.During this phase, females produce haploid eggs that develop into males. Fertilization of haploid eggs resulting in formation of resting eggs which are thick walled and highly resistant to desiccation, freezing and other environmental stresses(Segers, 2007). These resting eggs can remain dormant for extended periods and hatch when conditions become favorable, ensuring long term survival of the population.

In contrast, bdelloid rotifers reproduce exclusively by obligate parthenogenesis and males have never been observed in this group.Bdelloid rotifers produce diploid eggs That developed directly into females and their long term or sexuality represents a unique evolutionary strategy among metazoans.They are reproductive mode is closely associated with their ability to survive extreme environmental stresses, particularly desiccation, which allows them to persist and disperse without sexual reproduction (Ricci, 1998).

Development in rotifers is generally rapid and direct, with embryos undergoing a fixed and determinate pattern of cell division known as eutely, In which the number of somatic cells remains constant within a species (Wallace et al., 2006)Embryonic development typically occurs within the egg and results in a miniature but fully functional juvenile rotifer.The short generation time and early reproductive maturity enables rotifers to respond quickly to changing environmental conditions.

5.Genetics and Genomics of Rotifers

Genetics and genomic studies have provided important insights into the biology, evolution and adaptability of rotifers, particularly bdelloid rotifers. Early molecular analysis based on rRNA sequences helped establish phylogenetic relationships within the phylum, while recent whole genome sequencing efforts have revealed several unusual genomic characteristics (Wallace et al., 2006).One of the most remarkable discoveries is the presence of large number of genes of non metazoan origin in bdelloid rotifers.These genes, derived mainly from bacteria, fungi and plants, are believed to have been acquired through horizontal gene transfer and are actively expressed in rotifer cells (Gladyshev et al., 2008). Genome sequencing of species such as *Adineta vaga* have demonstrated that these foreign genes are stably integrated into the genome and contribute to core biological functions (Flot et al., 2013).

A significant proportion of these horizontally acquired genes show similarity to antibiotic like or antimicrobial resistance related genes and their retention is throughout to provide clear functional advantages to rotifers.These genes may enhance protection against pathogenic bacteria and fungi in microbe rich aquatic and terrestrial habitats by contributing to antimicrobial defense, detoxification processes, and cellular stress response (Gladyshev et al., 2008). Search functions are particularly beneficial during desiccation and rehydration cycles when bdelloid Rotifer's experience extensive DNA damage and increased exposure to opportunistic microorganisms. Genes involved in oxidative stress resistance, DNA repair, and cellular protection help rotifers survive these extreme conditions and recover rapidly once favourable conditions return (Flot et al., 2013).

Recent comparative genomic studies have further shown that genes associated with desiccation tolerance, DNA repair, and horizontal gene transfer are consistently enriched in bdelloid rotifers, highlighting their importance in long-term survival under extreme and fluctuating environmental conditions (Nowell et al., 2021).

In addition, antibiotic-like genes may reduce microbial competition for resources, allowing rotifers to exploit available food more efficiently in biofilms, temporary water bodies, and other nutrient limiting environments (Nowell et al., 2018). In contrast, monogonont rotifers possess more typical animal genomes, with sexual reproduction contributing to genetic diversity through recombination (Mark Welch & Meselson, 2000).

6.Feeding, Ecology and Trophic Strategies of Rotifers

Rotifers occupy an important ecological position in aquatic ecosystems due to their diverse feeding habits and trophic roles. They are primarily microphagous, feeders consuming a wide range of.4 particles, including bacteria, algae, protozoans, detritus, and dissolved organic matter(Wallace et al., 2006).Their small size, rapid feeding rates and high population turnover allow rotifers to efficiently exploit microbial resources and contribute significantly to energy transfer within aquatic food webs.

Feeding in rotifers is closely linked to the structure of corona and mastax, which together determine the mode of food capture and processing. Many planktonic rotifers are filter feeders using ciliary currents generated by the corona to capture suspended particles. Such as phytoplankton and bacteria, other species exhibit scraping or raptorial feeding, Praying on protozoans, small metazoans, Or filamentous algae with specialized trophy adapted for grasping and piercing prey (Nogrady et al., 1993).The diversity in feeding mechanisms allows different rotifer species to coexist by occupying distinct trophic niches.

Ecologically, rotifers are key components of zooplankton communities in freshwater and marine environments. They form an important link between primary producers and higher trophic levels, serving as major food sources for cladocerans, copepods and fish larvae (Segers, 2007). Through their grazing activity, rotifers influence phytoplankton abundance, bacterial population, and nutrient cycling, thereby regulating water quality and ecosystem productivity. In microbial food webs, rotifer play a central role in microbial loop by transferring Carbon and nutrients from bacteria and small algae to large consumers (Wallace et al., 2006).

Rotifiers' trophic strategies are highly flexible and respond rapidly to changes in environmental conditions such as food availability, temperature and nutrient status. Many species show seasonal shifts in feeding behaviour and population density, reflecting changes in phytoplankton consumption and productivity (Allan, 1976). This trophic plasticity enables rotifers to thrive in wide ranges of habitats, including lakes, ponds, rivers, temporary pools and wastewater systems. Overall, the feeding ecology and trophic diversity of rotifers contribute significantly to their ecological success and highlight their importance in maintaining the structure and functioning of aquatic ecosystems.

7.Rotifers in Extreme and Temporary Habitats

Rotifers are well adapted to survive in extreme and temporary habitats such as ephemeral ponds, drying wetlands, mosses, lichens and soil films where environmental conditions fluctuate rapidly. These habitats are characterized by periodic desiccation, temperature, stress, and nutrient instability, which limit the survival of many aquatic organisms. Rotifers, especially bdelloid rotifers, possess physiological and life history traits that allow them to persist under such conditions (Ricci, 1998; Wallace et al., 2006).

A key adaptation is anhydrobiosis, A reversible state of dormancy induced by desiccation during which metabolic activity is suspended and cellular structures are protected. Bdelloid Rotifers can survive prolonged drying and resume normal activity upon rehydration, enabling persistence and dispersal across harsh environments (Ricci, 1998). In contrast, monogonany rotifers rely mainly on resting eggs to survive unfavorable periods in temporary aquatic habitats. These resistant eggs remain viable in sediments and hatch rapidly when conditions improve, allowing quick population recovery (Segers, 2007). Through rapid colonization and grazing activity, rotifers play an important role in structuring microbial communities and initiating Tropic interactions in newly formed or disturbed ecosystems.

8.Role of Rotifers in Waste Water Treatment and Bioremediation

Rotifers play a beneficial role in wastewater treatment systems, particularly in activated sludge processes, where they contribute to the stabilization and clarification of treated effluent. They are commonly found in well functioning treatment plants and are considered indicators of good sludge quality and effective biological treatment (Curds & Cockburn, 1970; Wallace et al., 2006).By grazing on bacteria, protozoans, and fine organic particles, rotifers help regulate microbial populations and improve sludge settleability.

Species belonging to genera such as *Lecane*, *Brachionus*, and *Philodina* are frequently reported in wastewater environments. Their feeding activity reduces excessive bacterial biomass and controls filamentous bacteria, which are often responsible for sludge bulking problems (Madoni, 1994). This grazing pressure promotes the formation of compact flocs, enhancing sedimentation efficiency and leading to clearer effluent. As a result, rotifers indirectly support nutrient removal and overall process stability in wastewater treatment plants.

In addition to the treatment efficiency, rotifer potential application in bioremediation, their tolerance to organic pollution, heavy metals and fluctuating environmental conditions allow them to survive in contaminated waters where other zooplankton may be absent (Segers, 2007). Rotifers can accumulate pollutants through feeding and may facilitate the transfer of contaminants into higher Tropic levels or sediments, contributing to pollutant cycling and transformation Due to their sensitivity to changes in organic load and toxic substances, rotifer community structure is also used for biological monitoring of wastewater performance and environmental impact (Madoni, 1994).

9.Rotifers in Aquaculture and Fisheries

Rotifers are widely used in aquaculture and fisheries as one of the most important live feed organisms for the early larval stage of fish and crustaceans. Their small size, slow swimming behaviour and high digestibility make them particularly suitable for first feeding larvae. Which often cannot capture or ingest larger prey (Lubzens et al., 2001). Among rotting firms, species of genus *Brachionus* are most commonly cultured and used in marine and brackish water aquaculture systems.

One of the major advantages of rotifers in aquaculture is their ability to be mass cultured under control conditions. They can be produced at higher densities using microalgae, yeast based diets or formulated feeds allowing a reliable and continuous supply of live food (Wallace et al., 2006). In addition, rotifers serve as effective carriers for nutritional enrichment by feeding on algae or emulsion rich in essential fatty acids, vitamins and minerals. The rotifer can be nutritionally enhanced before being offered to live fish larvae, thereby improving larval growth, survival, and stress resistance (Lubzens et al., 2001).

In fisheries and hatchery operations, rotifers play a crucial role in improving larval rearing success, particularly for marine species with small mouth openings and limited feeding ability. Their use helps reduce early stage mortality and support the transition of larvae to larger life feeds such as *Artemia* nauplii. Beyond their direct uses, feed protocols are also studied as model organisms to optimize feeding protocols, assess nutritional requirements, and evaluate the effects of water quality and microbial management in hatchery systems (Segers, 2007).

10.Rotifers as Bioindicators, Monitoring Tools, and Models in Ecotoxicology and Risk Assessment

Rotifers are widely recognized as effective bioindicators of water quality due to their short life cycles, rapid population responses, and sensitivity to changes in environmental conditions. Variations in rotifer species composition, abundance and diversity reflect alterations in nutrient status, organic pollution and ecosystem stability making them useful tools for routine monitoring of freshwater bodies and wastewater treatment systems (Wallace et al., 2006; Segers, 2007).Certain rotifer taxa are associated with eutrophic or organically polluted waters, while others are characteristic of cleaner environments, allowing community based assessment of ecological status.

In applied monitoring, rotifers are frequently included in biotic indices and microfaunal assessment used to evaluate the performance of biological treatment processes. Changes in rotifer community structure can provide early warning signals of system imbalance, toxic shock or operational failure, often before physiochemical parameters show detectable shift (Madoni, 1994). Their ease of sampling and identification further enhances their particularity as routine monitoring organisms.

Refers are also extensively used in ecotoxicology and environmental risk assessment as model test organisms species such as *Brachionus calyciflorus* are commonly employed in standardized toxicity assays to assess the effects of heavy metals, pesticides, pharmaceuticals and emerging contaminants, including nanoparticles (Snell & Janssen, 1995). Toxicity endpoints measured in rotifer bioassays include survival, reproduction, population growth rate, and behavioral response, providing sensitive and ecologically relevant indicators of some lethal and chronic effects.

The use of rotifers in ecotoxicological testing offers several advantages like small size, ease of culture, short generation time, and ethical acceptability. Moreover, rotifers based assays help bridge the gap between microbial toxicity tests and higher organism bioassays, contributing valuable data for environmental risk assessment and regulatory decision making.

11.Limitations in the Applications and Usage of Rotifers

Despite their wide use in ecology, aquaculture, and ecotoxicology, rotifers have several limitations that restrict their broader application. A major constraint is the difficulty in maintaining stable cultures, as rotifer populations are highly sensitive to changes in temperature, food quality, oxygen levels, and microbial contamination, often leading to sudden population declines (Wallace et al., 2006).

Accurate species identification also remains challenging due to high morphological plasticity and the presence of cryptic species, which can reduce reproducibility in ecological monitoring and toxicity studies (Segers, 2007; Fontaneto, 2014). Although molecular tools improve taxonomic resolution, they are not always feasible for routine applications. In aquaculture, rotifers require nutritional enrichment to meet the dietary needs of fish larvae, increasing operational complexity and cost (Lubzens et al., 2001). Additionally, in ecotoxicological studies, species-specific sensitivity to pollutants limits standardization and the direct extrapolation of laboratory results to natural ecosystems (Snell & Janssen, 1995).

DISCUSSIONS AND CONCLUSION :

Rotifers constitute an ecologically significant group of microscopic metazoans characterized by diverse morphological, physiological, and reproductive features that support their wide distribution across aquatic and semi-terrestrial habitats. Advances in molecular and genomic studies have improved understanding of their evolutionary strategies, stress tolerance, and genetic adaptability, particularly in bdelloid rotifers. In addition to their biological importance, rotifers have demonstrated clear utility in aquaculture, wastewater treatment, ecological monitoring, and ecotoxicological assessment.Ongoing research on rotifers increasingly combines molecular, genomic, and ecological approaches to better understand their evolution, adaptation, and environmental responses. Future studies are expected to further clarify the functional roles of horizontally acquired and stress-related genes, particularly in relation to desiccation tolerance and survival in extreme habitats. Advances in sequencing and transcriptomic tools will improve insight into gene regulation and adaptive mechanisms across rotifer taxa.

Despite certain methodological and practical limitations, rotifers continue to serve as useful model organisms for integrating fundamental biological research with applied environmental studies.

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