Review Article

Resistance Mechanisms in Aquatic Insects against Environmental Stressors: A Review

ABSTRACT

Aquatic insects are found in nearly every kind of freshwater habitat and play an important role in the aquatic ecosystem as predators, parasites, shredders, grazers, filter feeders, and piercers. Due to their critical role in energy flow and cycling of nutrients, they are essential components of freshwater ecosystems. However, their survival in a particular habitat is threatened by various environmental stressors, including pollution, habitat degradation and climate change. These challenges affect their immune system, thereby weakening their natural defenses. To fight against infections, aquatic insects primarily rely on the innate immunity, which includes both humoral and cellular responses. However, environmental factors such as fluctuating temperatures, chemical pollutants, and low oxygen levels in aquatic bodies can damage these immune defenses, making the insects more susceptible to diseases. To defeat these challenges, some species have evolved adaptive strategies, both physiological and behavioural. Such changes include the production of antimicrobial peptides, improved phenoloxidase activity and the generation of heat shock proteins. In the present review, we explore the existing research on how environmental stressors impact the immunity of aquatic insects. Understanding the immunological mechanisms of aquatic insects can assist in conservation planning of aquatic insects by revealing their adaptability to environmental stressors. During our literature survey, we also examined the adaptive mechanisms the aquatic insects employ, the ecological implications of these changes and the importance of insect's immune adaptation in conservation efforts.

Keywords: *Aquatic insects, immunity, antimicrobial, conservation, ecological, adaptation*

1. INTRODUCTION

Insects belonging to the Phylum Arthropoda constitute the largest group not only of the animal kingdom but also of the whole living world. A large number of insects spend their entire life or at least a part of it in water, called aquatic insects. Aquatic insects make up only 3-5 percent of all insect species, but are exceedingly taxonomically diverse (Daly *et al.* 1998). They occupy every kind of freshwater habitat, including temporary streams and ponds, the shallowest and deepest areas of lakes, the most pristine and polluted rivers, roadside ditches, and within and on macrophytes, and are susceptible to all ranges of water chemistry, from acidified to alkaline bodies of water. They also represent all the functional feeding groups, including predators, shredders, grazers (or scrapers), filter feeders, gatherers, piercers and parasites (Mackie, 2001). A study on aquatic insect fauna is one of the important aspects of freshwater biology. Aquatic insects form an important link in many food chains. They consume other invertebrates, small fish, aquatic plants, algae, detritus and decaying matter. Aquatic insects are also an important food source for birds, fish, reptiles and amphibians. They have a trophic link with terrestrial consumers like insectivorous birds (Danforth, 1926), which gives them a higher consideration for the management of the wetland as a wildlife refuge. Aquatic insects are also often used to determine water quality based on the types and number of species. Due to their sensitivity to environmental variables, aquatic insects are frequently employed in biomonitoring (Singh *et al.* 2025). Many aquatic insects are biting pests to both humans and other animals. Some dipterans, most notably mosquitoes, are also vectors of diseases which include malaria, encephalitis and yellow fever. On the other hand, adult odonates can greatly reduce adult mosquito population (Daly *et al.,* 1998) while the predaceous diving beetle (Coleoptera) and several other predatory aquatic insects (mostly Hemiptera) can help to reduce mosquito population by feeding on their larvae (Lundkvist *et al.,* 2003, Saha *et al.,* 2007). Midges feed on algal mats and sediments in sewage treatment facilities, which helps them to keep them running properly (McCafferty, 1981). Some herbivorous aquatic insects have the potential to be used as biological control of invasive aquatic plants (Adler *et al.*, 2019).

The survival and evolutionary success of aquatic insects occupying various aquatic habitats are largely dependent on immune adaptation and resistance mechanisms (Schmid-Hempel, 2005). They live in habitats that are abundant in bacteria, fungi, and viruses; as such, they have evolved exceptional immune defenses and infection-resistance mechanisms to survive in such pathogen-rich environments (Mahanta *et al.*, 2023). According to Flatt *et al.* (2008), aquatic insects mostly depend on their innate immune system, which consists of humoral and cellular reactions. Eleftherianos *et al.* (2021) found that hemocytes are essential for cellular immunity because they carry out processes like phagocytosis, encapsulation, and melanization. In contrast, the humoral response produces enzymes, other proteins, and antimicrobial peptides (AMPs) that destroy infections (Strand, 2008). The immunological responses of different insect species have changed as a result of adaptation to various aquatic habitats. While some species strengthen their cuticle to prevent the entrance of pathogens, others increase their ability to resist infections by producing more AMPs (Siva-Jothy *et al.*, 2005). Furthermore, immune memory-like responses have also been seen in insects despite their lack of vertebrate-like adaptive immunity, indicating that previous exposure to pathogens may improve subsequent immune responses (Cooper & Eleftherianos, 2017).

The molecular and cellular mechanisms of immunological adaptation in aquatic insects are still poorly understood, despite the comprehensive research on immune responses in model organisms (Little *et al.*, 2005; Rolff & Reynolds, 2009). The effects of pollution and temperature changes on aquatic organisms have been the focus of recent research. But little is known about how multiple stressors, including habitat loss, chemical exposure, and climate change, affect immune system function (Segner *et al.*, 2014). The aim of the present review aims to scrutinize how immune system of aquatic insects living in different aquatic ecosystems is impacted by environmental stresses such as pollution, temperature swings, climate change, and habitat degradation. Additionally, it will assess the defence mechanisms that aquatic insects use against pathogen and parasite attacks.

2. ENVIRONMENTAL STRESSORS AFFECTING AQUATIC INSECT IMMUNITY

In a recent study carried out by Kataoka and Kashiwada (2021), it has been clearly shown that environmental factors such as temperature change, oxygen depletion in aquatic environment and pollution play a major role in the defense mechanisms of aquatic insects, making them more vulnerable to illness. The same is also supported by Le Moullac (2000) with his study on environmental factors affecting the immune system of crustaceans, an important group of aquatic arthropods. Increased water temperatures brought on by climate change can exacerbate thermal stress, which interferes with vital immune enzymatic functions (Siva-Jothy *et al*., 2005). On the other hand, Vogelweith et al., (2017) have found that long exposure to heavy metals such as lead and cadmium can damage the ability of an insect body to produce antimicrobial peptides, which are critical elements to fight against infections. Environmental pollutants such as pesticides, heavy metals and industrial wastes also harm the defence mechanisms of aquatic insects, reducing their ability to fight against diseases (*Kim et al.* 2021). This investigation highlights the immunotoxic effects on ecology, which can disrupt the stability of the ecosystem and population dynamics of aquatic insects. According to Rohr *(*2008), the key components of the innate immunity of aquatic insects such as haemocyte activity and phenoloxidase production are suppressed by the insecticides and pesticides used in agricultural activities. Eutrophication leading to reduced dissolved oxygen levels causes hypoxic conditions in aquatic insects, which potentially limit the energy resources necessary for the activation of the immune system (Ficke *et al.*, 2007; Brown *et al.,* 2004). On the other hand, Gorr *et al.* (2010) have already opined that hypoxia in an aquatic environment disturbs the regulation of heat shock proteins (HSPs), preventing the process of cellular-level apoptosis. Habitat destruction, one of the primary drivers of biodiversity change and sedimentation, can alter the environment of aquatic habitats by affecting the availability of food resources and other important factors and indirectly affect immunity of aquatic insects by reducing energy intake and increasing stress (Dudgeon *et al.*, 2006; Townsend *et al.*, 2008).

In addition to these, pathogens such as bacteria, viruses and fungi also affect the healthy life cycle of aquatic insects by altering their behaviour, reducing reproductive success and increasing mortality rates. For example, the fungus species *Lagenidium giganteum* causes high mortality in the mosquito population, especially in *Culex* (Merrim and Axtell, 1982; Jaronski and Axtell, 1983) and *Anopheles* species (Kerwin and Washino, 1987). Similarly, the fungal pathogen *Metarhizium anisopliae* attacks the cuticle and internal tissues of mosquito larvae and reduces their survival rate (Scholte *et al.,* 2004). According to Williams *et al.* (2005), viral infections, such as *Iridovirus,* cause mass mortality during larval stages in aquatic insects, which affects the food web dynamics and nutrient cycling. Understanding these environmental impacts is critically essential for the conservation of aquatic ecosystems and for reducing the effects of environmental change.

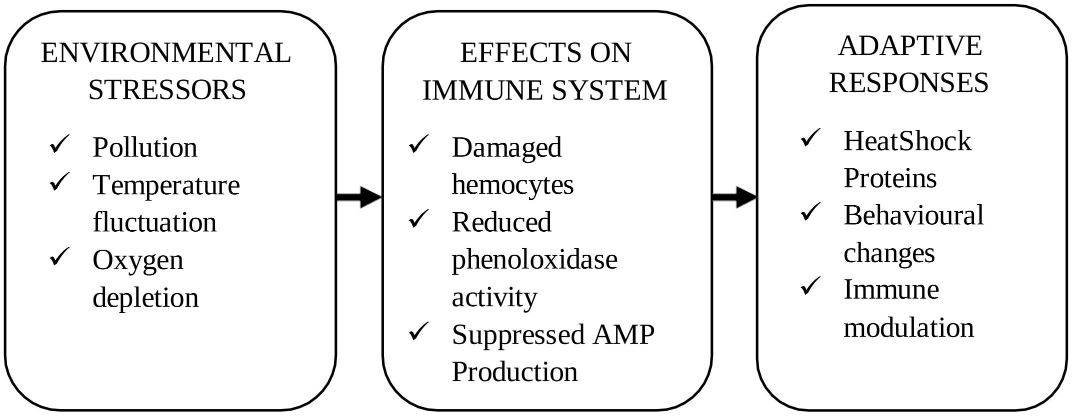

Figure1. A diagrammatic representation showing Environmental Stressors and Immune Responses in aquatic insects

3. MECHANISMS OF IMMUNE ADAPTATION TO STRESSORS

The innate immune system in the form of phagocytosis, antimicrobial peptides and melanin-based encapsulation, is the most reliable form of cellular and humoral responses in aquatic insects (Siva-Jothy *et al.,* 2005). However, the immune systems of aquatic insects are continually challenged by the environmental stressors, including pollution, temperature fluctuations and changes in water chemistry. The primary component of the aquatic insect immune system is the production of antimicrobial peptides (AMPs), which help in the protection against microbial infections by rupturing the cell membrane of the pathogens (Ezzati-Tabrizi *et al.*, 2013). The AMPs disorganize the microbial membranes by forming numerous pores, causing cell lysis or interfering with the intracellular targets, including DNA or protein synthesis (Bulet & Stocklin, 2005). Common AMPs identified in aquatic insect bodies include cecropins, effective against Gram-negative bacteria; defensins, which act against Gram-positive bacteria; and attacins, which target bacterial cell wall components (Vilcinskas, 2020). According to Cerenius & Soderhall (2004), the immune system of aquatic insects depends on phenoloxidase (PO) activity which is primarily involved in melanization, a process that encapsulates and neutralizes invasive foreign particles and microorganisms.

Pollutants like pesticides and heavy metals create major problems in aquatic insects by causing oxidative stress and interfering with cellular signalling pathways, and ultimately impair the immune system (Gill *et al.*, 2019). However, aquatic insects exhibit some remarkable adaptive changes through physiological and behavioural mechanisms. For example, some species demonstrate increased resistance to diseases by upregulating the PO activity (Laughton *et al.*, 2011). Furthermore, some species also produce heat shock proteins (HSPs), like HSP70 and HSP90, which serve as molecular chaperones and shield the cellular proteins from thermal stress-induced damage (Pockley, 2003). Moreover, as indicated by Vilcinskas (2020), changes in the microbiome and epigenetic modifications such as DNA methylation and histone acetylation allow aquatic insects to adapt to changing environmental conditions, a key factor in immune plasticity.

4. ECOLOGICAL AND EVOLUTIONARY IMPLICATIONS

Environmental stressors, such as temperature fluctuations and pollution, significantly influence the immune adaptation of aquatic insects, with significant ecological and evolutionary consequences.

These stressors directly impact reproduction, survival rates, and population dynamics (Schmid-Hempel, 2011). According to Gonzalez-Santoyo and Cordoba-Aguilar (2012), immune adaptations influence species interactions, including prey-predator relationships and disease transmission. The recent review carried out by Schmid-Hempel (2005) on variation in immune defense as a question of evolutionary ecology has clearly opined that animals with stronger immune adaptations tend to live in pathogen-rich environments, outcompeting weaker ones, which leads to shifts in ecosystem dynamics and alterations in community composition. Cerenius and Soderhall (2004) also found that insects with higher levels of phenoloxidase activity and antimicrobial peptides (AMPs) are better equipped to resist pathogens compared to individuals lacking such adaptations, leading to colonization in diverse habitats. Such changes in the immune system also influence reproductive success and population stability in aquatic insects, as shown by Rolff and Siva-Jothy (2003). Insects with weaker immunity expend more energy defending against the pathogens resulting, in fewer energy resources for reproduction and lower fecundity with slower population growth (Rolff and Siva-Jothy, 2003). From the evolutionary point of view, long-term exposure to environmental stressors can lead to natural selection, favouring species with stronger immune adaptations to survive and thereby passing their traits to next generations. Extreme environmental stressors, however, exceed the ability of an organism's adaptive capacity, which may lead to species extinction. This process may be a major driver of biodiversity change in aquatic ecosystems, determining the species that can live in certain ecosystems and species that face population decline (Rolff and Reynolds, 2009; Vilcinskas, 2020).

5. CONSERVATION PERSPECTIVES OF AQUATIC INSECTS

Because of different environmental stressors, insects regularly face population crises, which can be solved by applying different conservation methods. A study by Burdon *et al. (*2019) discusses about the importance of conservation and the effects of pollutants on aquatic invertebrate communities. According to them, conservation should focus on building an environment-friendly home for insects, which includes reducing the use of chemical pollutants, maintaining their habitat integrity and supporting methods to reduce the consequences of climate change on insects. Studies about the immunological side of aquatic insects can help conservation planning by showing their level of adaptation to different stressors (Rolff and Reynolds, 2009). Habitat restoration and enhancing the water quality also help in reducing their complexity and improving the population size of the insects by strengthening their adaptive capacity (Palmer *et al.,* 2010). According to Contador *et al.* (2012), the amount of research and publications about the conservation of aquatic insects is still very low. During their study, they found that from 1995 to 2008, only 5% of all the works published focused on the conservation of aquatic insects. More publications can attract more people’s eyes towards aquatic insect conservation and their health-related issues.

6. CONCLUSION

The present review highlights several key areas of research need to be focused on. One major gap is the limited understanding of molecular and genetic mechanisms during immune adaptation in aquatic insects inhabiting different ecosystems. Recent advancements in the field of genetic and epigenetic studies of different organisms will be of key importance to identifying different pathways involved in immune responses to environmental stressors such as temperature change, pollution and hypoxia. Additionally, it has been found that a knowledge gap still exists regarding the combined examination of the effects of multiple stressors on aquatic insect populations. The role of micro-biota in regulating the immunity in insects is still unclear and further study is needed to clearly understand how environmental changes impact gut microbes of aquatic insects and effect immune functions.

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