



Impact of pollutants on external fertilization process of aquatic animals: An ecological perspective

Biplab Bhowmik¹, Sanjib Ghosh^{2*}

¹ Department of Zoology, Diamond Harbour Women's University, Diamond Harbour, West Bengal, India

² Department of Zoology, Rishi Bankim Chandra College, Naihati, West Bengal, India

Abstract

Human activities such as urbanization, industrialisation, and agricultural operations all contribute to water contamination. Anthropogenic pollutants include a variety of synthetic organic chemicals and heavy metals that are widely diffused in the environment, usually in low amounts. External fertilisation is most common in aquatic habitats. When both eggs and sperm are discharged in the aquatic ecosystem, it is obvious that either gamete have chances to be encountered by the pollutants deposited in the system. Heavy metals, pesticides, microplastics, and nanoparticles are examples of anthropogenic pollutants that are mainly found in aquatic bodies. All these pollutants have a wide range of effects on the external fertilisation process through different ways. When the process of external fertilization is affected in any step, it may have a significant impact on individual reproductive success. On the broader range population parameters along with community level interactions may be hampered. Aquatic ecosystem in such cases become vulnerable to change its normal composition and structural entity. All these events have long term consequences on the evolutionary process.

Keywords: External fertilization, Pollutants, Polyspermy, Reproductive success.

Introduction

Fertilization is the most important event in the life cycle of sexually reproducing organisms. Most of the aquatic animals (both invertebrates and vertebrates) reproduce through external fertilization. In case of external fertilization both male and female release gametes into the aquatic environment. The whole process of fertilization occurs outside of the body in most of the aquatic animals. In such cases fertilization is regulated by a series of complex and multidimensional interactions between gametes (Kekäläinen and Evans, 2018) [14]. Success of external fertilization depends on four precisely organised events. First, gametes are released in aquatic environment. Then gamete communication and attraction occur through egg-derived chemicals. Next step is sperm-egg fusion which is mediated by interactions between surface proteins of both gametes. To regulate and confirm species specific interaction these three steps play the pivotal role in external fertilization process. The final step is repression of polyspermy. Gamete activation is a necessary for precise gamete dispersal. Sperm activation is a complicated and multistep process. Extracellular coat proteins of the oocyte play the most significant role for the activation of sperms of the same species in aquatic environment. Several morphological and functional modifications of sperms occur after activation. According to Tosti and Ménézo (2016) [29] these modifications of sperm result in sperm motility that promote sperm movement towards oocyte. As a result, binding, and fusion of sperm with the oocyte occurs in aquatic medium. After acrosomal reaction sperm release some proteins and factors that bring a cascade of electrical, structural, and metabolic modifications in oocyte and after this the oocyte become activated for further developmental processes (Dale *et al.*, 2010) [7]. Many anthropogenic pollutants have been released in the environment over the last few decades that were never been present before. Wurl and Obbard (2004) [32] described these agricultural and industrial substances as

xenobiotics. Many anthropogenic materials like pesticides, herbicides, nanoparticles, microplastics, pharmaceuticals and metals can be listed under xenobiotics.

These anthropogenic pollutants enter aquatic organisms' body mainly through marine, ground and drinking waters. Reproductive potential and survival capacity of aquatic organisms are compromised when they are exposed to xenobiotics (Ritter, 2002) [23]. Understanding the impact of environmental pollutants on aquatic organisms at all stages of their life cycle is critical because of the continually changing environment. Climate change is proportionately related to the anthropogenic influences that have ultimately resulted in dramatic changes in the temperature, pH, oxygen levels, and other important aquatic ecosystem parameters. Research on the effects of environmental pollutants has always focused on ecosystem, species, and population-level effects and different stages of life cycle that are vulnerable to environmental variations. Environmental stress has detrimental impact on gametes motility, structure and physiology at genetic level and molecular level. This is important because effects on reproduction have serious impacts for individual fitness, which in turn can affect population health and viability (Walash *et al.*, 2019). Gametes released in aquatic ecosystems are more vulnerable because they are directly exposed to anthropogenically-induced environmental pollution in aquatic systems (Albright and Mason, 2013) [2]. Environmental conditions of the aquatic system where external fertilization occur may have tremendous impact on the motility and viability of the released gametes. Pollution and climate change pose sharp threat to external fertilization and in consequence the community structure and interaction may be affected. All these have potential evolutionary consequences. In this review we will try to figure the probable evolutionary consequences of anthropogenic pollutants on externally fertilising animals in aquatic ecosystems.

Materials and method

All the information and data required to write this article are collected from different sources and previously published articles in prestigious journals from all over the globe. Mainly articles published in PubMed, Google Scholar, Science Direct, and Scopus are considered to gather information for this review article.

Potential anthropogenic pollutants

Industrialization, agriculture, and globalization are the main anthropogenic activities that are rapidly influencing the climate and all types of ecosystems of this planet. A little fluctuation in temperature, pH and salinity has severe impact on the living organisms of aquatic ecosystems. Any kind pollution in aquatic ecosystems may affect the reproductive potential and survival capacity of living organisms through affecting the overall fitness. Heavy metals, biocides, nanoparticles, microplastics, pharmaceuticals are the main types of pollutants that have immense effects on overall health of aquatic ecosystems. All these pollutants along with global warming and ocean acidification have various types of effects on the physiological parameters that regulate the process of external fertilization. As a result, reproductive success of aquatic organisms may be compromised.

In aquatic ecosystems pollutants are in direct contact with the organisms and the gametes that are released in the system. Interaction between pollutants and gametes have fatal impact on the process of external fertilization. Beirão *et al* (2018) ^[4] observed fertilizing capability of sperms are severely affected due to exposure to chemical dispersing agents in capelin fish (*Mallotus villosus*). Gallo (2018) ^[9] and Han *et al.* (2019) reported that contaminants in aquatic ecosystems have adverse effects on sperm swimming parameters of invertebrate organisms. Similar events in vertebrate sperm have been observed by Kowalska-Górska *et al.* (2019) ^[17] and Abascal *et al* (2007) ^[1]. When eggs in aquatic medium come in direct contact with different types of anthropogenic pollutants, it may also have deleterious impacts on fertilization success. Han *et al* (2019) ^[33] reported that titanium dioxide (a nanoscale pollutant in aquatic systems) can attach to the surface and damage the plasma membrane of oocyte of broadcast-spawning bivalves (*Tegillarca granosa*). As a result of this interaction between titanium dioxide and oocyte surface, the sperm egg fusion may be hampered. In case of fish when spawned eggs are exposed to certain metal pollutants it is found that the reproduction potential is compromised in such cases (Jeziarska *et al.* 2009) ^[13]. In table1 we have listed some potential anthropogenic pollutants along with their effects on external fertilization process.

Table 1: list of pollutants and their impact on external fertilization

Pollutants	Effects	References
Heavy metals	1. Mercury exposure may result in the sperm motility and viability. 2. Chronic exposure to cadmium may affect oocyte size and sperm quality	Martinez <i>et al.</i> , 2014 ^[20] Au <i>et al.</i> , 2001
Biocides	1. Endosulfan may affect the clumping pattern of spermatocytes in aquatic ecosystems. 2. In crayfish, atrazine causes reduced oocyte size. 3. Glyphosate exposure results in reduced oocyte swelling and may affect sperm motility.	Islam <i>et al.</i> , 2017 ^[12] Silveyra <i>et al.</i> , 2018 ^[27] Lugowska, 2018 ^[18]
Nanoparticles	1. In sea urchin, zinc oxide (a widespread nano particle and a potential pollutant of aquatic ecosystems) can damage sperm DNA and thus affect the fertility potential of sperm. 2. Sperm morphology of <i>Ciona intestinalis</i> is altered due to exposure at nickel nanoparticles.	Manzo <i>et al.</i> , 2013 ^[19] Gallo <i>et al.</i> , 2016 ^[10]
Microplastics	In oyster, polystyrene microplastics affect both gametes.	Talleg <i>et al.</i> , 2018 ^[28]
Global warming	1. Thermal stress affects both gametes of mytilids. 2. Adult mussels exposed to increased temperature resulted in decreased sperm motility.	Múgica <i>et al.</i> , 2015 ^[21] Boni <i>et al.</i> , 2016
Ocean acidification	In some sea urchin species, low pH significantly affects the motility of sperm that may have negative impact on fertilization process.	Schlegel <i>et al.</i> , 2012 ^[26]

Impact on external fertilization process

The successful fertilization of aquatic animals consists of a series of physical, biochemical, and molecular events. Sperm-egg collision, gamete fusion, and the prevention of polyspermy are the main steps for a successful fertilization to occur. In aquatic ecosystems swimming velocity is an important feature of motile sperm that help them to move towards the oocyte of the same species following the chemical signal. When an egg is encountered by a sperm a series of events occur thereafter like fusion of the sperm surface protein with corresponding ligand on the egg surface.

After successful gamete fusion, the event of polyspermy is blocked by a cascade of reactions through the depolarization of the oocyte membrane and the formation of the fertilization membrane to prevent the entry of competing sperms to ensure the normal cleavage of the fertilized oocytes. Successful fertilization in aquatic ecosystem requires proper cohesion between sperm head proteins and the oocyte membrane receptors and protein factors. Some reported evidences about the disruption of various steps of external fertilization due to anthropogenic pollutants are listed in table2.

Table 2: List of affected stages of external fertilization

Step in external fertilization	Reported evidences
Gamete structure and motility	Sperm movement is correlated to successful fertilization. Exposure to mercury have harmful effects on sperm motility and viability in aquatic ecosystems (Martinez <i>et al.</i> , 2014) ^[20] . it has also been reported (Dietrich <i>et al.</i> , 2010) ^[6] mercury can bind to the tail proteins of sperm and result in hampered sperm movement.
Species specific sperm-egg recognition	Deaker <i>et al</i> (2018) observed in <i>Heliocidaris tuberculata</i> that sperm motility could be affected due to ocean acidification. And this can result in compromised normal egg-finding behaviours under ocean acidification.

Sperm-egg fusion	Han <i>et al.</i> (2019) ^[11] found that titanium dioxide can bind to the surface of oocyte of broadcast-spawning bivalves (<i>Tegillarca granosa</i>) and can damage the plasma membrane. Overall result is reduced gamete fusion.
Polyspermy	1. In 2011, Reuter <i>et al</i> demonstrated that block to polyspermy in the red sea urchin (<i>Strongylocentrotus franciscanus</i>) was significantly prolonged by high pCO ₂ (1800 ppm) exposure. 2. Yu Han <i>et al</i> (2019) observed that the integrity of the oocyte membranes in bivalve (<i>Tegillarca granosa</i>) is disrupted by nTiO ₂ (a nanoparticle) exposure which may result in prevention of polyspermy.

Ecological consequences

From above examples it is clear to say that environmental pollution due to anthropogenic activities can affect the process of external fertilization in a broad variety of ways. Different steps of external fertilization are also vulnerable to environmental contaminants. As a result of anthropogenic pollution, both reproductive success and individual fitness face severe threat. Disruption of overall reproductive success of a population may have several impacts on the evolutionary process. Alteration in the reproductive success have direct effect on fitness of the affected population. In aquatic medium fertilization success, reproductive success and population fitness are closely related and are influenced by each other. Individuals exposed to pollution always have reduced fertility success due to impaired gamete movement or hampered gamete fusion. Pollution in aquatic ecosystems result in lowered reproductive success that in turn may result in population decline (Ghosh S *et al.*, 2021)^[24, 25]. In

extreme cases population extinction may occur in severely affected aquatic ecosystems. In 2007, Kidd *et al* conducted an experiment where they exposed fathead minnows (*Pimephales promelas*) to low concentrations of 17 α -ethinyloestradiol (EE2). They observed exposure to EE2 resulted in altered oogenesis in female fathead minnows and the females of this species faced a problem near to extinction after 7 years exposure to that pollutant. This experiment is strong evidence for supporting that reproductive impairment due to pollution can have detrimental effect at the population level. Alteration in reproductive success may impact species interaction. The need for research examining broader ecological effects, such as species interactions, when assessing environmental impacts of pollution (Ghosh S, 2021^[24, 25] and Windsor *et al.* 2018) is an important issue to support evolutionary implications of anthropogenic pollutants.

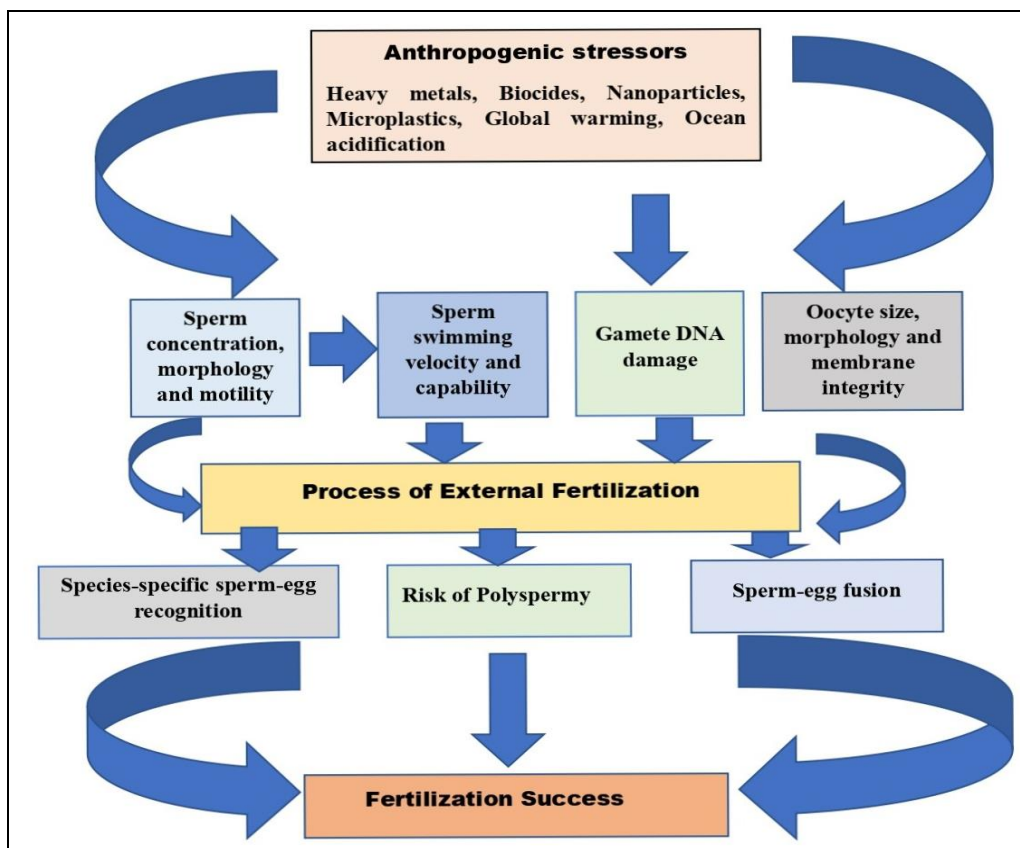


Fig 1: Diagram showing how anthropogenic pollutants impact fertilization success

Discussion

Invertebrates contribute to 95% of total animal population of this planet. In all aquatic ecosystems from marine to simple pond invertebrates are the largest groups of inhabitants. External fertilization is the main mean to have reproductive success for these animals. Vivid changes in

aquatic parameters (temperature, salinity etc) due to anthropogenic activities may affect the process of external fertilization. Various invertebrate organism plays crucial role in marine ecosystems by providing habitats or food source to other organisms. All of them participate in the energy flow of the existing food web either as predators or

as preys. In this situation, it is critical for the number and diversity of invertebrate species as well as the health of the marine ecosystem that invertebrate populations are successfully recruited through reproduction. The likelihood of external fertilisation is also influenced by biological parameters such as gamete lifetime, gamete closeness, timing of gamete release, etc. Several environmental factors like pH, temperature, turbidity, water velocity, osmotic pressure, mineral level and presence of predators may have greater influence on the success of external fertilization process. Even though successful external fertilization is hampered by several biological and environmental factors, this method of natural fertilization nevertheless produces many offspring with little parental effort. Both the male and the female create a lot of gametes because they have a decreased chance of becoming fertilised. In contrast, external fertilization results in fewer survivors due to parental neglect and a higher danger of being eaten by predators. Still, due to its sexual selection tactics, sexual dimorphism, restriction against being overpopulated, and higher possibility of genetic variants, external fertilisation is an evolutionary selected method of fertilisation for a vast number of aquatic species. Pollution due to anthropogenic causes may impair the process of external fertilization that in turn have detrimental issues on population fitness, community structure and energy flow in food webs. All these events for a long time may influence the direction of evolutionary trajectories.

Conclusion

In this review, we emphasised how various types of environmental contamination can affect a variety of processes involved in external fertilization. By hindering an organism's capacity to detect the gamete of the opposite sex or by reducing their ability to fertilise, these disruptions frequently limit the reproductive success of the organism. Additionally, pollution can decrease the survivability of the offspring through epigenetic effects, changes in the timing of conception, disruptions in the process of sexual selection, and disruptions in parental care. While it is well known that anthropogenic pollution can have an impact on the external fertilization cycle in aquatic environments, additional research is needed to determine how much these changes are affecting population expansion, ecosystem structure, and evolutionary trajectories.

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