Toxic Effects of Nanomaterials on Aquatic Animals and Their Future Prospective

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1 Introduction

Recently, nanotechnology in the context of big data for health analytics has been used as one of the most promising fields in wide-ranging domains, and it is also using a new frontier in aquatic animals, aquaculture, fisheries food webs, development, and understanding the remarkable response of aquatic life (Rather et al. 2011; Aklakur et al. 2016; Rayan et al. 2022; Rayan and Zafar 2021). In recent years, nanotechnology has emerged as one of the most promising fields of artificial intelligence, the Internet of Things, and industry 5.0, which are very suitable for a wide range of human activities to improve multiple health responses (Ferosekhan et al. 2014; Bundschuh et al. 2018; Rayan and Zafar 2021). Moreover, advances in nanotechnology are evidenced daily to assess the impact of nanomaterials (NMs) on our environment, especially autotrophs and heterotrophs. Moreover, the currently available evidence is varied and contradictory (Ashraf et al. 2011; Nandanpawar et al. 2013; Kakakhel et al. 2021) for the betterment of therapeutic life (Rayan et al. 2021). The introduction of NMs into the aquatic environment with the help of many intelligent methods like deep learning and machine learning response has many unpredictable consequences, which are most suitable for high-quality accuracy (Sajid et al. 2015; Zafar et al. 2021b). NMs are substances with less than 100 nm in diameter, which possess unique physiochemical characteristics that differ from their surrounding environment (Palmieri et al. 2021). NPs fall into different categories such as natural forms of NP are found in soil, water, or volcanic dust. They are created with the aid of using geological and organic processes (Rai et al. 2018). Many species are able to adapt and evolve in natural NP-rich environments even if they are detrimental (Shokry et al. 2021). Nanoparticles have been produced by companies for many years and used in fields such as agriculture, electronics, medicine, pharmacy, and beautifying materials such as cosmetics (Tijani et al. 2016). Silver NPs, titanium nitride NPs, and zinc oxide NPs from wastewater treatment could be harmful to marine organisms, as per earlier studies in different regions (Yu et al. 2021). Finally, NPs are visible in both (water and earth) environments, are taken up by living things, and build up until they are eliminated by the guard cell or other mechanisms (Selck et al. 2016). NPs are foreign components with unique physical and chemical properties in vivo that can disrupt typical physiological systems. They can occasionally impair embryonic development and cause fatal abnormalities (Rajput et al. 2018). In addition to responding to the known processes, chemicals that makeup NPs also interact with physiochemical attributes of living organisms exhibiting specific unique properties. NPs can readily pass through cell membranes and avoid defence mechanisms because of their tiny size (Cormier et al. 2021). As a result, NMs move about inside the cell, get to organelles like the mitochondria, change the metabolism of the cell, and lead to cell death (Rana et al. 2020). In turn these cause NPs to circulate. If the NPs are too tiny to enter the cell, they could interact with the cell membrane and obstruct processes like signal transduction and ion transport (Medici et al. 2021). NMs can be dangerous due to their chemical composition and physical properties. Positively charged NPs can damage cell membrane. Surface coating of NMs can disrupt cellular structures (Chakraborty et al. 2016). Furthermore, the effect of NMs can be influenced by other chemicals such as impurities. NMs can also absorb elements that are toxic to living organisms (Lei et al. 2018).

Numerous studies have been done throughout the years to identify and comprehend NMs impacts, many of which are still unknown. Understanding any potential negative direct or indirect impact on organisms is essential, given the abundance of NMs in modern society (Deshmukh et al. 2019). NPs have already been shown to be toxic to bacteria, algae, invertebrates, fish, and even humans. Several biological models have been used to evaluate the effects of nanoparticles on living organisms (McClements and Xiao 2017). NMs are detrimental to reproduction and embryonic development in studies on mammals such as mice, teleosts, and model organism zebrafish (Sharma et al. 2016; Okey-Onyesolu et al. 2021). Several studies conducted inside and outside adult tissues have defined Ag-NPs as highly reactive molecules with potential genotoxicity responsible for inducing cell death through oxidative stress (Thines et al. 2017). The inability to detect and quantify engineered nanoparticles in soil, sedimentary rocks, and liquid and other life forms has impeded research on their environmental impact. The outcomes of Co-NPs on *Eisenia fetida*, an earthworm specie, were also investigated using neutron activation (Zhang et al. 2022). Scintillation and autoradiography were employed to identify 4 nm Co NPs containing 59 m^2/g nano powder in spermatogenic cell waste or the environment. Following a literature review, similar findings have previously been discovered in microbes, roundworms, fishes, and cell lines (Ong et al. 2018). Fungicides are usually made from NMs, for example, Ag, ZnO, or CuO, etc. (Al-Bishri 2018). Nontarget species can be adversely affected after being released into the environment, like inhalation of pesticides or exposure to other harmful chemicals. However, our current understanding of the detrimental effects of nanoparticles is incomplete (Kuehr et al. 2021). As a result, earlier researchers have presented many ways to organise this field of research (Muthukumar et al. 2022). Collecting eco toxicological information to assess risk given the type of NP. Experiments with nitrogen dioxide NPs, zinc oxide NPs, copper oxide NPs, silver NPs, single-walled nanotubes (SWNTs) or single-walled carbon nanotubes (SWCNT-NTs), multi-walled nanotubes (MWCNTs), C_{60} fullerenes, are essential (Aruoja et al. 2015). We also raised the question of the experimental environment for understanding the impact and nature of the cytotoxic activity, target cell type, and sample treatment of NPs.

Toxicity can affect organisms living in any environment (air, freshwater, or seawater if inhaled, terrestrial environment) (Cai et al. 2018). Studies and analyses have been performed on different species, including protozoa, various invertebrates, chordates, adults, and embryos to investigate the harmful effects of NMs (Gehrke et al. 2015). This chapter presents some examples of recent research. Rats and fish included in the animal model are widely used in scientific research. On the other hand, rare species such as annelids and molluscs are employed in innovative and informative research. Influence of NMs on aquatic, semiaquatic, and terrestrial organisms is investigated in this chapter. Animal models and their natural habitats

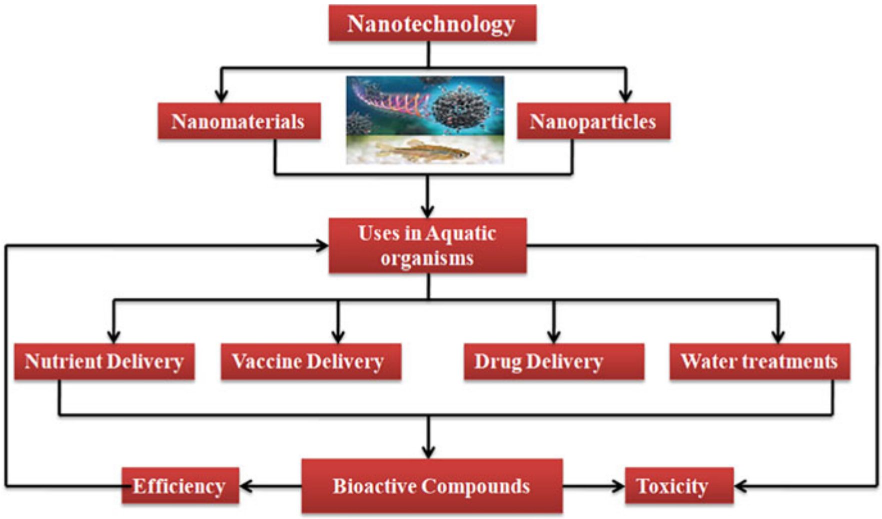

Fig. 1 A detailed overview of the use of nanotechnology in aquaculture

were the starting point for the logic of the text, but NP class may also be the starting point.

The use of nanotechnology enhances the cleaning of aquaculture pools, cure of water, handling and treatment of aquatic disorders, efficient transportation of food and medicine (including hormones and vaccines), and the inability of fish to acquire this matter (Ahmad et al. 2021; Alwash et al. 2022; Sundaray et al. 2022). Many publications are already available that provide detailed overviews of the use of nanotechnology in aquaculture (Fig. 1). However, despite their use, there is a risk of contributing to aquaculture contamination, which is unknown or unnoticed today (Asche et al. 2022; Larsson and Flach 2022). In addition, the excessive use of antibiotics to treat various diseases and other synthetic substances as growth promoters has adverse effects on aquatic ecosystems (Fujita et al. 2023). Worrying scenarios such as developmental and reproductive failure, mortality, and biochemical alterations can lead to enormous economic losses in fisheries (Selck et al. 2016).

On the other hand, they can pose problems regarding human health and environmental safety. It shows gaps, especially for lipophilic bioactive that can be used as natural remedies rather than artificial ones (Zhao et al. 2022). We highlight these innovative potential avenues that are projected to have a significant impact.

2 Aquatic Organisms and Penetration of Nanomaterials

In the field of aquatic animals, the role of bioinformatics and other high technological domains is very remarkable in penetrating reproductions in multiple organisms (Zafar et al. 2021c), and NMs are found to be very impressive domains for undertaking wide-ranging life responses. Furthermore, for domain applications, the infusoria (*Stylonychia mytilus, Tetrahymena pyriformis*), antlers (*Daphnia magna*), and amoeba *(Entamoeba histolytica*) are examples of a few aquatic invertebrates that can ingest C-based NPs. Carbon nanoparticles' capacity to penetrate organs is not entirely understood (Malhotra et al. 2020). *Lumbriculus variegatus* shallow water oligochaete, also known as California black worm, was retained in a similar liquid rich in tagged, unmodified carbon nanotubes at 14 °C, but the tissues were not able to see the nanotubes (Fischer 2015). Earthworms, in particular, and terrestrial oligochaetes, in general, showed similar outcomes (*Eisenia fetida*) (Diez-Ortiz et al. 2015). The structure and changes of carbon nanoparticles may alter their capacity to enter aquatic animals' bodies. Unmodified fullerene C_{60} entered zebrafish *(Danio rerio*) embryos through the chorion but not hydrolysed nanofibers ($C_{60}(OH)_{24}$) (Asil et al. 2020). Unlike fullerenes, the large single-walled nanotube compounds could not cross zebrafish chorion and instead settled on them. Electron microscopy revealed that zebrafish chorionic pores have a diameter of 0.5–0.7 m (Wu et al. 2021).

The tendency of C-based NPs to enter within organs is questionable yet. Only the gastrointestinal tract displayed the signs of nanotubes upon the maintenance of *L. variegatus* in a similar liquid enriched with labelled unmodified carbon nanotubes at 14 °C (Krzyżewska et al. 2016). All terrestrial oligochaetes displayed relatable outcomes. The structural confirmation and variations in NPs may influence their capacity to penetrate aquatic organisms (Thanigaivel et al. 2021). Unaltered and non-hydrolysed fullerene C_{60} penetrated in embryos of zebrafish through chorion. Unlike fullerenes, the large single-walled nanotube compounds could not cross zebrafish chorion and instead settled at their surface. Electron microscopy revealed that zebrafish chorionic pores have a diameter of 0.5–0.7 m (Follmann et al. 2017).

NMs are designed to 'persist as particles in aqueous media', allowing them to cross biological membranes due to their size. In aqueous solutions, NMs potentially generate aggregates, other colloidal suspensions, and colloidal suspensions interacting with aggregates (Yang et al. 2019). This happens because marine habitats are often highly alkaline, have high ionic strength, and already contain 'a wide variety of colloids and natural organic matter'. Due to their proximity to effluents and effluents, they are likely to contain high colloids, organic waste, and NMs (Zheng and Nowack 2022). In freshwater, nanoparticle aggregates slowly sink to the bottom and are more likely to aggregate into the sediment, which can harm benthic animals. In marine ecosystems, 'nanomaterials may concentrate at the boundary between cold and warm currents', but this is unlikely in the freshwater of recycling. This increases the risk for animals that feed in these cold and warm regions, such as tuna (Pulit-Prociak and Banach 2016). Klaine et al. (2008) have a new possibility: accumulation in 'sea surface microlayers' where nanomaterials are confined due to their surface tension and viscous properties (Klaine et al. 2008). This threatens not only seabirds and animals but also species that live in the surface microlayer (Waris et al. 2021). However, no research has been done to look into the different effects of nanomaterial accumulation in the surface microlayers of the ocean.

2.1 Toxicological Effects of Nanomaterials on Aqueous and Terrestrial Ecosystems

Nanotechnology and the excellent incorporation of NMs are part of a multibillion-dollar industry with diverse applications from biological sciences to electronics (Falanga et al. 2020). It is unavoidable that artificial and natural NMs will be released into the atmosphere, impacting water and soil. This might be due to purposeful or inadvertent emissions, which means assessing the expanding sector's possible implications on environmental, human, animal, and plant health (Kaloyianni et al. 2020).

Much research has been published on the transit and fate of putatively engineered nanoparticles (ENMs) availability of reliable toxicological information regarding their exploitation, and safe removal is still scarce. The disparity between ENM synthesis and toxicity data has prompted the scientific community to develop strong, stable, and environmentally acceptable procedures for safe manufacturing and removal (Caixeta et al. 2020). ENMs' inbound properties significantly impact their transit into the environment. Doped ENMs, for example, have a hazardous impact due to their high aggregation stability, low photo bleaching, and delayed photodegradation. Furthermore, recent studies have shown that the transport and toxicological impact of ENMs are primarily due to the dissolved ion concentration rather than the nanomaterial itself or its aggregated form (De Silva et al. 2021) (Table 1).

Although NMs exist naturally in the environment, technological advances have resulted in an abundance of novel and artificial nanomaterials that are not found naturally (Chaukura et al. 2020). Due to a lack of understanding, there is no control over emissions, and many experts are concerned that this might constitute a threat as a new class of environmental hazards. NMs are frequently used in various products due to their limited size and significant surface area, increasing the routes by which they can come in contact with organisms in the surrounding (Yoon et al. 2018). Nanomaterials released into the environment through emissions and industrial and commercial items can significantly impact them, leading them to wind up in wastewater treatment facilities and, in turn, surface water. NMs not screened in wastewater treatment facilities are more likely to 'accumulate in benthic sediments', posing a risk to numerous aquatic organisms (Kahlon et al. 2018). Because of their broad, weak respiratory epithelium, aquatic creatures are 'especially vulnerable to

Table 1 We compiled data on several NPs and target species with potential aquaculture applications, including the key comparative testing settings

Nanomaterials	Functions	Reference
Alginate NPs	Alginate, a naturally occurring polymer, is regularly employed in the food industry to thicken, emulsify and stabilise various products. Recently, successful testing of alginate NPs was successful. Nevertheless, there are significant concerns about its usage due to the absence of accurate toxicity knowledge about these substances	Guo et al. (2013), Khosravi-Katuli et al. (2017), Qi et al. (2015)
Al_2O_3 NPs	Al_2O_3 NPs have good insulating and abrasive characteristics. *Caenorhabditis elegans*, used as live food in aquaculture and aquaria for species larval development, were used to investigate the toxicity of nAl_2O_3. Concentrations greater than 102 mg/L immediately decreased worm development and the number of eggs within worm bodies and progeny, whereas concentrations greater than 203.9 mg/L considerably impeded worm reproduction	Wang et al. (2009)
Ag NPs	Silver nanoparticles can be found in various consumer products, including water purifiers, textiles, pharmaceuticals, and agrochemicals (nAg). nAg has been used in aquaculture to purify water due to its antibacterial properties, and there is a body of research on its toxicity to aquatic species relevant to aquaculture	Márquez et al. (2018)
Au NPs	According to Zhu et al., Au NPs (nAu) are used in various industries' detection. Although it is frequently used, nothing is clear about its ingestion in organisms living in water bodies. Further research observed that Au NPs do not exhibit toxicity (hatching delay)	Khosravi-Katuli et al. (2017), Mohandas et al. (2018)
CeO_2 NPs	CeO_2 nanoparticles are used in various applications, including fuel additives, coatings, electronics, and biomedical devices. There are still many unknowns about how it harms the environment and human health. After 14 days of nCeO_2 exposure, zebrafish accumulate only in the liver. During a five-day experimental study, *P. lividus* was exposed to the CeO_2 (50–105 nm) NPs at a concentration of 10 mg/L, causing death later on two days, while the testing model remained alive at 0.1 mg/l	Khosravi-Katuli et al. (2017), Roberta et al. (2021)
Chitosan NPs	Chitosan nanoparticles can cross tight junctions between epithelial cells, potentially	Ahmed et al. (2019), Bhoopathy et al. (2021)

(continued)

Table 1 (continued)

Nanomaterials	Functions	Reference
	threatening humans, animals, and the environment. Zhang (2011) found that *D. rerio* embryos treated with chitosan nanoparticles (200 nm) with high concentration died and deformed at 40 mg/L with nearly 100% mortality	
Cu NPs	Copper NPs (nCu), particularly nCuO, are one of the most prominent metallic nanoparticles (NPS) and display bactericide and antifouling properties, as well as solid heat conductivity, which may influence aquaculture The earlier researcher treated zebrafish juveniles to aquatic nCuO for 48 h and found histological damage, Cu accumulation in the gills, and 82 differentially expressed genes compared to controls	Shah and Mraz (2020), Vicario-Parés et al. (2018)
Fe NPs	The Fe_2O_3 NPs are widely utilised in biological applications such as cellular labelling, drug delivery, tissue regeneration, in vitro bioseparation, and hyperthermia, with additional applications including wastewater purification and as a food additive in aquaculture The researcher revealed both fatal and sub-lethal effects on medaka fish (*Oryzias latipes*) after a 14-day exposure to nFe, stating NPs coated with CMC or cellulose gum were less harmful compared to non-coated forms (ROS production and CAT change)	Mukherjee et al. (2022), Refsnider et al. (2021)
La NPs	According to Mácová et al. (2014), commonly used in water treatment, industry, and medicine. Mácová et al. (2014) exposed boy *D. rerio* and *P. reticulata* for 96 and 144 h, respectively, and reported the following LC50 values: 156.33 5.59 and 128.38 5.29 mg/L, followed by 152.98 8.06 mg/L. As a result, the use of La NPs can have potentially dangerous consequences	Mácová et al. (2014)
Quantum dots	Quantum dots are employed in biosensing, bioimaging, and monitoring the quality of water bodies. According to Khosravi-Katuli, Mykiss treated with O. 2 g/L QDs in 2 days exhibited a rise in overall metallothionein. Lewinsky et al. (2011) treated brine shrimp *(Artemia franciscana)* and crustacean (*Daphnia magna)* with 0.6 mg QD for 24 h. These were then presented to both immature and mature stages of *D. rerio* for 21 days as a	Hébert et al. (2008), Khosravi-Katuli et al. (2017), Wu and Yan (2013)

(continued)

Table 1 (continued)

Nanomaterials	Functions	Reference
	food source. Although zero post-exposure mortality was reported still 4% QD accumulation in young and 8% in adult stages were found. The researchers received comparable outcomes following an in vitro experiment using *O. mykiss* liver cells	
Selenium NPs	Se is a bionutrient product suitable for increasing aquaculture as it is a trace mineral that many species, including fish, need for proper physiological function and growth (Khan et al. 2016). Khan et al. (2016) studied the physiological and biochemical impacts of nSe supplements (0.68 mg/kg diet) on juvenile fish (*Tor putitora*), comparing RBC count, HB level, haematocrit levels, and lytic enzyme activity along conventional diets showed an increase in and other biochemical parameters	Singh and Onuegbu (2020)
Silicon dioxide NPs	According to Babu et al. 2013, they are beneficial for optical imaging and drug delivery, but their use in aquaculture has also been observed, reducing the risk of disease transmission in overcrowded aquaria. Nevertheless, the researcher observed increased mortality and malformations in zebrafish	Babu et al. (2013), Duan et al. (2013), Rahman et al. (2022)
Sn oxide NPs	Owning to the rigidity of low-temperature conductance, tin oxide NPs are crucial for developing optronics, gas sensors, and electrochemical energy storage systems. Regarding $nSnO_2$ toxicity to aquatic organisms, just two life forms are found, and their potential use in aquaculture is currently under investigation. After *P. reticulata* was exposed to 150 mg/L $nSnO_2$ for 5 days, Krysanov et al. (2009) found that tin accumulates in the gonads, spleen, intestine, liver, muscle, and thymus. The results of Falugi et al. (2012) on the effect of sea urchin (*Paracentrotus lividus)* on tin oxide have been mentioned in the 'Fe-NPs' section beforehand	Falugi et al. (2012), Krysanov et al. (2009)
SWCNTs	Carbon nanotubes have been employed in aquaculture setups to improve water treatment and food stability	Khan et al. (2021)
Titanium dioxide NPs	Varnishes, papers, fabric, synthetic polymers, sunblock, makeup, and edible items are some commercially accessible goods that employ $nTiO_2$. Aquaculture may utilise $nTiO_2$ in direct and indirect ways, as discussed in the preceding sections	Khosravi-Katuli et al. (2017), Müller (2007)

(continued)

Table 1 (continued)

Nanomaterials	Functions	Reference
	(Khosravi-Katuli et al. 2017). Investigating its possible toxicity to aquatic creatures is therefore required	
Zinc oxide NPs	According to Rather et al. (2018), ZnO NPs are employed in optoelectronics, cosmetics, catalysts, ceramics, pigments, and aquaculture. Based on concentrations, contact duration, and targeted species, different results have been found regarding the impacts of ZnO	Rather et al. (2018)

contaminants'. Changes in pH, water temperature, and oxygen levels can increase the dangers associated with nanomaterials in aquatic settings and should be considered when assessing risk. Plants are also vulnerable to nanomaterial exposure due to soil contamination or inadvertent discharge (Bakshi 2020).

Live NMs have been found to penetrate live creatures and 'exercise harmful effects' at the cellular level, including membrane rupture, protein inactivation, DNA damage, interruption of energy transmission, and toxic chemical release (Bobori et al. 2020). Due to the significant role of producers and microorganisms in the food chain, it is crucial to comprehend the potential impact that such vast industries may have on biodiversity in upcoming times (Grillo and Fraceto 2022). This study will discuss the toxicological consequences of waste-manufactured NMs in terrestrial and aquatic habitats and their implications for human health and environmental safety. The current investigation will be subjected to the hazardous effects of inappropriately disposed of nanomaterials in the environment and human health.

2.1.1 Uptake of Nanomaterials in Aquatic Ecosystems

Nanoparticles are designed to 'persist as particles in aqueous media', allowing them to cross biological membranes due to their size. In aqueous solutions, nanomaterials potentially generate aggregates, other colloidal suspensions, and colloidal suspensions interacting with aggregates (Wu et al. 2019). This happens because marine habitats are often highly alkaline, have high ionic strength, and already contain 'a wide variety of colloids and natural organic matter'. Due to their proximity to effluents and effluents, they are likely to contain high concentrations of colloids, organic waste, and nanomaterials (Saxena et al. 2020).

In freshwater, NMs' aggregates slowly sink to the bottom and are more likely to aggregate into the sediment, which can harm benthic animals. In marine ecosystems, 'nanomaterials may concentrate at the boundary between cold and warm currents', but this is unlikely in freshwater. In terms of recycling, the concentration of nanomaterials at the boundary between cold and warm currents is a phenomenon observed in marine ecosystems but is unlikely to occur in freshwater (Wu et al.

2017). This increases the risk for animals that feed in these cold and warm regions, such as tuna. Buffle and Leppard (2008) proposed a new possibility: accumulation in 'sea surface microlayers' where nanomaterials are confined due to their surface tension and viscous properties. This endangers not only seabirds and animals but also species that live in the surface microlayer. However, no studies have been performed before to investigate variable implications of nanomaterial accumulation in the surface microlayers of the ocean (Laux et al. 2018).

2.2 Toxicological Profiling of NMs in the Aquaculture Sector

Different TNPs are employed in the maritime sector. Several studies are underway to ensure their safety outside the aquaculture industry (Atamanalp et al. 2022). The details of potential NMs in aquaculture applications, including the critical comparative testing settings, are mentioned in Table 2. All their effects on live animals (especially aquatic ones) are unknown, and their use in aquaculture raises public concern. The toxicity of NPs, as mentioned in Fig. 2, might vary based on their delivery method, as well as toxic kinetics and toxic dynamics (Khosravi-Katuli et al. 2017). NP concentrations in feed, on treated surfaces, or in water might be more importantly broad than expected NP ambient levels of up to mcg per litre or more.

Algins, Al_2O_3, Au, Ag, cerium dioxide, CuO, and CsAg nanocomposites area a few examples of NPs along target species with potential aquaculture uses. A summary of crucial relative test parameters. Short-term exposure times have been studied mainly for species of tangential aquaculture relevance (i.e. A. *Salinna annua*).

3 Effects of NPs on Aquatic Animals

Both freshwater and marine environments contain significant amounts of NPs. Finding out how these NPs affect aquatic creatures was made possible by several studies. These results might vary, though (Exbrayat et al. 2015). Recent insights examined nanoparticles as novel contaminants that have variable effects depending on their sizes and are not yet completely understood. Numerous laboratory experiments have revealed that their constant exposure harms fish and invertebrates (Jenifer et al. 2020). The nature of these possible consequences was evaluated using traditional or less conventional animal models. As a result, several works focused on bony fish, specifically the trout *O. mykiss* and the *Danio rerio*. Other research focused on plankton, sea urchins, molluscs, daphnia, and other crustaceans.

Table 2 Profile of toxic nanomaterials

Nanomaterials	Functions	Reference
Carbon nanomaterials	Aggressive behaviour and respiratory disorder have been observed in *O. mykiss* upon nanotubes exposure to water at 0.5–0.1 mg concentration. (Smith et al. 2007). According to the studies, adding fullerene C_{60} induced biochemical alterations in large-mouth bass and fathead minnow, suggesting a detriment impact on the development of both fishes' gills, brain, and liver. A change in behavioural pattern and mortality was observed at 0.25 mL/L of the lowest possible fullerenes concentration in daphnia (*D. magna*). Fullerenes C_{60} and C_{70} are embryotoxic and genotoxic during the early stages of zebrafish embryogenesis by significantly increasing embryo abnormalities and subsequent mortality at 200 h/L maximum doses of fullerene allotrope Additionally, the hydroxylated forms of the fullerenes were less hazardous than the original. However, Petersen et al. (2014) showed that pure fullerene C_{60} dispersed through sonic waves in aquatic environments by 25 mg/l was not poisonous; however, C_{60} dispersed in tetrahydrofuran was toxic and altered the gene expression of larvae. On the other hand, single-walled carbon nanotubes did not affect the continued development of larvae and instead delayed zebrafish hatching Axolotl larvae and Xenopus tadpoles showed no acute or genotoxicity in amphibian tests using carbon nanotubes suspended in water. Xenopus tadpoles were toxic to nanotubes but at high levels. (500 mg/L) only	Haque and Ward (2018), Krysanov et al. (2010), Petersen et al. (2014), Sarasamma et al. (2019), Smith et al. (2007)
Metal oxides nanomaterials	The efficiency of photosynthesis in green algae (*Pseudokirchneriella subcapitata*) was not affected by tests to determine the toxicity of metal oxides (TiO_2, ZrO_2, Al_2O_3, and CeO_2). However, these algae could not grow at 600 g/L concentration.	Basiuk et al. (2011), Hou et al. (2018), Tetu et al. (2017), Wiench et al. (2009)

(continued)

Table 2 (continued)

Nanomaterials	Functions	Reference
	According to a Zn, Al, and TiO toxicity analysis in *D. rerio* juveniles, only ZnO concentration was found harmful for the fish. The zinc oxide nanoparticle lethal dose (LD_{50}) after 96 h was 1.8 mg/l The DAPHIA investigations showed that titanium dioxide nanoparticles are not hazardous, even at concentrations of 100 mg/l in 48-h testing. However, the length of exposure enhanced the toxicity of nanomaterials. For instance, the LD_{50} for titanium dioxide was 2 mg/l during 72 h. In contrast, TiO_2 nanoparticles decreased Daphnia seven's growth and reproduction in the case of prolonged exposure at values of 0.5–5 mg/l	
Titanium dioxide nanomaterials	Rainbow trout exposed to 1 mg/L TiO_2NPs did not experience adverse toxic effects, but sublethal effects such as internal organ disease and biochemical and respiratory abnormalities were found. For two months, TiO_2 nanoparticles were added to the meal of rainbow trout under a year old at doses of 10 and 100 mg/kg, although this did not affect the fish's growth or haematological features. However, it was found that the amounts of copper and zinc ions in the fish nervous system were disturbed, which altered the biochemistry of the gills and gut. The hydrated tin dioxide nanoparticles (SnO_2) in guppies did not have acute or genotoxicity	Handy et al. (2011), Smith et al. (2007)
Metal nanomaterials	Every aquatic organism exhibits different toxicity levels depending on the type of metallic nanoparticles they are exposed to. For instance, the Cu and Ag NPs showed 0.04 and 0.06 mg LD_{50} after 48 h. These nanomaterials, however, were less harmful to fish. Zebrafish died due to gill pathology brought on by copper and silver nanoparticles. For nanomaterials over 48 h, respective LD_{50} concentrations were found to be 7.2 and 0.9 mg/L. Morphological abnormalities in *D. rerio* larvae increased when their	El-Samad et al. (2022), Lacave et al. (2018), Zhao et al. (2013)

(continued)

Table 2 (continued)

Nanomaterials	Functions	Reference
	spawn was incubated with silver nanomaterials, and the scientists also showed a relationship between anomalies and Ag nanomaterial doses. Ag NPs at maximum concentrations accelerated morphological defects and mortality in zebrafish larvae	
Semiconductors	Freshwater muscle (*E. complanata*) reared in aquatic conditions enriched with cadmium telluride and QDs at a concentration range between 1.6 and 8 mg/l showed the vital signs of immunotoxin and Geno toxins presence. The viability and activity of the haemocytes decreased, while oxidative stress and the frequency of DNA fragmentation increased within gills	Giroux et al. (2022), Parolini et al. (2010)
Dendrimers	Sublethal concentrations of fourth-generation polyaminoamide (PAMAM) dendrimer with NH_2 group are found to be more poisonous, interrupting developmental processes and retard the growth of *D. rerio* embryos	Tamayo-Belda et al. (2022)

3.1 In Fish

The immature stage of salmon developed sodium borohydride ($NaBH_4$) after reducing silver NPs when subjected to silver nanoparticle suspension. The size range for colloidal Ag-NPs, both manufactured and purchased, was 3–220 nm (Stanková 2015). In all tests, fish gills collected Ag-NPs, except when NP concentration was least (1 g/L). The effect of response was dose-dependent, which caused a considerable spike in the stress level of gills through HSP70 and plasmatic glucose (Ackerman et al. 2000). Dose-dependent inhibition of Na/K ATPase ubiquitous enzyme exhibits an osmoregulatory default (Mackie et al. 2007). At maximum concentration, 100 g/L silver nanoparticles led to necrosis of gill lamella, resulting in the death of 73% of fish. All these experiments showed how nanoparticle preparation could adversely affect the surrounding organisms (Handy et al. 2008).

Considering their chemical characteristics and behaviour linked to aggregation dynamics and equilibrium of freely available metal ions may cause acute toxicity of metallic nanoparticles. Metallic-NPs can potentially be more toxic to some fish species than their dissolved versions (Barría et al. 2020). Numerous organ pathologies, including those of the gills, liver, gut, and brain, revealed some similarities between the responses to NPs and metal salts. Some consequences for development were also seen (Han et al. 2021). Ag-NPs were applied to the chorion, the egg's

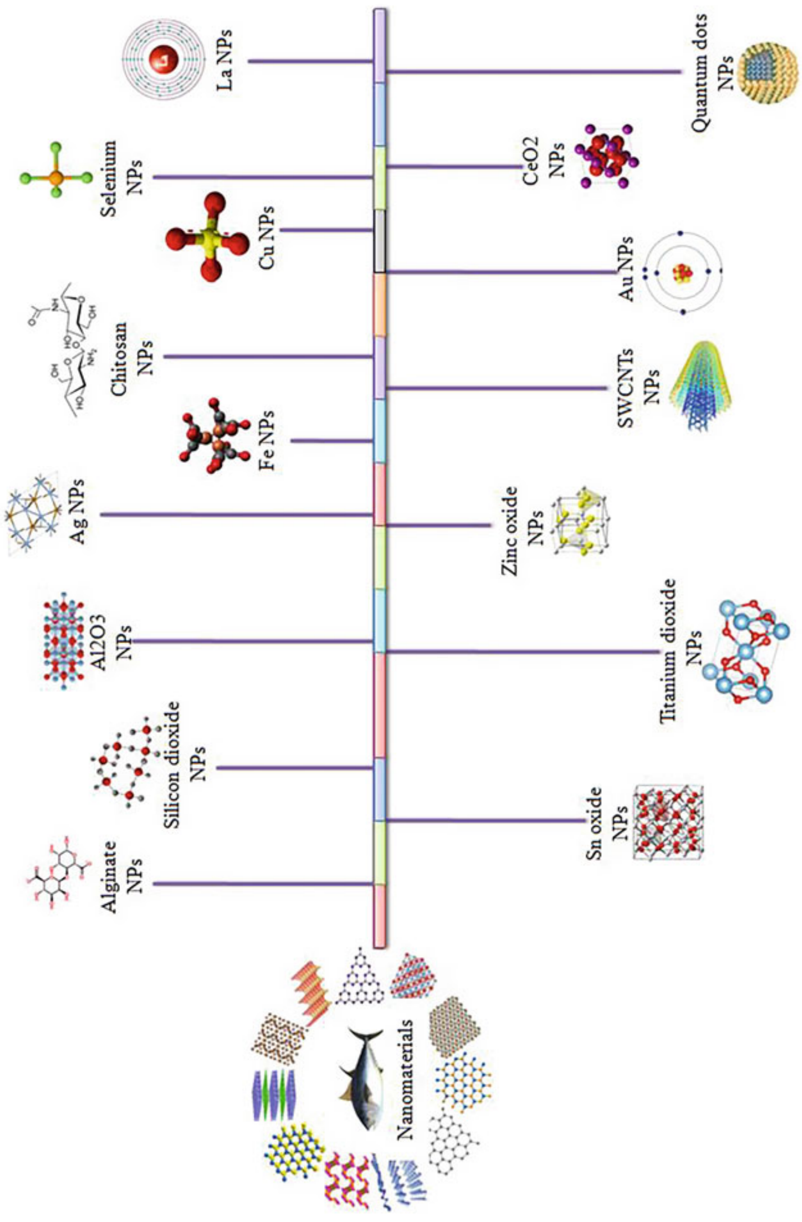

Fig. 2 The influence of NMs and their applications for delivery methods in the context of toxic kinetics and toxic dynamics

membrane, or the growing embryo. Zinc and copper nanoparticles show more adverse consequences for embryos and young animals than the equivalent salt (González-Fernández et al. 2021). It is still feasible that metal-NPs stimulate the relevant stress reactions to obstruct them. Since the end of the 2000s, researchers have been examining how fish react mechanically to NPs and other nanomaterials.

In contrast to other chemical compounds, this research compared the methods of substance absorption, distribution, metabolisation, and excretion in fish (Forouhar Vajargah et al. 2020). The TiO_2-NPs and C_{60} fullerene have been tested for these properties in the gills, digestive system, liver, and adrenals, among other organs. NPs more thoroughly enter the tissues by endocytosis than through diffusion or ionic carriers, such as the equivalent metal ion (Benavides et al. 2016). In fish, NPs might be removed with bile but are seldom expelled through the kidneys. The effects ZnO NPs were investigated in an in vitro experiment employing human and fish liver cell strains. These NPs clumped together, which significantly increased the toxicity of fish cells. The dissolved salts produced by NPs would be hazardous to human cells (George et al. 2014). A comparison of studies using tumour-bearing human hepatocytes Huh7 grown in vitro and in vivo revealed that the 120-nm-diameter Ag-NPs entered the hepatocytes and caused oxidative stress characterised by ROS production, IFN expression, and disruption of the endoplasmic reticulum (Daufresne and Boet 2007).

In vitro studies on *D. rerio* revealed that silver nanoparticles' neurotoxicity is distinct from silver ions. Different forms of Ag nanoparticles, coated with PVP or ionic forms, all have a variable impact on embryonic development (Kumar et al. 2020). Ag+ retards the swim bladder development and is directly connected to multiple deformities in fishes. In response to light stimuli, fish behaviour was also altered. Small-sized Ag nanoparticles coated with PVP induced hyperactivism, whereas large particles induced hypoactivism in affected fishes due to light exposure (Johnston et al. 2010). A thorough examination revealed that the adult nervous system was affected by 1–20 nm Ag–NPs was given to zebrafish embryos. Ag-NPs' production of Ag ions can potentially increase mortality and deformities (Parsai and Kumar 2020). Ag-NPs may affect cell differentiation by inhibiting cells using acetylcholine as an intermediate. In addition, Ni-NPs caused deformities and death in zebrafish embryos. Contrary to the Ni solution, which had no impact, the guts showed thinning upon contact with Ni-coated NPs (Lai et al. 2021). Soluble as well as Ni-NPs of 30, 60, and 100 nm sizes affected skeletal muscles.

A minimal difference between the toxicity of soluble NI and Ni-coated nanoparticles was found. On the other hand, skeletal muscles and the gut were susceptible to 60 nm massive aggregates of dendritic Ni-NPs toxicity (Shaw and Handy 2011). Zebrafish embryos carried 10 nm Au NPs that travelled throughout their whole bodies. However, the impacts on growth were inversely proportional to concentrations; these particles were collected in aggregates with sizes dependent on concentration (Geppert et al. 2021). The observed abnormalities could be the result of being randomly distributed. Ag NPs are more harmful than Au NPs when it comes to toxicity, which depends on chemical characteristics. *D. rerio* embryo can therefore serve as the perfect experimental model for in vivo studies, particularly regarding materials' biocompatibility (Guerrera et al. 2021). A comparison of the impact of $CuSO_4$ and Cu NPs on the gills of *O. mykiss* showed the accumulation of these substances in varying amounts. NP and salt were associated with increased Cu, although the spleen, brain, and muscle showed no signs of product accumulation (Shaw et al. 2012). Finally, at low concentrations, Cu NPs appear to have toxic effects comparable to $CuSO_4$.

Except for Cu and Zn, metallic concentration in tissues remains unaffected by NP accumulation in the brain. Na+/K+ ATPase decreased in gills and intestines. Thiobarbituric acid (TBA) increases in the brain and gills dose-dependently (Tabassum et al. 2016). Ag NPs dose-dependently reduced membrane integrity, and cell metabolism in hepatocytes culture from various species. Au NPs increased ROS without adverse effects. Indeed, the effects of Ag and Au NPs on trout hepatocyte cultures were sometimes contradictory (Singh et al. 2009). *D. rerio* juveniles and embryos were ingested with 25 nm TiO_2 NPs to investigate their impact on developmental processes. During an experimental activity, they were added to commercial food, while in another, fish were given algae that had already been exposed to TiO_2-NPs (Schultz et al. 2014). Hatching occurred early and minimally affected young animals at low concentrations. However, after 14 days of exposure to tainted food, the physiology of the digestive system changed.

4 Toxicity of Nanomaterials

In toxicity studies regarding engineered nanomaterials, numerous research groups have evaluated sublethal and lethal concentrations, cell proliferation, embryonic toxicity, chromosomal abnormalities, and fertility issues in animals.

5 Bio Modification and Migration Along Food Webs

Limited hydrophilicity and instability of aqueous suspensions of NPs are two of the main problems in their use in biology and medicine. Attempts to treat nanomaterials with organic solvents to make them more hydrophilic lead to increased toxicity of the nanomaterials (Wang et al. 2020). However, the ability to create nanoparticle suspensions in water without increasing nanoparticle toxicity has been met with some success. Very shortly, many biologically accessible nanoparticles may enter the environment (Wang et al. 2016). Engineered NMs have been shown to change spontaneously in an aqueous environment, making them more accessible to organisms. In addition, they can be artificially modified to make them more hydrophilic (Souza and Fernando 2016). Naturally present fulvic acid and humic enhance the stability of fullerene and nanotube suspensions. As a result, aggregates do not form or occur in moderate amounts.

In contrast, studies have shown that polysaccharides improve the sedimentation of nanomaterials and reduce their mobility. The ability of nanomaterials to adsorb organic environmental toxins has been shown to increase toxicological impact (Rhim et al. 2013). For example, fullerene C_{60} in water increases the toxicity of phenanthrene to daphnids by order of magnitude. In contrast, titanium dioxide nanomaterials increase the accumulation of arsenic and cadmium in carp organs (Krysanov et al. 2010). It is also recognised that organisms themselves can modify nanomaterials. For example, fullerene C_{60} has been shown to combine with vitamin A to form a molecule in the liver of house mice (Dellinger et al. 2013). Due to their chemical activity, carbon nanotubes can combine with other organic components in the body to produce chemical compounds (proteins, phospholipids, and DNA). Various organic substances bind to nanomaterials, allowing them to enter cells (Mu et al. 2014). Supplementing proteinaceous culture media with nanotubes has shown unexpected results in *Tetrahymena pyriformis* strains.

We found that culture development was stimulated with increasing nanotube concentration. The authors hypothesised that protein–nanotube interactions increase the amount of protein reaching the cell and promote cell development by increasing the amount of protein entering the cell can enter the bodies of aquatic invertebrates, but how far up the food chain it goes is unknown (Naskalska et al. 2021). It has been demonstrated that transportation of QDs from infusoria to rotifers could be due to the food chain. No data on vertebrates is available yet. NMs could potentially move down the food chain and focus on higher consumers. This may influence the severity of toxic effects for species with different trophic levels.

6 Current Nanotechnology in Aquaculture

The use of vaccination in aquaculture is essential as a defence strategy against pathogens to protect hosts against these pathogens. In silico investigations at the genome level (Rather and Dhandare 2019; Rather et al. 2020; Zafar et al. 2021a), oral management, and recent vaccinations in the aquaculture sector are the most reliable and efficient immunisation method (Okeke et al. 2022). The latter is a conventional adjuvant technique requiring an oil-in-water formulation to manufacture the vaccine, with some unfortunate consequences. These compositions and administration techniques occasionally result in fish death (Fajardo et al. 2022). To circumvent these problems, the scientific community has proposed a nanodelivery system as an alternative method of administering vaccines to fish that is believed to be safer and more effective. Among them, alginate particles were selected as the first candidate for oral administration of vaccines to aquatic animals (Sarkar et al. 2022). Alginate particles are often produced by emulsification, one of the most rapid and scalable NP production techniques. Several fish survival, weight, and antigenicity adjuvant researchers have reported alginate and management to improved immunostimulatory responses of carp (*Cyprinus carpio* L.), spotted grouper

(*Epinephelus fuscoguttatus*), and improved protection of flounder (*Scophthalmus maximus* L.) against several diseases (Harikrishnan et al. 2011).

PLG, or PLGA, is a biodegradable copolymer widely employed for encapsulating and transporting various substances into fish. Recent research discovered strong immune-stimulatory and antibody responses in these fish compared to the control group (Wang et al. 2018). Another study team in Japanese flounder also found similar outcomes, with DNA vaccine encased in PLGA demonstrating improved inducing effects on immunological measures against lymphocytes. Compared to the control group, carp (*Cyprinus carpio*) with liposomes encapsulating *Aeromonas salmonicida* antigen had a higher survival rate (83%) and fewer skin ulcers (Shah and Mraz 2020). Hydrophilic antigens significantly increased serum antibody counts, boosting the immunity of common carp.

7 Conclusions

With enormous growth, aquaculture represents one of the fastest-growing sectors. It provides a competent employment platform and significantly impacts the national economy through revenue generation. Integrating nanotechnology in aquaculture promises to reinvent traditional practices and serious challenges. Exceptional physiochemical properties of NMs have extensive applications in aquaculture research and development and promote aquatic organisms and life. NMs are employed in drug delivery, broad-spectrum antimicrobial activity, biomaterials engineering, and ecological remediation. In nanotechnology, NPs have become a significant source of economic and scientific innovation to provide remarkable results.

On the other hand, the widespread use leading to the uncontrolled discharge of these particles and other toxic effluents has negatively impacted multiple modes of life. Various poorly designed, newly engineered NMs and NPs are coming to light every other day, turning them into potential environmental pollutants. They come in sizes from 1 to 100, and their ecological toxicity has been suggested to be linked to their physiochemical properties. As aquatic organisms are directly exposed to distinct metallic nanoparticles via food, water, and sediments, thus, their low concentrations can induce toxicity in fishes and other aquatic organisms. Biomagnification of their mixtures in aquatic life harm terrestrial biodiversity by accumulating in the food chains. The intrinsic chemical reactivity of nanoparticles causes inflammation, oxidative stress, and genotoxicity of biological systems. It has adverse impacts on human health, increasing animal disease rates and degrading the ecosystem.

A sustainable approach regarding the employment of NMs in aquaculture and fisheries demands a deeper insight into their accumulation into ecological systems and impacts on contemporary life forms. Public engagement is crucial in terms of food and safety to preserve confidence in nanotechnology. Moreover, multidisciplinary collaboration between researchers public and private sectors is mandatory for the future success of aquaculture resulting in global benefit.

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