Chapter

Catfish as an Ecotoxicological Model for Assessment of Nanoparticle Toxicity Profiling

Muhammed Atamanalp, Arzu Ucar and Gonca Alak

Abstract

The developing technological infrastructure has accelerated the evolution of nanoscience and encouraged the use of nanomaterials in very large areas. However, environmental liberation of nanomaterials can pose potential risks. Although different toxicity screening methodologies have been successfully used to assess the potential risks of these substances, little is known about their environmental impact. Fish are the most visible members of the aquatic ecosystem, vulnerable to toxicants. Although the ecotoxicology of fish and nanoparticles are complex, this review evaluates approaches to using catfish as a bio-indicator for the effects of nanoparticles on fish.

Keywords: nanoparticle, toxicity, catfish, fish metabolism

1. Introduction

Nanotechnology is the branch of science that deals with the characterization, production, management, and manufacturing use of nanostructured materials (NM) for different sectors/applications. The NMs produced with this technology generally have an intermediate size between 1–100 nm and can be converted to desired lengths. This process (size reduction) increases the surface-to-volume ratio (thus surface energy), biological efficiency, and adsorption capacity of the obtained product. In addition, its chemical/physical (such as diffusion, strength, color, solubility, and quantum effects), optical, magnetic, and thermodynamic properties are significantly improved [1, 2]. Innovative nanostructured materials and nanocomposites equipped with these superior properties have a wider application area (environment, agriculture, medicine, food, etc.) than their macro counterparts and are one of the fastest developing research areas, especially in the food industry. Due to nanotechnological advances, NMs are estimated to be components of more than 2,000 commercial products, and this number is expected to increase significantly in the coming years. However, during the production, carrying, use, and exterminating of these products, NMs are inevitably released into the environment, especially in the waters as the final destination [2]. Keller et al. [3] reported that 0.4–7% of these products eventually enter the aquatic environment, assuming that there is approximately 309,000 tons of NM production globally. Contaminations in aquatic environments, which are the final destination of all pollutants, can occur through industrial wastewater, domestic sewage, and coastal recreational activities (e.g. swimming and diving) [4–6]. Especially with the increasing environmental awareness in recent years, the NMs' risk to the aquatic ecosystem has become an increasing concern [7].

Although at present, the development of NM-related adverse outcome pathways has mainly focused on human toxicity, an additional nanosafety component to consider in risk assessment of this class of material is eco-toxicity [8]. The unique physicochemical properties of NMs enable them to interact with biomolecules and change essential biochemical pathways. However, the abundance of NMs in water bodies can affect water quality and threaten the survival of aquatic species also they can be accumulated through the food chains [9]. The reaching of nanoparticles to aquatic environments and possible action mechanisms had been figured out by Bundschuh et al. [10] and shown in **Figure 1**.

As in all vertebrates, fish's general physiological response to threatening situations is called "stress." A short time after the perception of a stressor, the stress response begins in the organism. The physiological response (Stress response) triggered by stressors is a set of adjustments that can maintain internal homeostasis to a certain level and sustain vitality [11]. Mildly stressful situations may have positive effects (eustress), while higher intensities may have negative consequences. The stress response is initiated and controlled by two hormonal systems that lead to the production of corticosteroids (mainly cortisol) and catecholamines (such as adrenaline and noradrenaline). Together, these regulate secondary stress response factors that alter the distribution of essential resources such as energy

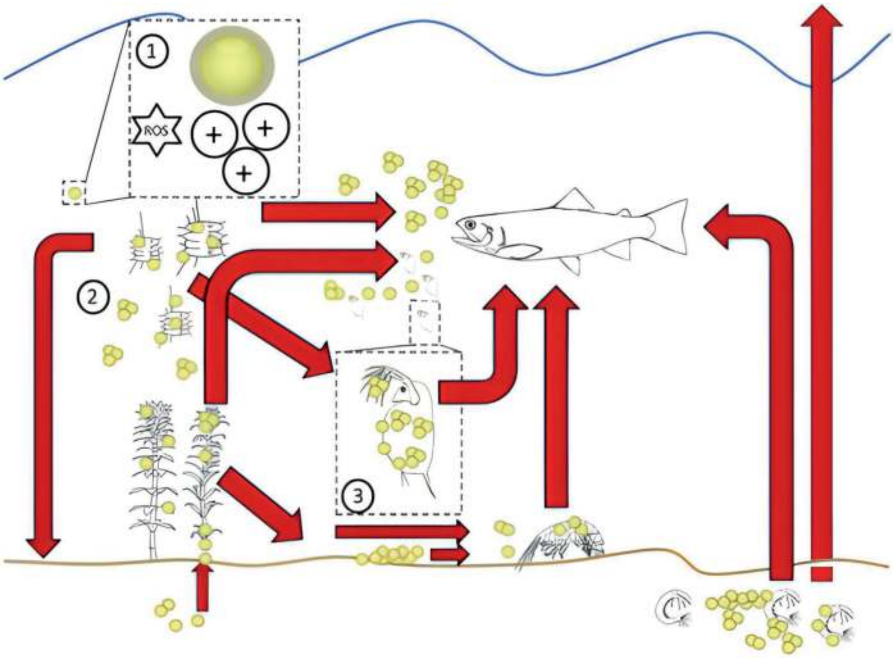

Figure 1.
Exposure and potential pathways to toxicity of nanoparticles in aquatic environments (red), (1) toxic properties, (2) biomagnification potential induced by adsorption leading to assimilation, and (3) aquatic absorption onto organisms and fish, aquatic plants, various invertebrates, and uptake by algae and other organisms. ROS, reactive oxygen types Bundschuh et al. [10].

and oxygen to tissues and organs and also compromise hydro-mineral imbalance and the immune system. It is known that long-term exposure to stress negatively affects basic life functions (growth, development, disease resistance, energy balance, behavior, and reproduction) [12].

Stress response of organisms sent to a stimulus (stressor) that is perceived as dangerous helps maintain homeostasis [13]. These reactions are grouped as primary, secondary, and tertiary phases (**Figure 2**) [14]. The primary phase represents a neuroendocrine response. Cortisol is released from interrenal cells and catecholamines are released from chromaffin. High levels of these hormones trigger a secondary response. The secondary phase presents as hyperglycemia, vasodilation of the arteries in the gill filaments, increased heart rate, and decreased immunity [15]. The first two stages are considered adaptive and maintain homeostasis by enabling the fish to adapt to stress factors. On the other hand, in the tertiary phase, it includes systemic changes in which organisms are not able to adapt to stress factors and this leads to negative effects on the situation. Its effects on behavior, health, growth, and reproduction, including swimming performances, emerge in this context [14].

Behavioral alterations are the other most widely used biomarkers at the individual level. Because changes in behavior are the integration of many cellular processes necessary for the viability of the organism, population, and community. Therefore, the observation of behavioral changes provides a unique toxicological perspective connecting both the ecological and biochemical consequences of environmental pollution [16]. Behavioral changes of living things in aquatic ecosystems are accepted as the most sensitive indicators of possible toxic effects. Social interactions such as changes in feeding activities, swimming behaviors, competition, hunting, reproduction, and aggression of fish exposed to different insecticides have been determined [17].

Since behavior acts as a link between physiological and ecological processes, it is an ideal parameter for studying environmental pollutant effects. Fish are the prominent aquatic indicators in this parameter due to the ease of monitoring their behavior. However, a very good knowledge of their physiology is an advantage for ecological monitoring of contamination [18]. Individual fish's behavioral performance follows certain physiological sequences triggered by external stimuli acting through neural networks [19].

The metabolism of fish is closely related to its behavioral state and is affected by many varied physiologic functions. Metabolic dysfunction caused by aquatic pollutants can result from disruption at many different physiological levels [20–24]. Metabolic degradation of the whole organism had been expressed in a number of different ways, most commonly indicated by varying resting metabolic rates (ventilation

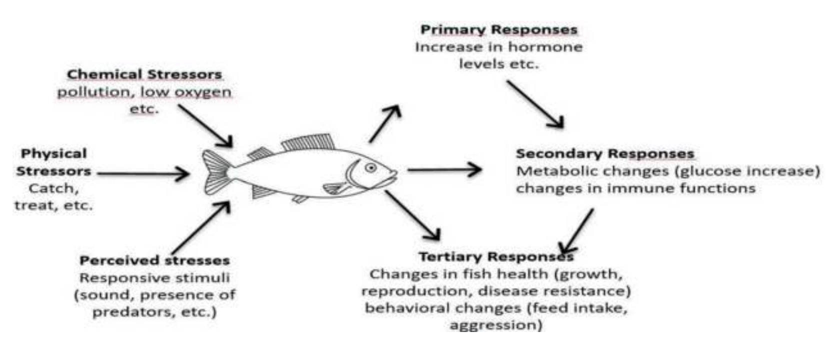

Figure 2.
Stress response phases [14].

rate or oxygen consumption) or reduced swimming performance (critical swimming rate, U_{crit}) [25–28].

Catfish are gaining increasing attention as bioindicators for monitoring NP-fish interaction. In this section, eco-toxicological concerns of the NMs/NPs and their effects on the ecosystem are presented, with special emphasis on catfish health. For this purpose, we wanted to prepare a data pool for future research by integrating the data and information found in scientific publications with catfish as a bio-indicator, emphasizing where targeted analyzes are needed among different potential pathways/mechanisms of toxic effect in ecotoxicological findings for NMs. It is aimed to gather NM effect studies on catfish, which has an important place in aquaculture. The results of different researchers on different catfish species are summarized in **Table 1**. In this way, the NMs' biological effects on this fish species, including negative effects, aim to provide a complete picture of the situation, which will provide a better understanding of the mechanisms of the biological effects of NMs and assist in the sustainable development of nanotechnology, which is increasingly used.

Although it has clarified the potential hazards of NPs on aquatic organisms and their environmental effects, the knowledge about the mechanisms of cellular toxicity caused by NP/NM due to overproduction of reactive oxygen species (ROS) is not very extensive. In order to overcome this lack of information, studies on different fish species are continuing intensively, thanks to these studies, the effects of NPs on bioaccumulation, oxidative stress, and subsequent activation of the antioxidant defense system have been revealed [44–46]. NPs are taken up by fish, the most important component of Aquatic ecosystems, and transported to various tissues – organs via blood [47]. In vitro and in vivo studies on NM in fish had shown that NPs can induce oxidative stress by triggering the ROS formation. Stimulation of oxidative stress causes extensive damage to biomolecules such as DNA, proteins, lipids and cellular membranes [48]. Oxidative stress in the cellular system is produced as a result of an imbalance between oxidative and reducing processes and is typically induced when the physiological antioxidant defense system is unable to counteract the increased level of ROS [35]. Like other vertebrates, teleosts attempt to convert ROS into harmless metabolites to maintain and restore normal cellular homeostasis and functions. For this, a wide variety of enzymatic and non-enzymatic antioxidant defense systems have been developed [49, 50]. These include low molecular weight antioxidants such as glutathione (GSH) and high molecular weight defenses with enzymes such as superoxide dismutase (SOD), catalase (CAT) as the first line of defense, and enzymes involved in glutathione metabolisms such as glutathione peroxidase (GPx), glutathione reductase (GR) and glutathione-S-transferase (GST), and glutathione reductase (GR) [51]. However, some fish species may be at the forefront due to their advantages in monitoring NP-induced oxidative stress processes in different cellular systems of teleost fish. One of these species, catfish (Siluriformes) is one of the important species worldwide in aquaculture, with an annual production of approximately 6 million tons in 2018 [52]. They live mainly in freshwater and are widely distributed in the tropics of Africa, South America, and Asia. Consisting of more than 3000 species and an estimated 1750 undescribed species, the Siluriformes is one of the largest orders of the Teleostei [53, 54]. Catfish are of paramount importance not only for commercial but also for recreational fishing. Their high domestication potential and adaptability to intensive breeding conditions, high fecundity, and nocturnal foraging habits characteristics are attractive. The ability to live in turbid waters, high resistance to diseases, successful tolerant to

Nanomaterial	Live material	Obtained alterations/Effects	References
Silica nanoparticles (SiNPs)	African catfish, *Clarias gariepinus*	8-OHdG and MDA elevation, reduction in AChE, effects on GPX, SOD	Rahman et al. [29]
Copper ferrite nanoparticles ($CuFe_2O_4$NPs)	Channel catfish ovary cells	Significant increase in LPO, GST, and GPX was observed in CCO cells exposed to $CuFe_2O_4$NPs after 24 h of treatment. However, the CAT and GSH levels in CCO cells exposed to $CuFe_2O_4$NPs decreased significantly after 24 h. The CCO cells exposed to 10 μg/mL concentration of $CuFe_2O_4$NPs for 24 h showed remarkable changes in their morphology.	Srikanth and Nutalapati [30]
Tucumã nanocapsules	Silver catfish, *Rhamdia quelen*	The most abundant carotenoid in tucumã oil was *all-trans*-beta-carotene. Nanocapsules are good carriers for tucumã oil. Tucumã oil nanocapsules do not have a toxicity effect in catfish.	Nascimento et al. [31]
Nano-sized zinc oxide (nano-ZnO)	Yellow catfish *Pelteobagrus fulvidraco*	Increased intestinal Zn contents. The *zip6* and *zip10* mRNA expression levels were higher in the H-Zn group than those in the control (0 mg/kg nano-ZnO). Epsl5, *dynamin1, dynamin2, caveolin1*, and *caveolin2* mRNA expression levels tended to reduce with dietary nano-ZnO addition. Dietary nano-ZnO increased TG content and G6PD activities.	Chen et al. [32]
Amme-functionalized single-carbon nanotube (NH_2 f-SWCNT)	Channel Catfish (*Ictalurus punctatus*)	Decrease of CAT and SOD activity, an increase in MDA and LDH. Real-time PCR assay showed inflammatory response with a dose-dependent increase of tumor necrosis factor alpha (TNFα) and transient increase of IL-1β in the liver.	Gao et al. [33]
Chitosan nanoparticles (CSNPs)	African catfish, *Clarias gariepinus*	FSH and 17-β estradiol (E2) were significantly decreased in female catfish. While testosterone and luteinizing hormone (LH) were increased after exposure to BPA. Significant reduction in CAT, GSH-px, TAC, GSH, and GST levels.	Hamed et al. [34]
ZnO NPs	Magur catfish *C. magur*	Resulted in oxidative stress as evidenced by an initial sharp rise of intracellular concentrations of H_2O_2 and malondialdehyde (MDA) but decreased gradually at later stages. GSH level increased gradually in all the tissues after a mitial decrease.	Koner et al. [35]
Gold nanoparticles AuNPs	African catfish *C. gariepinus*	The embryo's hatching rate and larvae's survival rate decreased. Embryonic malformations such as pericardial edema, yolk sac edema, neck, and head defects	Marimuthu et al. [36]
Nano-Zn	Intestinal epithelial cells of yellow catfish	Increased the contents of TG and free fatty acids (FFA), the activities of G6PD, 6GPD, ME, and FAS.	Ling et al. [37]

Nanomaterial	Live material	Obtained alterations/Effects	References
Single-walled carbon nanotube (COOH-SWCNT) chitosan (CS) hybrid (COOH-SWCNT-CS).	Magur catfish *C. magur*	DNA damage was observed in fish injected with nanotubes alone than chitosan hybrid groups. Histological observations revealed severe liver cell damage at higher concentrations of COOH-SWCNT whereas, in COOH-SWCNT-CS, no such damage was observed. However, kidney tissue remained unaffected in all groups.	Wisdom et al. [38]
Titanium dioxide nanoparticles (TiO_2 NPs)	African catfish, *C.gariepinus*	Neurotoxicity, changes of antioxidant enzymes, and retardation of food uptake.	Matouke and Mustapha [39]
Titanium dioxide nanoparticles ($FeTiO_2$ NPs)/ Nickel ferrite nanoparticle ($NiFe_2O_4$ NPs)	Catfish	Abnormal behaviors such as loss of equilibrium, pigmentation, and lying down at the bottom of the aquaria were observed.	Rao et al. [40]
Chitosan nanoparticles (BD+CHN)	African catfish (*C. gariepinus*)	Significantly improved water quality, daily weight gain, feed utilization, and survival as well as body composition	Udo et al. [41]
Copper (Cu) as nanoparticle (Cu-NPs)	Catfish, *C.batrachus*	Effects on expression levels of several steroidogenic enzymes (*3β-hsd, cyp11a1, 11β-hsd2, 11β-h*, and *star*) and transcription factor genes (*wt1, ad4bp/sf-1, dmrt1, sox9a*, and *gata4*)	Murugananthkumar et al. [42]
Nano-ZnO, TiO_2, CuO, and CO_3O_4	Primary culture of channel catfish hepatocytes	Significant toxicity in both HepG2 cells and catfish primary hepatocytes. The results demonstrate that HepG2 cells are more sensitive than catfish primary hepatocytes to the toxicity of metal oxide NPs.	Wang et al. [43]

8-OHdG: 8-hydroxy-2-deoxyguanosine, MDA: Malondialdehyde, AChE: Acetylcholine esterase, GPX: Glutathione peroxidase, SOD: Superoxide dismutase, CAT: Catalase, LDH: Lactin dehydrogenase, TNFα: Tumor necrosis factor alpha, H_2O_2: Hydrogen peroxide, FFA: Free fatty acids, TAC: Total antioxidant capacity, LH: Luteinizing hormone

Table 1.
Obtained alteration/effects of NM/MPs on catfish reported by different researchers.

low dissolved oxygen levels, efficient feed conversion, and ease of fillet processing, make them important in aquaculture [52, 55].

As in other aquatic organisms, the effects of NPs on catfish had attracted the attention of researchers and had been the subject of many studies. According to their origin, NPs caused different sizes of changes/negatives in catfish. As can be seen from **Table 1**, the neurotoxicity effect [39] is one of the effects that should be considered the most. In addition, the negative effects on hormonal balance [34] are undesirable in terms of breeding catfish with its economic importance. Similarly, behavioral changes [40] will be effective upon reproduction. Studies on enzymes that show general health and well-being in fish [33, 35] also show how effective NPs are for catfish.

2. Conclusion

Nanoparticles, which have an important place in developing technology, cause problems in aquatic ecosystems, as well as in other fish species. In this book chapter, which brings together studies by different researchers on different catfish in the Siluriformes group, it draws attention to taking the necessary precautions to prevent this economically important species from being exposed to NPs.

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