

Effects of nanoparticles in species of aquaculture interest

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Abstract Recently, it was observed that there is an increasing application of nanoparticles (NPs) in aquaculture. Manufacturers are trying to use nano-based tools to remove the barriers about waterborne food, growth, reproduction, and culturing of species, their health, and water treatment in order to increase aquaculture production rates, being the safe-by-design approach still unapplied. We reviewed the applications of NPs in aquaculture evidencing that the way NPs are applied can be very different: some are directly added to feed, other to water media or in aquaculture facilities. Traditional toxicity data cannot be easily used to infer on aquaculture mainly considering short-term exposure scenarios, underestimating the potential exposure of aquacultured species. The main outputs are (i) biological models are not

recurrent, and in the case, testing protocols are frequently different; (ii) most data derived from toxicity studies are not specifically designed on aquaculture needs, thus contact time, exposure concentrations, and other ancillary conditions do not meet the required standard for aquaculture; (iii) short-term exposure periods are investigated mainly on species of indirect aquaculture interest, while shrimp and fish as final consumers in aquaculture plants are underinvestigated (scarce or unknown data on trophic chain transfer of NPs); little information is available about the amount of NPs accumulated within marketed organisms; (iv) how NPs present in the packaging of aquacultured products can affect their quality remained substantially unexplored. NPs in aquaculture are a challenging topic that must be developed in the near future to assure human health and environmental safety.

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Abbreviations

NPs	Nanoparticles
nTiO ₂	Titanium dioxide NPs
selenium	NPs nSe
nZnO	Zinc oxide NPs
nFe	Iron NPs
nSiO ₂	Silicon dioxide NPs
nAu	Gold NPs
SWCNTs	Single-walled carbon nanotubes
C ₆₀	Fullerene
nAg	Silver NPs
QDs	Quantum dots
nSnO ₂	Tin oxide NPs
nCeO ₂	Cerium oxide NPs
nAl ₂ O ₃	Aluminum oxide NPs
nCuO	Copper oxide NPs

ZFL	Zebrafish liver cell line
WSSV	White spot syndrome virus
CAGNCs	Chitosan-silver nano composites
MIC	Minimum inhibitory concentration
RFID	Radio frequency identification
DAG-PEG	Diacylglycerol-polyethyleneglycol
Cu ²⁺ -MMT	Copper-bearing nanomontmorillonite
TBT	Antifouling pesticide tributyltin
HSP	Heat shock proteins
CYP	Cytochrome P450
HEK 293	Human embryonic kidney 293 cells
UV	Ultraviolet light
EC ₅₀	Half maximal effective concentration
SOD	Superoxide dismutase
CAT	Catalase
LPO	Lactoperoxidase
GOT	Glutamic-oxaloacetic transaminase
GPT	Glutamic-pyruvic transaminase
GSTs	Glutathione-S-transferase
ROS	Reactive oxygen species
RBC	Red blood cell
WBC	White blood cell
HB	Hemoglobin
HTC	Hematocrit
SGOT	Serum glutamic-oxaloacetic transaminase
SGPT	Serum glutamic-pyruvic transaminase
GRP	Glucose-regulated protein
LMS	Lysosomal membrane stability
TBARS	Thiobarbituric acid reactive substances
MWNTs	Multiwalled carbon nanotubes
PVP	Polyvinylpyrrolidone
PEG	Polyethylene glycol
LC ₅₀	Lethal concentration 50
BHAL	Bi-potential human liver cells
GSH-Px	Glutathione peroxidase

Introduction

Aquaculture and fisheries supply about 15% of the average animal protein consumption to 2.9 billion people worldwide in, and is still increasing. Approximately 43.5 million people are directly employed within these sectors, and 520 million people indirectly derive their livelihoods from aquaculture and fisheries industries (Asche et al. 2015).

Similarly, nanotechnology is no more a niche for researchers, but a really fast growing and impacting key economical field providing new nanoenabled products with novel and unique functions. The new-engineered nanoenabled products, improved by nanoparticles (NPs), have been the key factor for the success of the nanotechnology industry. With a size between 1 and 100 nm on at least one dimension, NPs present unique physico-chemical properties that differ from their bulk materials,

such as a greater surface area to volume ratio, resulting in a larger reactivity. Due to their remarkable properties, NPs have been widely used in different fields such as energy and electronics, wastewater treatment, personal care products, and medicine and agriculture (ETC 2003; Karnik et al. 2005; Aitken et al. 2006; Libralato et al. 2013; Callegaro et al. 2015; Dasgupta et al. 2015; Perera et al. 2015; Libralato 2014; Libralato et al. 2016a; Minetto et al. 2014, 2016; Podyacheva and Ismagilov 2015; Vale et al. 2016). Recently, nanotechnology has found several applications in aquaculture, but their implications are still unknown.

In the fishery and aquaculture industry, NPs are used for several direct and indirect applications as summarized in Fig. 1. Indirect uses include water and wastewater treatment, fishpond sterilization, and harvested fish packaging for commercialization like as barcoding and tagging; direct uses involve feeding industry and animal healthcare like fish disease control.

The escalating production and application of NPs have raised concerns about their safety to human health and the environment. While a significant number of studies have been conducted on NP potential toxicity toward humans and other organisms, few have been directed toward the effects in aquaculture. The assessment of potential bioadverse effects of NPs would allow the determination of a safe limit concentration to be used on food production activities such as fishery and aquaculture. Moreover, this could trigger the discussion on the regulatory use of NPs in the food industry and the creation of proper legislation, which are still currently missing.

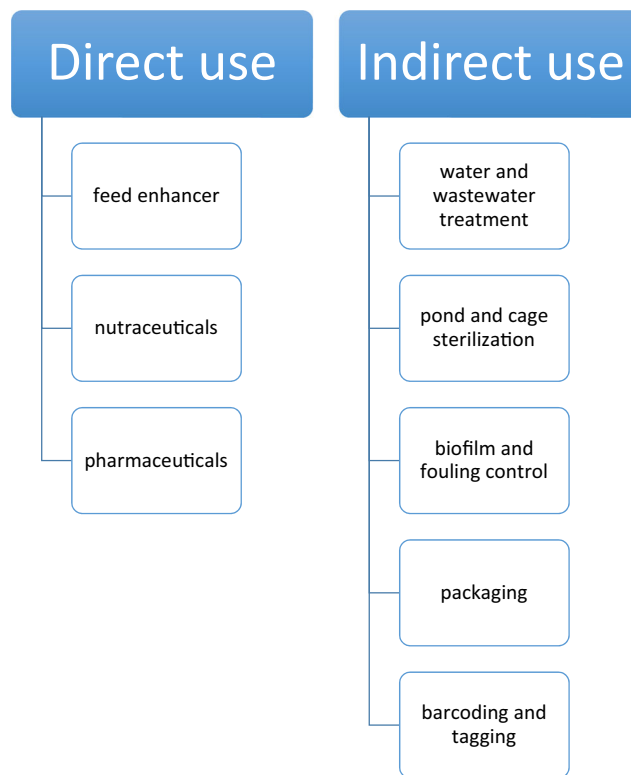


Fig. 1 Direct and indirect use of nanotechnology in aquaculture activities

The present study reviewed for the first time the potential toxicity of NPs in aquaculture providing a critical summary of recent scientific literature on their potential hazardous effects. Our focus is not the environment, but aquacultured species intentionally treated with NPs or indirectly exposed to NPs used in aquaculture activities.

Aquaculture industry and nanotechnology

Nanotechnology and aquatic feed

One of the most important nanotechnology application in aquaculture is the feed production where the use of NPs have proved to be effective for (i) micronutrient delivery (e.g., chitosan NPs), (ii) amount of produced feed per unit time (e.g., single-walled carbon nanotubes (SWCNTs), fullerenes (C₆₀), and nTiO₂), and (iii) growth promotion (e.g., nFe, nSe, nTiO₂, and nZnO) (Table 1).

Chitosan [poly(1,4-β-D-glucopyranosamine)] is a polysaccharide with low immunogenicity, low toxicity, and antimicrobial potential being widely used on feed production for human and animals (Rather et al. 2013; Luo and Wang 2013; Ferosekhan et al. 2014; Vendramini et al. 2016). Novel applications of chitosan NPs, for the delivery of unstable and/or hydrosoluble micronutrients, are in early stages of development. Alishahi et al. (2014) showed that the use of chitosan NPs significantly increased shelf life and delivery of vitamin C in rainbow trout after 20 days of feeding. Jiménez-Fernández et al. (2014) conducted a similar study applying chitosan NPs for delivering ascorbic acid (AA) in (i) zebrafish liver cell line (ZFL) and (ii) in vivo to the rotifer *Brachionus plicatilis*. NPs had the ability to penetrate fish intestinal epithelium showing a significant increase of AA on both models. Rotifers fed with AA-NPs increased up to twofold their AA levels in comparison to the control groups.

During the administration of feed directly to water, nutrients can be released from feed pellets to water. Chitosan NPs can be used as an encapsulating agent for nutrients that can easily degrade when in contact with water (Chatterjee and Judeh 2016; Ji et al. 2015). Peniche et al. (2004) prevented the leakage of liver oil of shark when encapsulated with calcium alginate coated with chitosan. Klinkesorn and McClements (2009) conducted an in vitro study and demonstrated that encapsulation of tuna oil droplets, with chitosan NPs, increased physical stability and subsequently decreased the fatty acids released from the emulsions.

Addition of SWCNTs (Fraser et al. 2011; Bisesi et al. 2015), C₆₀ (Fraser et al. 2011), and nTiO₂ (Ramsden et al. 2009) to rainbow trout fathead minnows and rainbow trout food changed the physical properties of fish pellet resulting more compact than usual, decreasing the nutrients' leaching and their subsequent waste in fishpond.

Selenium (Se) is a trace element essential for life, and has been recently considered in many case studies for animal nutrition (Poletini et al. 2015; Sabbioni et al. 2015). Se is a component of glutathione peroxidase (GSH-Px) enzymes (Rotruck et al. 1973) that protect the cell membrane through glutathione reduction. Supplemental Se can be acquired through diet (Fotedar and Munilkumar 2016; Wang et al. 2013), and Se NPs are gaining a great deal of attention due to its bioavailability and antioxidant defense properties (Sonkusre et al. 2014). Supplemental nSe increased the final weight, protein content in muscle, and GSH-Px activity in liver and blood plasma as well as decreased FCR in crucian carp (*Carassius auratus gibelio*) that were fed with supplemented diets (Zhou et al. 2009). Additionally, Wang et al. (2013) evidenced that nSe caused an increase in LDH, cellular protein contents, Na⁺/K⁺-ATPase, SOD, and GSH-Px in crucian carp (*C. auratus gibelio*), being this effect both NPs size and dose dependent. Deng and Cheng (2003) reported that nSe promoted a significant effect on the growth of Nile tilapia (*Oreochromis niloticus*) at moderate (0.5 mg/kg) and high (2.5 mg/kg) doses of Se NPs via spiked feed presenting a weight gain rate of 86.3 ± 4.7 g.

Zinc (Zn) is another essential micronutrient involved in several metabolic pathways and is essential for the regulation of protein synthesis, energy consumption, and as well as vitamin A and lipid metabolism (Muralisankar et al. 2014). Faiz et al. (2015) investigated nZnO as a source of dietary Zn evidencing improved growth and immune response in grass carp (*Ctenopharyngodon idella*). Muralisankar et al. (2014) showed a significant increase in protein content, antioxidant enzymes activity, and increased weight in freshwater prawn (*Macrobrachium rosenbergii*) after 90 days feeding with feed improved with nZnO. Bhattacharyya et al. (2015) investigated the use of nanomaterials (NMs) to induce the growth in aquatic species increasing the proportion of nutrients passing across the gut tissue and into the organism rather than passing through the digestive system and excreted partially or totally unused. Ramsden et al. (2009) used nTiO₂ to improve growth performance in rainbow trout (*Oncorhynchus mykiss*).

Nanotechnology and aquatic reproduction

In artificial reproduction of commercial aquatic animal, one of the most common problems is the incomplete vitellogenesis in females leading to failure of the final oocyte maturation and ovulation. To overcome this problem, it is necessary to develop methods for controlling the reproductive process. Chitosan NPs can be used to carry and release in a controlled way endogenous hormone (Pulavendran et al. 2011). Rather et al. (2013) used salmon hormone chitosan-nAu to overcome the problem of the short life of reproductive hormones in blood, thus avoiding the use of multiple injections in order to enhance reproductive efficacy. Results showed that reproductive

Table 1 Summary of in vitro and in vivo evaluations of most frequently used/found NPs in aquaculture-related species

NPs	Biological model	Concentration, size, contact time, and route(s) of administration	System action, cell, and tissue target	Major outcomes	References
Alignate	<i>D. rerio</i> embryos	10 µg; 24 h; added to cell plat	HEK 293 cells	No significant changes	Rafiee et al. (2014)
Al ₂ O ₃	Bacterial activity	NPs ranging from 0 to 5 mg/mL (5.0, 2.5, 1.25, 1.0, 0.5, 0.62, 0.31, 0.25, 0.15, 0.1, 0.078, 0.062, 0.031, 0.025, 0.015, 0.01, 0.005, 0.007, and 0.001 mg/mL)	Antibacterial activity of AlNPs	No inhibition exhibited by AlNPs against different bacterial isolates	Swain et al. (2014)
	<i>D. tertiolecta</i>	Exposure concentrations were 0.00, 0.005, 0.026, 0.14, 0.7, and 3.8 mg/L	Cell changes in morphology and size	After 24 h: EC ₁₀ = 8.71 × 10 ³ mg/L; EC ₅₀ = 0.54 mg/L; EC ₉₀ = 33.88 mg/L; NOEC = 5.4 × 10 ⁻² mg/L; after 72 h: EC ₁₀ = 1.66 × 10 ⁻³ mg/L; EC ₅₀ = 0.162 mg/L; EC ₉₀ = 15.31 mg/L; NOEC = 16.2 × 10 ⁻² mg/L	Shirazi et al. (2015)
	<i>C. elegans</i>	30–206 mg/L; 60 nm; 5 days; added to test media	Growth and reproduction	Growth and eggs number reduction	Wang et al. (2009)
	<i>D. rerio</i>	72-h static aquatic exposure; 51 nm	Ingestion	No lethality was recorded at concentrations up to 500 g/L, reduced gill ATPase activity	Barber et al. (2005)
Ag	<i>H. diversicolor</i>	250 mg/kg; 30 nm; 10 days; add to water sediment	Ag bioaccumulation	<i>N. diversicolor</i> accumulated 79.35 ± 31.0 ng Ag/g when exposed to sediment spiked with aqueous Ag, and 93.77 ± 28.16 ng Ag/g when exposed to AgNPs in sediment	García-Alonso et al. (2011)
	<i>H. diversicolor</i>	Sediment spiked with AgNO ₃ , Ag NPs (63 ± 27 nm), and larger bulk Ag particles (202 ± 56 µm)	Glutathione, SOD, CAT, GPx, SeGPx, GST, and GR	Ag NPs and bulk Ag particles, changes in glutathione, SOD, CAT, GPx, SeGPx, GST, and GR occurred without significant Ag accumulation, while differences in biomarker profiles between the three Ag forms suggest that the mechanism of oxidative stress caused by particulate Ag is distinct from that of dissolved Ag	Cozzari et al. (2015)
	<i>L. variegatus</i>	Ag (252 nmol/L), nAg@ (PVP (polyvinylpyrrolidone) (464 nmol/L), PEG (polyethylene glycol) (928 nmol/L), and citrate (1392 nmol/L)	Accumulation dynamics and acute toxicity	Uptake rate constants for AgNPs were ~2–10 times less than for dissolved Ag and showed significant rank order concordance with acute toxicity. Ag elimination fitted a 1-compartment loss model	Khan et al. (2015)
	<i>V. verrucosa</i>	500 µg/L; 15 nm; 28 days; add to clam media	Breathing behavior, reproduction, ROS, antioxidant enzymes, osmoregulation	Decrease breathing and fecundity, induction of ROS and antioxidant enzymes, decrease Na ⁺ /K ⁺ /ATPase activity in mitochondria rich cell	Völker et al. (2015)
	<i>M. galloprovincialis</i>	10 µg/L	Genotoxic effects in hemocytes using the comet assay	Ag (nanoparticles and ionic forms) induced DNA damage in hemolymph cells with a time-response effect. Ionic forms presented higher genotoxicity than NPs, suggesting different mechanisms of action that may be mediated through oxidative stress	Gomes et al. (2013)
	<i>A. salina</i>	up to 12 nM; 30–40 nm; 24–48 h; added to media	Survival, body accumulation, genotoxicity, decapsulation	50% mortality in 27 µg/L, aggregation in gut region, apoptotic cells, and DNA damage increased and decrease of hatching percentage	Arulvasu et al. (2014)
	<i>D. magna</i>	10 mg/L; ~45 nm; 24 h; added to media	Survival	50% mortality in 17 µg/L	Blimova et al. (2013)
	<i>T. platyrurus</i>	10 mg/L; ~45 nm; 24 h; added to media	Survival	50% mortality in 27 µg/L	Blimova et al. (2013)
	<i>D. rerio</i>	71 mg/L; 5–50 nm; 14 days; add to fish media	Liver and gill	Specific bioaccumulation of AgNPs; oxidative stress, induction of stress and immune response-related genes	Krishnamaj et al. (2016)
		1 mg/L; 20 nm and 110 nm; 4 days; add to fish media	Gill and intestine accumulation, histological alteration, osmoregulation	Accumulation and destructive effect of AgNPs on gill and intestine structure, effect on Na ⁺ /K ⁺ /ATPase activity	Osborne et al. (2015)

Table 1 (continued)

NPs	Biological model	Concentration, size, contact time, and route(s) of administration	System action, cell, and tissue target	Major outcomes	References
	<i>C. carpio</i>	0.62 mg/L; 11.3 nm; 7 days; add to fish media	Liver, gill, gastrointestinal tract, skeletal muscle, brain, blood	Specific bioaccumulation of AgNPs	Jang et al. (2014)
	<i>Perca fluviatilis</i>	63, 129 and 300 µg/L; 30–40 nm; 14 days; add to fish media	Basic metabolism and breathing system	No effect on basal metabolic rate, significant decrease in critical oxygen tension	Bilberg et al. (2010)
	<i>R. labeo</i>	10, 25, 50, and 100 mg/kg; 50 nm; 7 days; add to live food	Immunity response, antioxidant response, muscle, gill and liver histology	Decrease of hematology parameters, increase of antioxidant enzymes, histological alteration in muscle, gill, and liver	Rajkumar et al. (2016)
Au	<i>Headise diversicolor</i>	0.1 mg/L; 5–40 nm; 16 days	Behavior; oxidative stress	Impairment of borrowing behavior and feeding rate were noticed like increase in stress-related biomarkers	Mouneyrac et al. (2014)
	<i>M. edulis</i>	750 µg/L; ~15 nm; 24 h; added to water suspension	Accumulation and oxidative stress (OS)	Gold accumulation in digestive gland; reduction of oxidized glutathione ratio in digestive gland; decreased levels of thiol proteins in response to GNP; OS = hemolymph increased; CAT activity and ubiquitination reduced in digestive gland, gill and mantle, caronylation decreased in gill and mantle	Tedesco et al. (2008)
	<i>D. rerio</i>	10, 25, 50, 75, and 100 ng/L; 15–35 nm; 72 h; added to eggs' suspension	Survival; development; accumulation	No toxic effect	Asharani et al. (2011)
C ₆₀	<i>Mytilus</i>	1, 5, and 10 µg/L; ~0.7 nm; 72 h; add to water suspension	Immune system, oxidative stress	None of the NP tested significantly affected lysosomal membrane stability, indicating the lack of a major toxic effect; significant increase of lysosomal enzyme release, superoxide, and nitric oxide (NO) production	Canesi et al. (2010a)
	<i>O. mykiss</i>	500 mg/kg; 1.1 nm; 6 weeks; dietary administration	Growth, hematology, accumulation, histopathology, osmoregulation	No overt toxicity	Fraser et al. (2011)
C ₆₀ and nano carbon black	<i>M. galloprovincialis</i>	0.05, 0.2, 1, and 5 mg/L; 22 nm; 24 h; added to water	Oxidative stress	Significant lysosomal membrane destabilization in both the hemocytes and the digestive gland; involve changes in lysosomal and oxidative stress biomarkers in the digestive gland, MAPK signaling	Canesi et al. (2010b)
CeO ₂	<i>P. lividus</i>	10 ⁻² or 10 ⁻⁴ g/L; 50–60 nm; 5 days; dietary administration	Survival; bioaccumulation; nervous system; gene expression	100% mortality at 10 ⁻² g/L after 48 h; Ce bioaccumulation in digestive apparatus, the reproductive and immune systems; severe reduction in the number of stained vesicles; reduction of enzymatic activity of the three different cholinesterase isoforms (AChE, BChE, and PChE) was found in all the exposed samples; reduction of HSP 70 and GRP78 gene expression	Falugi et al. (2012)
	<i>D. rerio</i>	500 and 5000 µg/L; 10 nm; 14 days; add to water suspension and dietary administration	Ce bioaccumulation	Ce bioaccumulation in liver	Johnston et al. (2010)
Chitosan	<i>D. rerio</i>	40 mg/L; 200 nm; 96 h; added to egg media	Biomarkers and whole organism	Decreased hatching rate; increased mortality; edema; opaque yolk; cell death; overexpression of hsp70	Hu et al. (2011)
		1%; 20 nm; 4 h; added to cell plat	Bi-potential human liver cells (BHAL)	Destruction of the cell membrane; increase in CYP3A4 enzyme activity; autophagic cell death	Loh et al. (2010)
		1 µg/L; 265 nm; 5 days; added to cell plat	A549 cells	Increase cell death	Huang et al. (2004)
Chitosan-silver nano composites CAgNCs	<i>A. salmonicida</i>	<i>A. salmonicida</i> overnight culture was inoculated with fresh marine broth in 1:100. It was further incubated at 25 °C until reached up to 0.5 OD at 600 nm. Then, culture (4 mL) was treated by different concentrations of CAgNCs (6.25 to 75 ng/L). MIC and MBC, final concentrations of 0, 12.5, 25.0, 50.0, 75.0, and 100.0 ng/L CAgNCs. Cell viability was	Cells; ROS; protein content; DNA integrity; toxicity to <i>D. rerio</i> and <i>O. fasciatus</i> through dietary exposure	Concentration- and time-dependent ROS were generated like as protein content decrease and DNA degradation; no effects on <i>D. rerio</i> at 12.5 mg/kg of body weight/day and <i>O. fasciatus</i> testis cells up to 50 µg/µL	Damanjaya et al. (2016)

Table 1 (continued)

NPs	Biological model	Concentration, size, contact time, and route(s) of administration	System action, cell, and tissue target	Major outcomes	References
CuO		determined by 3-(4, 5-dimethyl-2-thiazolyl)-2, 5-diphenyl-2H-tetrazolium bromide (MTT) assay. Cell membrane integrity of CAgNC-treated bacteria was assessed by monitoring PI uptake. Formation of genomic DNA-CAgNC complex was determined by 0.1% agarose gel electrophoresis	Accumulation; behavior, oxidative enzymes	Cu accumulation; increase in GSTs and CAT. Only ionic Cu affects burrowing; no behavioral effect on worm burrowing was observed	Buffet et al. (2011)
	<i>H. diversicolor</i>	10 µg/L; 10–100 nm; 7 days; add to water suspension	Genotoxic effects in hemocytes using the comet assay	Cu (nanoparticles and ionic forms) induced DNA damage in hemolymph cells with a time-response effect. Ionic forms presented higher genotoxicity than NPs, suggesting different mechanisms of action that may be mediated through oxidative stress	Gomes et al. (2013)
	<i>M. galloprovincialis</i>	10 µg/L	Growth; reproduction	Marginal influence on the growth and reproduction	Adam et al. (2015)
Fe	<i>D. magna</i>	~0.5–1 mg/L; 140 nm; 21 days; added to water	Survival; growth; bioaccumulation; nervous system	Lethal exposure had no toxic effect but sub-lethal exposure cause growth and cholinesterase activity reduction, tissue-specific bioaccumulation	Zhao et al. (2011)
	<i>C. carpio</i>	10, 50, 100, 200, 300, 500, and 1000 mg/L; 20–40 nm; 4 days (lethal scenario) and 30 days (sub-lethal scenario); added to water	Gill structure; Cu bioaccumulation; global gene expression	Gill histopathological alteration; Cu bioaccumulation in gill; change in gene expression pattern	Griffitt et al. (2007)
	<i>C. dubia</i>	20–40 nm; 20, 50, and 100 mg/L; 48 h; added to water	Survival; Fe bioaccumulation	Increase mortality in dose- and time-dependent manner; increase bioaccumulation in highest doses and in lowest sampling time point	Hu et al. (2012)
	<i>P. lividus</i>	10 ⁻² or 10 ⁻⁴ g/L; 50–60 nm; 5 days; dietary administration	Survival; bioaccumulation; nervous system; gene expression	100% mortality in 10 ⁻² g/L in 2h day; iron bioaccumulation in digestive apparatus, the reproductive and immune systems; severe reduction in the number of stained vesicles; reduction of enzymatic activity of the three different cholinesterase isoforms (AChE, BChE, and PChE) was found in all the exposed samples; reduction of HSP 70 and GRP78 gene expression	Falugi et al. (2012)
La	<i>O. latipes</i>	25 mg/L; 50 nm; 14 days; added to water	Survival; molecular level; oxidative stress	Lethal and sub-lethal toxicity on exposed fish; CAT gene expression; generation of ROS	Chen et al. (2011)
	<i>Oreochromis mossambicus</i>	2.5–200 mg/L; 27 nm; 7 days; added to water	Breathing system, oxidative stress	Exposure to NPs led to a combination of hypoxia and production of ROS	Chen et al. (2013)
	<i>D. rerio</i>	0.5, 5, and 50 µg/L; 29–40 nm; 96 h; added to water	Blood biochemical	Significant change in hematological (RBC, WBC, Hb, and HCT) and biochemical parameters (SGOT, SGPT)	Karthikeyeni et al. (2013)
	<i>Chlorella</i>	≥10 mg/L; 30; 7 days; added to egg media	Embryonic development	Decrease survival, hatching rate, and malformation	Zhu et al. (2012)
	<i>D. magna</i>	10, 50, 100, 250, 500, and 1000 mg/L; >100 nm; 72 h; add to water suspension	Biomass and growth	Reduction of biomass at 1000 mg/L; no toxic effects on the growth	Balusamy et al. (2015)
		10, 50, 100, 250, 500, and 1000 mg/L; >100 nm; 72 h; add to water suspension	Survival and motility	Immobilization of <i>D. magna</i> following 48 h; 70% mortality after 48 h in 1000 mg/L	Balusamy et al. (2015)
	33, 100, 330, and 1000 µg/L; 14 days; add to water suspension	Life history	Significant decrease in growth in 1000 µg/L; decrease size at first reproduction; no effect on age at first reproduction and number of offspring	Lüring and Tolman (2010)	

Table 1 (continued)

NPs	Biological model	Concentration, size, contact time, and route(s) of administration	System action, cell, and tissue target	Major outcomes	References
QDs	<i>D. rerio</i>	~156 mg/L (juvenile), ~150 mg/L (embryo); 96 h (juvenile) and 144 h (embryo); added to water	Survival	Mortality in life stage dependent	Máková et al. (2014)
	<i>D. magna</i>	0, 0.95, 3, 9.5, 30, and 94.9 µg/L; 3, 24 nm; 47 h; added to water	Survival	Changing the light condition on QD toxicity.	Kim et al. (2010)
		2–5 nm; 48 h; 4.6×10^{13} – 1.8×10^{16} QD particles/L; add to water suspension	Survival; 48-h acute tests; end point: mortality; QD type: MUA = mercaptopropionic acid; PEO = polyethylene oxide	EC ₅₀ = 3.84 (2.79–5.46); CdSe/ZnS (Green PEO) EC ₅₀ = 0.77 (0.70–0.88); CdSe/ZnS (Red PEO) EC ₅₀ = 3.84 (2.79–5.46); CdSe/ZnS (Red MUA) EC ₅₀ = 0.11 (0.07–0.16); CdSe/ZnS (Green MUA) EC ₅₀ = 0.35 (0.28–0.45); QD stability has significant impact on the NPs' short-term toxicity	Pace et al. (2010)
	<i>C. dubia</i>	8 nM; 10–20 nm; 24 h; add to water suspension	Uptake and depuration	Accumulation of QDs independent of their surface charge but in dependent of surface functionalization; rapid initial elimination of QDs, after 4 h of depuration	Feswick et al. (2013)
	<i>L. plumulosus</i>	3.6 mg/L; 15–20 nm; 48 h; add to water suspension and dietary administration	Bioavailability; toxicity; bioaccumulation	Increase mortality in dose-dependent manner in both types of administration routes; both modes of exposure, QD were accumulated	Jackson et al. (2012)
	<i>D. rerio</i>	0.6 mg/L; 7.7 nm; 21 days; dietary administration	Survival; bioaccumulation	No mortality; assimilation efficiency was 8 and 4% for adult and juvenile zebrafish, respectively	Lewinski et al. (2011)
	<i>O. mykiss</i>	0, 0.4, 2, 10, 50, and 250 µg/L; 48 h; add to cell media	Oxidative stress; gene expression	Induction of metallothioneins; increase hsp70 gene expression; no effect on lipid peroxidation	Gagné et al. (2008)
Se	<i>Oreochromis niloticus</i>	From 0.5 to 2.5 mg/kg	Oxidative stress; gene expression	Induction of total metallothioneins and lipid peroxidation; increase hsp70 gene expression	Louis et al. (2010)
	<i>Tor putitora</i>	Dietary supplementation of Se-NP at the rate of 0.68 mg/kg	Ingestion with feed	Growth with weight gain rate	Deng and Cheng (2003)
SiO ₂		0.05, 0.2, 1, and 5 mg/L; 22 nm; 24 h; added to water	Oxidative stress	Beneficial effects on the physiological aspects (like red blood cell count, hemoglobin level, hematocrit values, and lysozyme activity) and biochemical parameters (serum growth hormone levels, tissue total protein content, and GSH-Px activity in liver and muscle tissues of <i>T. putitora</i>)	Khan et al. (2016)
	<i>M. galloprovincialis</i>	1, 5, and 10 µg/L; ~12 nm; 72 h; add to water suspension	Immune system, oxidative stress	Significant lysosomal membrane destabilization in both the hemocytes and the digestive gland; involve changes in lysosomal and oxidative stress biomarkers in the digestive gland	Canesi et al. (2010a)
	<i>D. rerio</i>	2.5, 50, 100, and 200 ng/L; 60 nm; 96 h; add to eggs and larvae media	Survival, development, behavior	None of the NP tested significantly affected lysosomal membrane stability, indicating the lack of a major toxic effect; significant increase of lysosomal enzyme release, superoxide and nitric oxide (NO) production	Canesi et al. (2010b)
SnO ₂	<i>P. lividus</i>	10^{-2} or 10^{-4} g/L; 50–60 nm; 5 days; dietary administration	Survival; bioaccumulation; nervous system; gene expression	Hatching rate of zebrafish embryos was decreased; mortality and malformation were increased; total swimming distance was decreased	Duan et al. (2013)
				100% mortality in 10^{-2} g/L after 48 h; tin bioaccumulation in digestive, reproductive, and immune systems; severe reduction in the number of stained vesicles; reduction of enzymatic activity of the three different cholinesterase isoforms (AChE, BChE, and PChE) was found in all the exposed samples; did not effect on HSP 70 and GRP78 gene expression	Falugi et al. (2012)

Table 1 (continued)

NPs	Biological model	Concentration, size, contact time, and route(s) of administration	System action, cell, and tissue target	Major outcomes	References
SWCNTs	<i>P. reticulata</i>	150 mg/L; 27–210 nm; 5 days; add to water suspension	Tin bioaccumulation; survival	Tin bioaccumulation in gill, spleen, intestine > liver, gonads, muscles, and thymus; none of the experimental or control fish died during the experiment	Krysanov et al. (2009)
	<i>A. marina</i>	0.003–0.03 g/kg g/kg; 1–2 nm; 10 days; add to sediment	Oxidative stress; DNA damage in coelomocytes; gut histology; titanium accumulation; gut histology	Reduction of lysosomal stability; did not affect on feeding behavior; DNA damage and SWCNT accumulation	Galloway et al. 2010
	<i>O. mykiss</i>	500 mg/kg; 1.1 nm; 6 weeks; dietary administration	Growth, hematology, accumulation, histopathology, osmoregulation	At week 4, but not on weeks 2 and 6, significant elevation in brain TBARS was observed in fish exposed to SWCNTs compared to the control; no overt toxicity for all other parameters	Fraser et al. (2011)
SWNTs and MWCNTs	<i>L. variegatus</i>	Single-walled carbon nanotubes (SWNTs), multiwalled carbon nanotubes (MWNTs), were spiked to sediment samples, and the respective uptake and depuration of these nanotubes were assessed by the oligochaete, <i>Lumbriculus variegatus</i>	Biological uptake and depuration	Biota-sediment accumulation factors for SWNTs and MWNTs suggest that the nanotubes studied have not been absorbed into organism tissues but rather are associated with sediment matter remaining in the gut of the organism	Petersen et al. 2008
	<i>D. neapolitana</i> and <i>H. diversicolor</i>	0.01, 0.10, and 1.00 mg/L of MWCNTs	Regenerative capacity and respiration rate, energy reserves, metabolic activities, oxidative stress-related biomarkers, and neurotoxicity markers	<i>D. neapolitana</i> : negative effects on the regenerative capacity, stimulated its respiration rate (at higher concentrations), altered energy-related responses (higher values of electron transport system activity, glycogen, and protein concentrations); <i>D. neapolitana</i> and <i>H. diversicolor</i> : oxidative stress with higher LPO, lower ratio between reduced and oxidized glutathione, and higher activity of antioxidant (CAT and SOD) and biotransformation (glutathione-S-transferases) enzymes	De Marchi et al. (2017)
TiO ₂	<i>M. galloprovincialis</i>	0.05, 0.2, 1, and 5 mg/L; 22 nm; 24 h; add to water suspension	Oxidative stress	Reduction of lysosomal membrane stability in hemocyte and digestive gland; increase in lipofuscin content; increase in catalase specific activity	Canesi et al. (2010a)
	<i>Haliotis diversicolor</i>	1, 5, and 10 µg/L; ~22 nm; 72 h; added to water suspension	Immune system, oxidative stress	None of the NP tested significantly affected lysosomal membrane stability, indicating the lack of a major toxic effect; significant increase of lysosomal enzyme release, superoxide, and nitric oxide (NO) production	Canesi et al. (2010b)
	<i>Artemia</i>	0.1, 1, and 10 mg/L; ≤10 nm; added to water suspension	Oxidative stress	Lipid peroxidation and nitric oxide production increased; GSH activity decreased; nTiO ₂ at the highest concentration (10 mg/L) had no appreciable effect on mortality	Zhu et al. (2011)
	<i>D. magna</i>	0.01 mg/L; 20 nm; 24 h; added to media 0.1, 0.5, 1, 5, 10, 50, and 100 mg/L; 21 nm; 72 h (acute toxicity study) and 21 days (chronic toxicity study)	Survival Survival; growth; reproduction; titanium accumulation	83% naupli survival Acute test: 72-h NOEC of nTiO ₂ 0.1 mg/L; 72-h EC ₅₀ and LC ₅₀ : 1.62 mg/L (0.87–2.45) and 2.02 mg/L (1.22–2.86), respectively; chronic test: mortality: 0% at 0.1 and 0.5 mg/L nTiO ₂ ; 20 ± 10% at 1.0 mg/L nTiO ₂ ; 60 ± 10% at 1.0 mg/L nTiO ₂ ; length, average offspring in each brood and total living offspring were significantly decreased in exposed groups	Barelds (2010) Zhu et al. (2010a, b)

Table 1 (continued)

NPs	Biological model	Concentration, size, contact time, and route(s) of administration	System action, cell, and tissue target	Major outcomes	References
		Assays were conducted using the USEPA standard operating procedure 2024 (1994); exposure to filtered TiO ₂ used seven concentrations (0.2, 1, 2, 5, 6, 8, and 10 mg/L), and exposure to the sonicated, unfiltered TiO ₂ used six concentrations (50, 200, 250, 300, 400, and 500 mg/L); 48-h acute test	Survival	LC ₅₀ = 5.5 mg/L; LOEC = 2.0 mg/L; NOEC = 1.0 mg/L	Lovren et al. (2007)
	<i>Arenicola marina</i>	0, 1, 1.8, 3.24, 5.83, and 10.5 mg/L with UVA light; 300–400 nm; 48 h; add to water suspension	Accumulation; survival	Titanium accumulated in gut tract; water fleas were not immobilized	Amiano et al. (2012)
	<i>D. rerio</i>	1–3 g/kg; 23.2 nm; 10 days; add to sediment	Oxidative stress; DNA damage in coelomocytes; gut histology; titanium accumulation; gut histology	Impact on feeding behavior; reduction of lysosomal stability; increase in DNA damage; no uptake of particles across the microvilli or gut epidermis into the epithelium cells or gut tissues	Galloway et al. (2010)
	<i>D. rerio</i>	1, 10, and 100 mg/L; 25 nm; 96 h; added to egg media	Development; oxidative stress	Both TA and TM caused accelerated hatching of the larvae; under UV irradiation, there was greater mortality of the larvae of the groups exposed to TM, compared to those exposed to TA; exposure to TM under UV irradiation altered the equilibrium of the larvae; alterations in the activities of CAT and GSTs were also observed (indicative of oxidative stress), although no clear dose-response relationship was observed	Clemente et al. (2014)
	<i>C. carpio</i>	10 mg/L; 21 nm; 20 days; added to water suspension (waterborne exposure and dietary exposure)	Tissue-specific accumulation	The carp accumulated considerably more Cd in presence of TiO ₂ ; Cd concentration increased and reached 22.3 lg/g at day 25, which increased by 146% than that without TiO ₂ NP	Zhang et al. (2007)
ZnO	<i>Lumbriculus variegatus</i>	10 (lethal scenario) 2.5 mg/L (chronic scenario); 90 nm; 94 h and 28 days; add to media	Behavior; oxidative stress	Negative effect of both lethal and chronic exposure to nZnO; chronic exposure toxicity of nZnO on oxidative stress biomarkers	O'Rourke (2013)
	<i>Crassostrea gigas</i>	30 mg/L; 28–88 nm; 96 h; added to water	Zn bioaccumulation, pathological destruction, oxidative stress	Zinc bioaccumulation in gill > and digestive glands; mitochondrial ultrastructure in tissues; induction of oxidative stress	Trevisan et al. (2014)
	<i>Macrobryachium rosenbergii</i>	0, 10, 20, 40, 60, and 80 mg/L; 50 nm; 90 days; dietary administration	Growth, antioxidant enzymes, immune system	Improved performance in survival, growth, and activities of digestive enzymes (protease, amylase, and lipase) (up to 60 mg/L); increase biochemical constituents (total protein, total amino acid, total carbohydrate, and total lipid), total hemocyte count (up to 60 mg/L); significant elevations in SOD, CAT, LPO, GOT, and GPT (in 80 mg/L)	Muralisankar et al. (2014)
	<i>D. rerio</i>	1, 5, 10, 25, 50, and 100 mg/L; 20 nm; 48 h; added to egg suspension	Hatching and development	High mortality in high doses (50 and 100 mg/L); decrease in hatching rate reduces the length and weight growth of larvae	Bai et al. (2010)
	<i>Cyprinus carpio</i>	5 mg/L; ≤100 nm; 14 days; waterborne exposure	Zinc accumulation	No significant uptake of zinc in fish tissues was observed for concentrations in the water spanning 500–5000 µg/L	Johnston et al. (2010)
	<i>Cyprinus carpio</i>	50 mg/L; 30 nm; 30 days; add to water suspension	Gill, liver, brain, intestine, muscle	Severe histopathological alteration, zinc bioaccumulation in liver > gill > intestine > brain and muscle, decrease SOD activity	Hao et al. (2013)

hormones were present in blood for a longer period in treated organisms and the relative number of eggs and their fertilization rate also significantly increased. Moreover, chitosan nanoconjugated salmon luteinizing hormone-releasing hormone (CsLHRH) increased the expression level of Sox9 transcripts in gonads and steroid hormonal levels in blood of male and female of *Clarias batrachus* being helpful for proper gonadal development (Bhat et al. 2016).

Nanotechnology and aquacultured species health

Aquaculture industry has experienced great problems with pathogens (bacteria, fungi, and viruses) that were generally controlled with chemical disinfectants and antibiotics (Huang et al. 2015). Shaalan et al. (2016) reviewed the use of NPs as potential antimicrobials, emphasizing on antibiotic-resistant bacteria in fisheries, nanoparticle-based vaccines, and the development of specific and sensitive tool for diagnosis of bacterial, fungal, and viral diseases in aquaculture. Ramya et al. (2014) showed the protective efficacy of a DNA construct containing extra small virus antisense (XSVAS) gene of nodavirus encapsulated with chitosan NPs in *M. rosenbergii* increasing its survivability. The fish nanomedicine is in its infancy and several gaps about potential adverse effects to target and non-target species still needs to be addressed.

Rapid detection of pathogens in aquatic organisms can be very effective to disease control, but the available methods are time consuming, costly, and might experience some difficulties in pathogen separation and detection. Guo et al. (2016) conducted a study to design an immunomagnetic NP-based microfluidic system to detect *Staphylococcus aureus* creating a microfluidic chip with indium tin oxide. Results evidenced that sensitivity and specificity of the detection system were the same of the colony counting method, with a whole shorter detection time without colony cultivation.

Due to chitosan antimicrobial properties, several studies investigated its application for seafood packaging (Alishahi et al. 2014; Hosseini et al. 2016). Ramezani et al. (2015) studied the effect of chitosan and chitosan NPs on silver carp (*Hypophthalmichthys molitrix*) fillets stored at 4 °C, evidencing that chitosan NPs exhibited interesting antimicrobial activity and the ability to inhibit the TVB-N content improving the general storage potentiality of the product.

Disease prevention and control are crucial for aquaculture under an economical and environmental viewpoint. Thus, vaccination plays an important role on large-scale commercial fish farming. Nanoencapsulated vaccines against *Listonella anguillarum* in Asian carp (Rajeshkumar et al. 2009), white spot syndrome virus (WSSV), and infectious myoncronis virus (IMNV) (i.e., shrimp farming) (Rajeshkumar et al. 2009; Chalamcheria 2015) have been developed. Polyanhydride NPs were used for encapsulating and releasing vaccine

antigens determining immunization of shrimp via immersion or with feed (Ross et al. 2014). Rajeshkumar et al. (2009) investigated DNA constructed vaccines based on nanotechnologies to produce immunologic proteins protecting shrimps from WSSV for up to 7 weeks per application. NP-based carriers, like chitosan, alginates, and poly-lactide-co-glycolide acid (PLGA) for vaccine antigens, together with mild inflammatory inducers orally, showing a high level of protection to fish and shellfish with a relative survival rate of up to 85% in cultured shrimp (Rajeshkumar et al. 2009).

In addition, silica-based NPs can be used for drug (i.e., pharmaceuticals or other therapeutics) administration due to its porous structure and ability to incorporate high doses (Strømme et al. 2009). Some authors (García-Rodríguez et al. 2008; Bhattacharyya et al. 2015) evidenced their potential use in aquaculture in the near future.

Silver (Ag) NPs (nAg) are the most investigated multiple mechanism nano-based antibacterial. The release of silver ions (Ag⁺) and their binding onto bacterial cell membrane proteins lead to cell membrane disruption and to cell death (Lara et al. 2010; Huang et al. 2011). Dananjaya et al. (2016) investigated the antibacterial function of chitosan-Ag nanocomposites (CAgNCs) against fish pathogenic *Aliivibrio salmonicida*. CAgNCs inhibited *A. salmonicida* growth indicating minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) at 50 and 100 mg/L, respectively. No effects of CAgNCs were detected to *Danio rerio* at 12.5 mg/kg of body weight/day (BW/day) as a feed ingredient and *Oplegnathus fasciatus* testis cells up to 50 mg/L, thus suggesting its potentiality as an antibacterial agent to the control fish pathogenic bacteria.

Further investigations are also necessary about potential side effects of nanotagging and nanobarcoding when applied directly to organisms. The barcode can be detected by the application of nanoscale components such as radio frequency identification (RFID). These tags can hold more information and can be used as a tracking device, monitoring their metabolism or swimming ability. In the processing and export industry, nanobarcoding can be used effectively to observe various aspects of delivery process and management, tracking the source or delivery status of products (Rather et al. 2011).

Nanotechnology and (waste)water treatment in aquaculture

The physico-chemical properties of water in aquaculture ponds can be influenced by various parameters such as soil composition, environmental pollution, and food waste (Venkat 2011; Katuli et al. 2014a, 2014b), while in coastal or open-sea cages, water quality is generally influenced by the natural environment.

Aquatic pollution is one of the greatest threats for aquaculture production. Recently, the application of nanoenabled

products based on aerogels, polymers and functionalized composites, hydrophobic organoclays, and magnetic engineered NPs for water treatment and purification has been studied (Bhattacharyya et al. 2015; Lofrano et al. 2016a). nAu, nAg CNTs, nFe, lanthanum (La), and nTiO₂ were used for the removal of pesticides, ammonia, heavy metals, and phosphates from water and wastewater (Ren et al. 2011; Xu et al. 2012; Pradeep 2009; Rather et al. 2011). Quantum dots (QDs) due to their unique optical properties (Vázquez-González and Carrillo-Carrion 2014) have been proposed for the detection of heavy metals in aquaculture media (Chen et al. 2013).

Intensive farming of shrimps and fish led to growing problems with bacterial diseases such as *A. salmonicida*, *Flavobacterium columnare*, and *Yersinia ruckeri* (Pulkkinen et al. 2010). In aquaculture, traditional disinfectants (e.g., hydrogen peroxide and malachite green), antibiotics (e.g., sulfonamides and tetracyclines), and anthelmintic agents (e.g., pyrethroid insecticides and avermectins) are frequently used in large amounts, but presenting several limitations like high cost of chemical drugs, negative effects on non-target organisms, and increased resistance of pathogens (Romero et al. 2012).

The proliferation of opportunist pathogens (bacteria, virus, fungi, or protozoa) is a known problem in fish farming due to the high density of organism stocks and the food residues; thus, the use of quick and effective antipathogens is of crucial interest (Twiddy et al. 1995; Castillo-Rodal et al. 2012). For example, nAg was used for the treatment of fungal infections in rainbow trout egg showing inhibitory effect on fungi growth (Johari et al. 2015). nZnO exhibited antibacterial activity disrupting bacterial cell membrane integrity, reducing cell surface hydrophobicity and downregulating the transcription of oxidative stress-resistance genes (Pati et al. 2014). Mühling et al. (2009) showed that nTiO₂ and nAg reduced the build-up of bacteria in estuarine water.

The use of Ti photoelectrolysis was used in environmental applications including sterilization and disinfection. Under ultraviolet irradiation conditions, TiO₂ NPs produce highly active hydroxyl (OH[•]), superoxide ion (O₂^{•-}), and peroxy radical (O₂⁻) having high oxidation capacity. Free radicals change cell membrane structure, leading to their apoptosis, thus sterilizing and disinfecting (Yu et al. 2002; Sonawane et al. 2003; Zhao et al. 2000).

Liu et al. (2009) reported bactericidal effects of copper-bearing nanomontmorillonite (Cu²⁺-MMT) on three aquatic (*A. hydrophila*, *Vibrio parahaemolyticus*, and *Pseudomonas fluorescens*) and two intestinal pathogens (*Lactobacillus acidophilus* and *Bacillus subtilis*), showing that the efficiency of Cu²⁺-MMT depended on temperature and contact time. The bacterial removal efficiency was 100% for *A. hydrophila*, in *V. parahaemolyticus*, and *P. fluorescens*, and 24.9% for *L. acidophilus* and 25.6% in *B. subtilis* after 12 h at 30 °C.

Wen et al. (2003) stated that the nanodevices are very useful to improve water quality in shrimp aquaculture, reducing the rate of water exchange, improving shrimp survival rate and yield.

Another major challenge in aquaculture is the biofouling control. The bacterial biofilm allows the attachment of macrofoulers, like in the case of mariculture cages causing serious problems like corrosion, weight increase, surface alteration, and distortion of submerged structures (Champ 2003). To get rid of fouling organisms, antifoulings are directly applied, but with potential undesired adverse effects on other non-target species (e.g., TBT) (Lofrano et al. 2016b). NP-based antifoulings like nCuO, nZnO, and nSi seem to be potential good candidates (Rather et al. 2011) with their high-surface-to-volume ratio creating a more efficient barrier to fouling agents (i.e., at equal or lower concentrations). Ashraf and Edwin (2016) used nCuO to treat cage nets evidencing a significant reduction of fouling after 90 days from application.

“NanoCheck” (Altair Nanotechnologies, Reno, NV, USA) is a commercial product for fishpond management using 40-nm particles based on La compounds supporting the absorption of water phosphates thus limiting algae growth (Mohd Ashraf et al. 2011). Moreover, La oxides NPs were used as phosphate scavenger leading microorganisms to starvation showing promising effects on *Escherichia coli*, *Staphylococcus carnosus*, *Penicillium roqueforti*, and *Chlorella vulgaris* (Gerber et al. 2012).

Vijayan et al. (2014) assessed the bacterial antibiofilm activity of nAg and nAu synthesized from *Turbinaria conoide* extracts highlighting that nAg was efficient in controlling biofilm formation, while nAu was not.

Toxicological profiling in tissue-based target

Engineered NPs are applied in various aquaculture sectors, and, currently, many studies are being carried out to check their safe use, but out the aquaculture sector. Since all of their effects on living organisms (especially aquatic organisms) have not been fully identified, public concern raises from their use in aquaculture. Toxicity of NPs can be different in relation to the way they are administered, and toxicokinetics and toxicodynamics. Concentrations of NPs administered via feed, present in treated surfaces (i.e., cage nets), or waterborne (i.e., fishponds) could be significantly higher than the expected NP environmental concentrations (Minetto et al. 2016) being up to micrograms per liter or greater.

We tried to consider a system-based approach, focused on the (eco-)toxicological profile of engineered NPs. In Table 1, we summarized the information related to various NPs and target organisms of potential aquaculture interest, including the main relative testing conditions. NPs were listed and presented considering the following order: alginate, Al₂O₃, Ag,

Au, CeO₂, chitosan, chitosan-Ag nanocomposites CAgNCs, CuO, Fe, La, QDs, Se, SiO₂, SnO₂, SWCNTs and MWCNTs (including C₆₀ and nano carbon black), TiO₂, and ZnO. Discussion about the comparison of negative or positive effects of NPs has been very tricky for four main reasons: (i) biological models are not recurrent, and in the case, testing protocols are frequently different; (ii) most data derived from toxicity studies are not specifically designed on aquaculture needs, thus contact time, exposure concentrations, and other ancillary conditions (i.e., acclimation periods) do not meet the required standard for aquaculture; (iii) short-term exposure periods (generally up to 14 days) are investigated mainly on species of indirect aquaculture interest (i.e., *A. salina* and *D. magna* as feed for other organisms), while shrimp and fish as final consumers in aquaculture plants are underinvestigated (scarce or unknown data on trophic chain transfer of NPs): little information is available about the amount of NPs accumulated within marketed organisms; and (iv) how NPs present in the packaging of aquacultured products can affect their quality remained substantially unexplored.

Alginate NPs

Alginate is a natural polymer extensively used in food industry as thickening, emulsifying, and stabilizing agent (George and Abraham 2006; Klinkesorn and McClements 2009). Alginate NPs were recently evaluated with positive results (Guo et al. 2013; Guo et al. 2015). However, due to the limited number of toxicity data, concern is present about its use.

Al₂O₃ nanoparticles

Al₂O₃ NPs are good dielectric and abrasive agents. Toxicity of nAl₂O₃ was checked with *Caenorhabditis elegans* (used as live food in the larval breeding of species in aquaculture and aquaria), showing that concentrations >102 mg/L significantly inhibited the growth and number of eggs inside worm body and offspring, and the worms' reproduction was inhibited at concentrations >203.9 mg/L of nAl₂O₃ (Wang et al. 2009).

Shirazi et al. (2015) demonstrated that nAl₂O₃ presented growth inhibition effects on *Dunaliella salina*, showing a direct relationship between NP concentration and effect. Moreover, the increase in NP concentration corresponded to a chlorophyll and carotenoid decrease in microalgae.

Swain et al. (2014) explored the antimicrobial activity of nAl₂O₃ (<50 nm) against microbes responsible to diseases in aquaculture. Results showed that nAl₂O₃ is not able to inhibit the activity of the isolated bacteria.

Barber et al. (2005) exposed nAl₂O₃ for 72 h to *D. rerio*, evidencing that ingested NPs were mainly present in the fish intestine and no lethality was recorded up to 500 g/L. Reduced gill ATPase activity was observed, indicating compromised gill function.

Ag NPs

Silver NPs (nAg) are widespread in several consumer products such as cosmetics and plastics, water purifiers, textiles, drugs, and agrochemicals. Due to their antibacterial activity, nAg has been used in aquaculture for water treatment (Mühling et al. 2009; Johari et al. 2015) and several studies on its toxicity are available on aquatic organisms of aquaculture interest.

Völker et al. (2015) exposed *Sphaerium corneum* to sub-lethal nAg concentrations (up to 500 µg/L), evidencing a significant ROS generation and antioxidant enzyme activity compared to the control group. Rajkumar et al. (2016) exposed *Labeo rohita* up to 100 mg/kg of nAg for 7 days, highlighting a significant reduction in hematological parameters. Antioxidant enzymes significantly increased in gills, liver, and muscle; histopathological lesions were evidenced.

Kandasamy et al. (2013) assessed nAgNO₃ (synthesized by leaf extract of *Prosopis chilensis*), showing an antibacterial effect on four species of *V. pathogens* on shrimps *Penaeus monodon* after 30 days of exposure. Shrimps fed with nAgNO₃ exhibited higher survival rates, associated to immunomodulation in terms of higher hemocyte counts, phenoloxidase, and antibacterial activities of hemolymph. Blinova et al. (2013) studied the adverse effects of nAg to *D. magna* and *Thamnocephalus platyurus*. After 24 h of exposure, EC₅₀s of nAg for *D. magna* and *T. platyurus* were 17 and 27 µg/L, respectively. According to Arulvasu et al. (2014), *Artemia salina* was exposed to a series of nAg concentration up to 12 nM for 24–48 h observing that mortality rate, aggregation in gut region, apoptotic cells, and DNA damage increased in a concentration-dependent way, like cysts hatching rate.

Large-scale culture of *Hediste diversicolor* provides an increasing market of live baits and can be an important food source for a variety of cultured species like marine prawns or flatfish. Garcia-Alonso et al. (2011) exposed *H. diversicolor* to nAg@citrate (30 ± 5 nm; 250 ng/g sediment; 10 days), showing aggregations of NPs in close association with the villi, and in the glycolax matrix of the worms' gut lumen. Cong et al. (2011) investigated *H. diversicolor* exposed to nAg-spiked sediment, highlighting genotoxicity effects. It is not yet well understood the mechanism of oxidative stress response elicited by nAg and how it relates to the Ag tissue burden. Cozzari et al. (2015) exposed *H. diversicolor* to sediment spiked with dissolved Ag (added as AgNO₃), Ag NPs (63 ± 27 nm), and larger bulk Ag particles (202 ± 56 µm) for up to 11 days at sub-lethal concentrations. Concentration- and time-dependent differences were present in the accumulation of the three Ag forms, but all three forms elicited an oxidative stress response. In the cases of Ag NPs and bulk Ag particles, changes in glutathione, SOD, CAT, GPx, SeGPx, GST, and GR occurred without significant Ag accumulation, while differences in biomarker profiles

between the three Ag forms suggest that the mechanism of oxidative stress caused by particulate Ag is distinct from that of dissolved Ag.

Gomes et al. (2013) evaluated the genotoxic impact of nAg using *M. galloprovincialis* exposed to 10 µg/L of nAg (and its bulk form) for 15 days, assessing genotoxic effects in hemocytes using the comet assay. Ag (nanoparticles and ionic forms) induced DNA damage in hemolymph cells with a time-response effect. Ionic forms presented higher genotoxicity than NPs, suggesting different mechanisms of action that may be mediated through oxidative stress.

Khan et al. (2015) reported on bioaccumulation dynamics in *Lumbriculus variegatus* of ionic Ag and three differently coated nAg@ (PVP (polyvinylpyrrolidone), PEG (polyethylene glycol), and citrate). Uptake rate constants for nAg were ~2–10 times less than for Ag⁺, showing significant rank order concordance with acute toxicity; Ag elimination fitted a 1-compartment loss model.

The effects of AgNPs in *Labeo rohita* liver were investigated at genomic and cellular level for 7 days at the concentrations of 100, 200, 400, and 800 µg/L (with AgNPs of 18 and 29 nm) (Sharma et al. 2016). After histopathological examination, the liver highlighted vacuolar degeneration, presenting hepatocytes with total degeneration and high accumulation of AgNPs, depicting both time and dose-dependent relationships. Moreover stress-related genes showed downregulation, due to the production of free radicals and reactive oxygen species.

Au NPs

Au NPs (nAu) is used in a variety of fields such as electronics, catalysis, cosmetics, food quality control, and cancer detection (Zhu et al. 2010a, b). Despite its use, little is known about its uptake in aquatic organisms. Asharani et al. (2011) conducted a study to evaluate and compare the effect of Ag, Au, and Pt NPs on the development of zebrafish embryos, evidencing that nAu presented no toxicity compared to nAg (concentration-dependent increase in mortality and phenotypic changes, hatching delays) and nPt (hatching delays).

Mytilus edulis exposed for 24 h to 750 mg/L of Au@citrate NPs highlighted increased CAT activity in the hemolymph, and reduced ubiquitination and caronylation in the digestive gland, gill, and mantle (Tedesco et al. 2008). According to García-Negrete et al. (2013), *Ruditapes philippinarum* accumulated nAu@citrate (21.5 ± 2.9 nm; 6–30 mg/L) more readily in digestive gland heterolysosomes (plateauing after 12 h), while ionic Au was more associated to gills.

CeO₂ nanoparticles

CeO₂ NPs are used in coatings, electronics, and biomedical devices and as fuel additives (Falugi et al. 2012). There are still several uncertainties about its effect for human health and

the environment. Johnston et al. (2010) exposed *D. rerio* for 14 days to nCeO₂, evidencing Ce accumulation in liver, but not in gill, brain, and skin. A 5-day study (Falugi et al. 2012) investigated the exposure of *P. lividus* to CeO₂ (50–105 nm) NPs at 10 mg/L, resulting in total mortality after only 2 days, but animals survived for 5 days at 0.1 mg/L.

Chitosan NPs

Chitosan is a natural polysaccharide that presents interesting biodegradability (Rather et al. 2013), biocompatibility (Luo and Wang 2013), and mucoadhesiveness (De Campos et al. 2004) properties with potential applications for drug delivery and gene transfer (Chatterjee and Judeh 2016; Ji et al. 2015). Chitosan NPs can pass through tight junctions between epithelial cells (Dodane et al. 1999), posing potential risks to humans, animal, and environment. Hu et al. (2011) reported death and malformation of zebrafish embryos exposed to increasing concentrations of chitosan NPs (200 nm) with almost 100% mortality at 40 mg/L. ROS and hsp70 confirmed that are concentration and size dependent. Rather et al. (2016) studied the effects of kisspeptin-10 (K-10) (i.e., an essential gatekeeper of various reproductive processes) and chitosan-encapsulated K-10 nanoparticles (CK-10) on gene expression, evidencing that chitosan nanoparticles increased by 60% the entrapment efficiency for K-10 being potentially useful for developing therapies against various reproductive dysfunctions in vertebrates. Loh et al. (2010) evaluated the cytotoxicity of chitosan NPs in human liver cells showing that CYP3A4 enzyme activity increased in a dose-dependent way. Results highlighted that the destruction of cell membrane was influenced by different zeta potential of chitosan NPs. Similar results were reported by Huang et al. (2004) after exposing A549 cells to chitosan NPs to assess their uptake and cytotoxicity.

Cu NPs

Copper NPs (nCu), especially nCuO, present bactericide and antifouling properties, and an excellent thermal conductivity, being one of the most widely used metallic NPs (Buffet et al. 2011) with potential implications in aquaculture.

Griffitt et al. (2007) exposed *D. rerio* juveniles for 48 h to waterborne nCuO, observing histological damages, Cu accumulation in gill, and also 82 genes differentially expressed compared to the controls.

Zhao et al. (2011) evaluated the effect of lethal and sub-lethal concentration of nCuO in *C. carpio* showing that after 4-days exposure, no acute effect was observed, but after a 30-day exposure to sub-lethal concentrations, it was observed a reduced growth and Cu accumulation (intestine > gill > muscle > skin and scale > liver > brain). Moreover, the reduction of cholinesterase activity evidenced that Cu sub-lethal concentrations could have potential neurotoxicity for juveniles.

Buffet et al. (2011) assessed the exposure of *H. diversicolor* to nCuO (197 nm, 10 µg/L) showing Cu accumulation and oxidative stress evidenced by the increase of GSTs and CAT activities.

Gomes et al. (2013) evaluated the genotoxic impact of nCuO using *M. galloprovincialis* exposed to 10 µg/L of nCuO (and its bulk form) for 15 days assessing genotoxic effects in hemocytes using the comet assay. Cu (nanoparticles and ionic forms) induced DNA damage in hemolymph cells with a time-response effect. Ionic forms presented higher genotoxicity than NPs, suggesting different mechanisms of action that may be mediated through oxidative stress.

Adam et al. (2015) demonstrated that nCuO had less negative effect than Cu salt on growth and reproduction of *D. magna*.

Fe NPs

Low toxicity and special surface chemistry of nFe₂O₃ widespread its use in biomedical applications like cellular labeling, drug delivery, tissue repair, in vitro bioseparation, and hyperthermia, with other applications like water and wastewater treatment (Chen et al. 2011), and in aquaculture as food supplement (Ren et al. 2011).

Chen et al. (2011) exposed medaka fish (*Oryzias latipes*) to nFe for 14 days evidencing lethal and sub-lethal effects (ROS generation and CAT alteration), showing that coated NPs with carboxymethyl cellulose were less toxic than uncoated ones.

Karthikeyeni et al. (2013) biosynthesized nFe₂O₃ and evidenced that after 96 h exposure to *Oreochromis mossambicus*, hematological (RBC, WBC, Hb, HCT) and biochemical parameters (SGOT, SGPT) significantly changed. Chen et al. (2013) found after 7 days exposure of *O. latipes* to nFe⁰ high mortality due to a combination of hypoxia and ROS production.

Zhu et al. (2012) have investigated the effects of nFe₂O₃ on the embryonic development of zebrafish resulting in embryos mortality, hatching delay, and malformation after 7 days exposure to ≥10 mg/L.

In Falugi et al. (2012), groups of 5–10 adults of *Paracentrotus lividus* of a similar size (50–60 mm) were forced to ingest of metal oxide NPs (SnO₂, CeO₂, and Fe₃O₄) (nominal concentrations 10⁻² and 10⁻⁴ g/L). Results showed that after 1–2 days, none of the treated organisms at 10⁻² g/L nFe survived. Iron bioaccumulation in digestive apparatus, severe reduction in the number of stained vesicles, as well as down-expression of hsp70 and GRP 78 were observed. The exposure of nFe₃O₄ to *M. galloprovincialis* (50 nm, polyethylene glycol capped, 0.370 mg/L) showed an accumulation in digestive gland after 8 h (>90%) remaining after 72-h depuration (>75%) (Hull et al. 2013).

La NPs

Lanthanides are widely used in industry, medicine (Máková et al. 2014), and for water treatment (Rather et al. 2011). Máková et al. (2014) exposed for 96 h juveniles of *D. rerio* and *P. reticulata*, and for 144 h embryonic stages of *D. rerio*, reporting the following LC₅₀ values 156.33 ± 5.59 and 128.38 ± 5.29 mg/L, and 152.98 ± 8.06 mg/L, in that order. Thus, potential toxicity events could be associated to the use of La NPs.

Lürling and Tolman (2010) exposed *D. magna* for 14 days to different concentrations of La-QD, observing a size decrease in organisms after the first reproduction, but with no changes in the reproductive age and number of offspring.

Balusamy et al. (2015) exposed *Chlorella* sp. to up to 1000 mg/L of La-QD, and fed it to *D. magna*. Results evidenced that both *Chlorella* sp. biomass and *D. magna* mobility decreased. The LC₅₀ value for La-QD for *D. magna* was 500 mg/L, and after 48 h at 1000 mg/L, the mortality of exposed daphins was 70%.

Quantum dots

QDs are used in electronic bioimaging, and biosensing (Feswick et al. 2013), and recently for water quality monitoring (Vázquez-González and Carrillo-Carrion 2014).

Louis et al. (2010) showed that *O. mykiss* exposed to 2 µg/L of QDs for 48 h presented an increase in total metallothioneins and LPO. Lewinski et al. (2011) exposed *A. franciscana* and *D. magna* for 24 h to 0.6 mg/L of QD. These microorganisms were fed to juvenile and adult of zebrafish for 21 days. Results showed no mortality after exposure, but QDs accumulated up to 4 and 8% for juveniles and adults, respectively. Gagné et al. (2008) obtained similar results after in vitro study with hepatocyte of *O. mykiss*.

Jackson et al. (2012) investigated the effects of QD-spiked algae (3.6 mg/L) fed to *Leptocheirus plumulosus* compared to water spiked with QDs. Results showed that mortality increased after 4 h exposure in a concentration-dependent manner in both administration routes with QD accumulation.

Kim et al. (2010) studied the influence of light wavelength on QD LC₅₀ on *D. magna* evidencing after 48 h exposure. Toxicity increased from darkness to white fluorescence light, natural sunlight, and up to UV-B. Moreover, the QDs' coatings seemed to be able to influence its toxicity, changing its stability and the potential release of toxic components (Kim et al. 2010; Feswick et al. 2013).

Selenium NPs

Se is an essential trace element required in diet for normal growth and physiological function of several organisms (Poletini et al. 2015), including fish (Khan et al. 2016); thus,

it is an excellent bionutrient product for aquaculture enhancement. Khan et al. (2016) investigated the effects of dietary supplementation of nSe (0.68 mg/kg feed) on physiological and biochemical aspects of juvenile mahseer fish (*Tor putitora*), evidencing an increase in red blood cell count, hemoglobin level, hematocrit values, and lysozyme activity compared to the traditional diet as well as other biochemical parameters (serum growth hormone levels, tissue total protein content, and GSH-Px activity in liver and muscle tissues).

Silicon dioxide NPs

SiO₂ NPs (nSiO₂) are effective for drug delivery and optical imaging (Ramesh et al. 2013), but applications in aquaculture were reported as well in order to reduce the risk of disease spread in crowded fish pools (Strømme et al. 2009). Anyhow, Duan et al. (2013) observed an increase in zebrafish mortality and malformation after 96 h exposure to Si NPs.

Sn oxide NPs

Tin oxide NPs (nSnO₂) present unique features such as rigid structure and low-temperature conductivity attracting great interest especially in the development of gas sensors, optoelectronic devices, catalysis, and electrochemical energy storage. Little data are available on nSnO₂ toxicity on aquatic organisms, and its potential applications in aquaculture are still under evaluation with information on only two species of potential interest. Krysanov et al. (2009) exposed *P. reticulata* to 150 mg/L of nSnO₂ for 5 days, showing that tin accumulated in gill, spleen, intestine, liver, gonad, thymus, and muscle. Falugi et al. (2012) reporting *P. lividus* effects on nSnO₂ were already discussed in the “Fe NPs” section.

SWCNTs

Carbon nanotubes (CNTs) present unique properties including high electrical conductivity, very high tensile strength, and hydrophobicity, which are valuable for wide-ranging industrial and biomedical applications such as electronic, drug delivery, and biosensing technology (McEuen et al. 2002; Galloway et al. 2010). In aquaculture, CNTs are used to increase food stability and promote water treatment (Fraser et al. 2011; Ren et al. 2011).

Fraser et al. (2011) compared the potential toxicity of SWCNT and C₆₀. After 6 weeks feeding rainbow trouts (*Oncorhynchus mykiss*) by supplemented diet (500 mg SWCNT or C₆₀), SWCNT had toxic effects, but C₆₀ had not significantly effect on thiobarbituric acid reactive substances (TBARS—an indication of LPO) compared to the control. Smith et al. (2007) found after 10 days of exposure to SWCNT to *O. mykiss* damaged gill structures, and breathing

and osmoregulation adversely affected, while TBARS decreased and total glutathione levels increased.

Petersen et al. (2008) investigated sediment samples spiked with SWCNTs and multiwalled carbon nanotubes (MWNTs) exposed to *Lumbriculus variegatus*, looking for uptake and depuration kinetics. Depuration behaviors suggested that nanotubes detected within the organisms were associated to the sediment remaining in organism guts, and not absorbed by tissues.

De Marchi et al. (2017) assessed the toxic effects of MWCNTs (0.01; 0.10 and 1.00 mg/L) in *Diopatra neapolitana* and *Hediste diversicolor* (regenerative capacity and respiration rate) and biochemical performance (energy reserves, metabolic activities, oxidative stress-related biomarkers, and neurotoxicity markers) after 28 days of exposure. They evidenced that exposure to MWCNTs induced negative effects on the regenerative capacity of *D. neapolitana*, stimulated its respiration rate (at higher concentrations), and altered energy-related responses (higher values of electron transport system activity, glycogen, and protein concentrations) In addition, both species showed oxidative stress with higher LPO, lower ratio between reduced and oxidized glutathione, and higher activity of antioxidant (CAT and SOD) and biotransformation (glutathione-S-transferases) enzymes in exposed organisms.

Titanium dioxide NPs

nTiO₂ is used in several commercially available products such as paints, papers, textiles, plastics, sunscreens, cosmetics, and food products (Zhu et al. 2010a, b). As reviewed in the previous section, nTiO₂ can be used both directly and indirectly in aquaculture (Sonawane et al. 2003; Ramsden et al. 2009). Therefore, it is necessary to investigate its potential toxicity in aquatic organisms.

Embryos of *D. rerio* were exposed during 96 h to different concentrations of nTiO₂ in the form of anatase (TA) or anatase/rutile mixture (TM), under either visible light or a combination of visible and ultraviolet light (UV). Results showed that both crystallographic forms of nTiO₂ caused accelerated hatching of larvae, alteration of the antioxidant enzymes (CAT and GSTs), and increased malformation of larvae (Clemente et al. 2014). nTiO₂ facilitated the transport of Cd into carp (*Cyprinus carpio*) after 20 days of exposure (Zhang et al. 2007).

Bivalvia are highly vulnerable to ingestion of NPs from the water column. The NP uptake primarily occurs via the gills, and for this reason, it would be expected a higher accumulation in these tissues (Canesi et al. 2012). *Mytilus galloprovincialis* of 4–5 cm were kept for 24 h under static test condition containing different concentrations of nTiO₂ (Canesi et al. 2010a, 2010b). Results showed that NPs induced significantly lysosomal membrane destabilization and

lysosomal lipofuscin accumulation both in hemocytes and in digestive gland, as well as increase GSTs in gills. Abalones (*Haliotis diversicolor*) were exposed to lethal concentrations of nTiO₂ and after 96 h exposure showing an increase of the lipid peroxidation (LPO), and a decrease in GSH activity and nitric oxide production (Zhu et al. 2010a, b).

Artemia spp., *Daphnia* spp., *Ceriodaphnia dubia*, and *Lumbrinereis variegates* are used as live food source in freshwater larviculture, and in ecotoxicological studies (García-Alonso et al. 2011; Jackson et al. 2012; Feswick et al. 2013). *A. salina* is one of the most studied organisms in marine ecotoxicity (Radhika Rajasree et al. 2010; Libralato et al. 2016b). In Ates et al. (2013), *A. salina* was exposed to different concentrations of nTiO₂. Their results showed that after 96 h exposure, no mortality occurred and LPO levels did not change (Libralato 2014).

Acute and chronic ecotoxicity nTiO₂ studies on *D. magna* showed a dose-dependent mortality (Zhu et al. 2010a, b). Results showed that Ti accumulated in the gut, but did not cause any immobilization (Amiano et al. 2012). Lovern et al. (2007) reported concentration-dependent mortality of *D. magna* exposed to filtered nTiO₂ (≈30 nm), with an LC₅₀ 5.5 mg/L. An EC₅₀ >100 mg/L was reported by Warheit et al. (2007) and Zhu et al. (2010a, b) for nTiO₂ (100–140 nm) for *D. magna* after 48 h of exposure. Wiench et al. (2009) found EC₅₀ >100 mg/L for both uncoated and coated TiO₂ NPs. Amiano et al. (2012) found an EC₅₀ = 3.4 mg/L of nTiO₂ after exposure to 0.56 mW/cm² UVA radiation using river water as testing matrix. Marcone et al. (2012) showed no toxicity of TiO₂ during light and dark conditions up to 100 mg/L. Dalai et al. (2013) evidenced after 48 h two EC₅₀s considering light (8.26 mg/L) and dark (33.65 mg/L) scenarios for *C. dubia*.

A synergistic effect of nTiO₂ and As⁵⁺ was observed on *C. dubia* showing that at low concentrations of nTiO₂, the toxicity of As⁵⁺ can significantly increase (Wang et al. 2011). *Arenicola marina* was exposed for 10 days to SWNT (0.003–0.03 g/kg) and nTiO₂ (1–3 g/kg) (Galloway et al. 2010). Results showed that SWCNTs did not affect feeding behavior, but nTiO₂ did, in addition to lysosomal stability causing DNA damage.

Zinc oxide NPs

ZnO NPs are used in optoelectronics, cosmetics, catalysts, ceramics, pigments (Bai et al. 2010), and aquaculture (Faiz et al. 2015). Contradictory results exist about nZnO effects according to concentrations, contact time, and target organisms (Berube 2008).

Bai et al. (2010) exposed zebrafish embryos to various concentrations of nZnO, showing a significant decrease in survival, hatching, and larval growth rate after 94 h. Hao et al. (2013) carried out a 30-day study on juvenile of *C. carpio* exposed to nZnO, highlighting severe histopathological alterations and

intracellular oxidative stress. Muralisankar et al. (2014) demonstrated that *M. rosenbergii* after 90 days exposure to nZnO showed impaired growth and survival rates, and alterations in the activities of digestive enzymes (protease, amylase, and lipase), and biochemical constituents (total protein, total amino acid, total carbohydrate, and total lipid).

Trevisan et al. (2014) showed that after 96 h exposure of *Crassostrea gigas* to lethal concentration of nZnO (30 mg/L), Zn accumulated in gill and in digestive glands, causing oxidative damage. O'Rourke (2013) evidenced that short-term exposure (up to 96 h) to lethal concentrations of nZnO (10 mg/L) had no negative effect on *Lumbriculus variegatus*, but long exposure (up to 28 days) showed toxic effects.

The effects of nZnO evidenced effects on embryo development, Zn bioaccumulation, oxidative stress, and behavior according to exposure scenario and target organisms. In aquaculture, the use of nZnO can improve growth and immune response and the quality of water in fishponds, but waterborne and dietary exposure can have also undesired toxic effects. Focused studies are required to determine the safe exposure concentration of nZnO for aquaculture activity.

Conclusions

Nanotechnology is still in its infancy in aquaculture with just few applications documented mainly in the packaging sector. Little data were produced with the specific aim of checking the effects of NPs on aquacultured species, while several NPs are used in aquaculture. Thus, aquaculture must pay great attention in keeping food security along the production process in a cradle-to-grave perspective considering both human health and the environment potential adverse effects of NPs. Currently, it is unworthy to provide a toxicity ranking of NPs in aquaculture, mainly because the amount of information is aggregated just on few NPs (nAg and nTiO₂) with scattered data for all the remainings. Thus, results could be strongly unbalanced.

Researchers and manufacturers are trying to use nano-based tools to remove the barriers about waterborne food, growth, reproduction, and culturing of species, their health, and water treatment in order to increase aquaculture production rates. Anyway, nanosafety-related concerns still exist and must be tackled before their full-scale implementation. Toxicological effects of NPs depend on various factors including complex interplay between particle features (e.g., diameter, form, surface charge, and chemistry), concentration, time of exposure, nature of the NPs, medium composition, route of particle administration, and target species immune system. Despite the available information, several points of criticism are hindering the exact understanding of NPs safety in aquaculture. Firstly, the way NPs are used in aquaculture can be very different: addition to food, to water media, or in

aquaculture facilities (i.e., surface treatments). Nevertheless, the existing amount of studies in aquatic toxicology, the available exposure scenarios, are inadequate to fulfill the request for NP safety in aquaculture like as their route of administration, their concentration, and exposure time. Concentrations are sometimes lower (i.e., concentration administered via feed) or higher (i.e., concentration administered via water or surface treatments) than what it is applied or expected to be applied in aquaculture leading to unrealistic results. Thus, it is not possible to infer about the potential adverse effects on the final consumer. It is necessary to explore the safety of nano-based aquaculture considering not only relatively short-term treatment periods (<40 days) but also the whole aquacultured products along their life cycle from the egg/larva to the table, including water quality. Moreover, due to the fact that aquatic organisms are cultured in different environments (e.g., freshwater and saltwater or tropical and temperate regions), nano-based products can behave very differently like as the derived effects; thus, it would be interesting to explore how nanosafety could be influenced by environmental factors mainly salinity, pH, and temperature.

References

- Adam N, Vakurov A, Knapen D, Blust R (2015) The chronic toxicity of CuO nanoparticles and copper salt to *Daphnia magna*. *J Hazard Mater* 283:416–422
- Aitken R, Chaudhry M, Boxall A, Hull M (2006) Manufacture and use of nanomaterials: current status in the UK and global trends. *Occup med* 56:300–306
- Alishahi A, Proulx J, Aider M (2014) Chitosan as biobased nanocomposite in seafood industry and aquaculture seafood science. *Ad Chem Technol Appl* 211
- Amiano I, Olabarrieta J, Vitorica J, Zorita S (2012) Acute toxicity of nanosized TiO₂ to *Daphnia magna* under UVA irradiation. *Environ Toxicol Chem* 31(11):2564–2566
- Arulvasu C, Jennifer SM, Prabhu D, Chandhirasekar D (2014) Toxicity effect of silver nanoparticles in brine shrimp *Artemia*. *Sci World J* 2014
- Asche F, Bellemare MF, Roheim C, Smith MD, Tveteras S (2015) Fair enough? Food security and the international trade of seafood. *World dev* 31(67):151–160
- Asharani P, Lianwu Y, Gong Z, Valiyaveetil S (2011) Comparison of the toxicity of silver, gold and platinum nanoparticles in developing zebrafish embryos. *Nanotoxicol* 5:43–54
- Ashraf PM, Edwin L (2016) Nano copper oxide incorporated polyethylene glycol hydrogel: an efficient antifouling coating for cage fishing net. *Int Biodeter Biodegr* 115:39–48
- Ates M, Daniels J, Arslan Z, Farah IO (2013) Effects of aqueous suspensions of titanium dioxide nanoparticles on *Artemia salina*: assessment of nanoparticle aggregation, accumulation, and toxicity. *Environ Monit Assess* 185:3339–3348
- Bai W, Zhang Z, Tian W, He X, Ma Y, Zhao Y, Chai Z (2010) Toxicity of zinc oxide nanoparticles to zebrafish embryo: a physicochemical study of toxicity mechanism. *J Nanopart res* 12:1645–1654
- Balusamy B, Taştan BE, Ergen SF, Uyar T, Tekinay T (2015) Toxicity of lanthanum oxide (La₂O₃) nanoparticles in aquatic environments. *Environ Sci: Processes & Impacts* 17:1265–1270
- Barber D, Garcia N, Denslow N, Hyndman K, Evans D, Freedman J (2005) Effects of aluminum nanoparticle exposure in zebrafish (*Danio rerio*) SETAC
- Barelds HP (2010) The uptake and effects on survival of nano silver and nano titanium dioxide in brine shrimp (*Artemia nauplii*). PhD thesis. Faculty of Veterinary Medicine Theses, University of Utrecht, Netherlands. Available from: <http://dspace.library.uu.nl/handle/1874/44547>
- Berube DM (2008) Rhetorical gamesmanship in the nano debates over sunscreens and nanoparticles. *J Nanopart res* 10:23–37
- Bhat IA, Rather MA, Saha R, Pathakota G-B, Pavan-Kumar A, Sharma R (2016) Expression analysis of Sox9 genes during annual reproductive cycles in gonads and after nanodelivery of LHRH in *Clarias batrachus*. *Res vet Sci* 106:100–106. doi:10.1016/j.rvsc.2016.03.022
- Bhattacharyya A, Reddy SJ, Hasan MM, Adeyemi M, Marye RR (2015) Nanotechnology—a unique future technology in aquaculture for the food security. *Int J Bioass* 4:4115–4126
- Bilberg K, Malte H, Wang T, Baatrup E (2010) Silver nanoparticles and silver nitrate cause respiratory stress in Eurasian perch (*Perca fluviatilis*). *Aquat Toxicol* 96(2):159–165
- Bisesi JH et al (2015) Examination of single-walled carbon nanotubes uptake and toxicity from dietary exposure: tracking movement and impacts in the gastrointestinal system. *Nano* 5:1066–1086
- Blinova, I., Niskanen, J., Kajankari, P., Kanarbik, L., Käkänen, A., Tenhu, H., ... & Kahru, A. (2013). Toxicity of two types of silver nanoparticles to aquatic crustaceans *Daphnia magna* and *Thamnocephalus platyurus*. *Environmental Science and Pollution Research*, 20(5), 3456–3463.
- Buffet P-E et al (2011) Behavioural and biochemical responses of two marine invertebrates *Scrobicularia plana* and *Hediste diversicolor* to copper oxide nanoparticles. *Chemosphere* 84:166–174
- Callegaro S, Minetto D, Pojana G, Bilanicová D, Libralato G, Volpi Ghirardini A, Hassellöv M, Marcomini A (2015) Effects of alginate on stability and ecotoxicity of nano-TiO₂ in artificial seawater. *Ecotoxicol Environ Saf* 117:107–114
- Canesi L, Ciacci C, Vallotto D, Gallo G, Marcomini A, Pojana G (2010a) In vitro effects of suspensions of selected nanoparticles (C₆₀ fullerene, TiO₂, SiO₂) on *Mytilus* hemocytes. *Aquat Toxicol* 96:151–158
- Canesi L, Fabbri R, Gallo G, Vallotto D, Marcomini A, Pojana G (2010b) Biomarkers in *Mytilus galloprovincialis* exposed to suspensions of selected nano-particles (nano carbon black, C₆₀ fullerene, nano-TiO₂, nano-SiO₂). *Aquat Toxicol* 100:168e177
- Canesi L, Ciacci C, Fabbri R, Marcomini A, Pojana G, Gallo G (2012) Bivalve molluscs as a unique target group for nanoparticle toxicity. *Mar Environ res* 76:16–21
- Castillo-Rodal A, Mazari-Hiriart M, Lloret-Sánchez L, Sachman-Ruiz B, Vinuesa P, López-Vidal Y (2012) Potentially pathogenic nontuberculous mycobacteria found in aquatic systems. Analysis from a reclaimed water and water distribution system in Mexico City. *Eur J Clin Microbiol Infect dis* 31:683–694
- Chalamcheria V (2015) Nano vaccines: new paradigm in aqua health sector. *J Aquac mar Biol* 3(2):00061
- Champ MA (2003) Economic and environmental impacts on ports and harbors from the convention to ban harmful marine anti-fouling systems. *Mar Pollut Bull* 46:935–940
- Chatterjee S, Judeh ZM (2016) Impact of encapsulation on the physicochemical properties and gastrointestinal stability of fish oil. *LWT-Food Sci Techn* 65:206–213
- Chen P-J, Su C-H, Tseng C-Y, Tan S-W, Cheng C-H (2011) Toxicity assessments of nanoscale zerovalent iron and its oxidation products in medaka (*Oryzias latipes*) fish. *Mar Pollut Bull* 63:339–346
- Chen P-J, Wu W-L, Wu KC-W (2013) The zerovalent iron nanoparticle causes higher developmental toxicity than its oxidation products in early life stages of medaka fish. *Water res* 47:3899–3909

- Clemente Z, Castro V, Moura M, Jonsson C, Fraceto L (2014) Toxicity assessment of TiO₂ nanoparticles in zebrafish embryos under different exposure conditions. *Aquat Toxicol* 147:129–139
- Cong Y, Banta GT, Selck H, Berhanu D, Valsami-Jones E, Forbes VE (2011) Toxic effects and bioaccumulation of nano-, micron- and ionic-Ag in the polychaete, *Nereis diversicolor*. *Aquat Toxicol* 105:403–411
- Cozzari M, Elia AC, Pacini N, Smith BD, Boyle D, Rainbow PS, Khan FR (2015) Bioaccumulation and oxidative stress responses measured in the estuarine ragworm (*Nereis diversicolor*) exposed to dissolved, nano- and bulk-sized silver. *Environ Pollut* 198:32–40
- Dalai S, Pakrashi S, Chandrasekaran N, Mukherjee A (2013) Acute toxicity of TiO₂ nanoparticles to *Ceriodaphnia dubia* under visible light and dark conditions in a freshwater system. *PLoS One* 8(4):e62970
- Dananjaya S, Godahewa G, Jayasooriya R, Lee J, De Zoysa M (2016) Antimicrobial effects of chitosan silver nano composites (CAgNCs) on fish pathogenic *Aliivibrio (Vibrio) salmonicida*. *Aquaculture* 450:422–430
- Dasgupta N, Ranjan S, Mundekkad D, Ramalingam C, Shanker R, Kumar A (2015) Nanotechnology in agro-food: from field to plate. *Food Res Int* 69:381–400
- De Campos AM, Diebold Y, Carvalho EL, Sánchez A, Alonso MJ (2004) Chitosan nanoparticles as new ocular drug delivery systems: in vitro stability, in vivo fate, and cellular toxicity. *Pharm Res* 21:803–810
- De Marchi L, Neto V, Pretti C, Figueira E, Chiellini F, Soares AMVM, Freitas R (2017) Physiological and biochemical responses of two keystone polychaete species: *Diopatra neapolitana* and *Hediste diversicolor* to multi-walled carbon nanotubes. *Environ Res* 154:126–138
- Deng Y, Cheng Q (2003) Affects of nano-selenium on the growth of Nile tilapia (*Oreochromis niloticus*). *Inland Aquat Prodd* 6:28–30
- Dodane V, Khan MA, Merwin JR (1999) Effect of chitosan on epithelial permeability and structure. *Int J Pharm* 182:21–32
- Duan J, Yu Y, Li Y, Yu Y, Sun Z (2013) Cardiovascular toxicity evaluation of silica nanoparticles in endothelial cells and zebrafish model. *Biomaterials* 34(23):5853–5862
- ETC (Action Group on Erosion, Technology and Concentration) (2003) Down on the farm: the impact of nanoscale technologies on food and agriculture. [http://www.etcgroup.org/en/materials/publications.html?pub_id=80]
- Faiz H, Zuberi A, Nazir S, Rauf M, Younus N (2015) Zinc oxide, zinc sulfate and zinc oxide nanoparticles as source of dietary zinc: comparative effects on growth and hematological indices of juvenile grass carp (*Ctenopharyngodon idella*). *Int J Agr Biol* 17:568–574
- Falugi C et al (2012) Toxicity of metal oxide nanoparticles in immune cells of the sea urchin. *Mar Environ Res* 76:114–121
- Ferosekhan S; Gupta S; Singh AR; AM Rather; R Kumari; DC Kothari; AK Pal; SB Jadhao 2014. RNA-loaded chitosan nanoparticles for enhanced growth, immunostimulation and disease resistance in fish. *Curr Nanosci* 10(3), 453–464.
- Feswick A, Griffitt RJ, Siebein K, Barber D (2013) Uptake, retention and internalization of quantum dots in *Daphnia* is influenced by particle surface functionalization. *Aquat Toxicol* 130:210–218
- Fotedar R, Munilkumar S (2016) Effects of organic selenium supplementation on growth, glutathione peroxidase activity and histopathology in juvenile barramundi (*Lates calcarifer* Bloch 1970) fed high lupin meal-based diets. *Aquaculture* 457:15–23
- Fraser TW, Reinardy HC, Shaw BJ, Henry TB, Handy RD (2011) Dietary toxicity of single-walled carbon nanotubes and fullerenes (C₆₀) in rainbow trout (*Oncorhynchus mykiss*). *Nanotoxicol* 5:98–108
- Gagné F, Maysinger D, André C, Blaise C (2008) Cytotoxicity of aged cadmium-telluride quantum dots to rainbow trout hepatocytes. *Nanotoxicol* 2:113–120
- Galloway T, Lewis C, Dolciotti I, Johnston BD, Moger J, Regoli F (2010) Sublethal toxicity of nano-titanium dioxide and carbon nanotubes in a sediment dwelling marine polychaete. *Environ Pollut* 158:1748–1755
- García-Alonso J et al (2011) Cellular internalization of silver nanoparticles in gut epithelia of the estuarine polychaete *Nereis diversicolor*. *Environ Sci Technol* 45:4630–4636
- García-Negrete CA, Blasco J, Volland M, Rojas TC, Hampel M, Lapresta-Fernández A et al (2013) Behaviour of Au-citrate nanoparticles in seawater and accumulation in bivalves at environmentally relevant concentrations. *Environ Pollut* 174:134–141
- García-Rodríguez D, Carro AM, Lorenzo RA, Fernández F, Cela R (2008) Determination of trace levels of aquaculture chemotherapeutics in seawater samples by SPME-GC-MS/MS. *J Sep Sci* 31:2882–2890
- George M, Abraham TE (2006) Polyionic hydrocolloids for the intestinal delivery of protein drugs: alginate and chitosan—a review. *J Control Release* 114:1–14
- Gerber LC, Moser N, Luechinger NA, Stark WJ, Grass RN (2012) Phosphate starvation as an antimicrobial strategy: the controllable toxicity of lanthanum oxide nanoparticles. *Chem Commun* 48:3869–3871
- Gomes T, Araújo O, Pereira R, Almeida AC, Cravo A, Bebianno MJ (2013) Genotoxicity of copper oxide and silver nanoparticles in the mussel *Mytilus galloprovincialis*. *Mar Environ Res* 84:51–59
- Griffitt RJ, Weil R, Hyndman KA, Denslow ND, Powers K, Taylor D, Barber DS (2007) Exposure to copper nanoparticles causes gill injury and acute lethality in zebrafish (*Danio rerio*). *Environ Sci Technol* 41:8178–8186
- Guo H, Lai Q, Wang W, Wu Y, Zhang C, Liu Y, Yuan Z (2013) Functional alginate nanoparticles for efficient intracellular release of doxorubicin and hepatoma carcinoma cell targeting therapy. *Int J Pharm* 451:1–11
- Guo H, Hong Z, Yi R (2015) Core-shell collagen peptide chelated calcium/calcium alginate nanoparticles from fish scales for calcium supplementation. *J Food Sci* 80:N1595–N1601
- Guo J, Zhang R, Yang N (2016) An Immunomagnetic-nanoparticle-based microfluidic system for rapid separation and detection of aquaculture pathogens. *J Comput Theor Nanosci* 13:2226–2231
- Hao L, Chen L, Hao J, Zhong N (2013) Bioaccumulation and sub-acute toxicity of zinc oxide nanoparticles in juvenile carp (*Cyprinus carpio*): a comparative study with its bulk counterparts. *Ecotoxicol Environ Saf* 91:52–60
- Hosseini SF, Rezaei M, Zandi M, Farahmandghavi F (2016) Development of bioactive fish gelatin/chitosan nanoparticles composite films with antimicrobial properties. *Food Chem* 194:1266–1274
- Hu Y-L, Qi W, Han F, Shao J-Z, Gao J-Q (2011) Toxicity evaluation of biodegradable chitosan nanoparticles using a zebrafish embryo model. *Int J Nanomedicine* 6:3351–3359
- Hu J, Wang D, Wang J, Wang J (2012) Bioaccumulation of Fe₂O₃ (magnetic) nanoparticles in *Ceriodaphnia dubia*. *Environ Pollut* 162:216–222
- Huang M, Khor E, Lim L-Y (2004) Uptake and cytotoxicity of chitosan molecules and nanoparticles: effects of molecular weight and degree of deacetylation. *Pharm Res* 21:344–353
- Huang C-M, Chen C-H, Pornpattananangkul D, Zhang L, Chan M, Hsieh M-F, Zhang L (2011) Eradication of drug resistant *Staphylococcus aureus* by liposomal oleic acids. *Biomaterials* 32:214–221
- Huang S, Wang L, Liu L, Hou Y, Li L (2015) Nanotechnology in agriculture, livestock, and aquaculture in China. *Rev Agron Sustain Dev* 35:369–400
- Hull MS, Vikesland PJ, Schultz IR (2013) Uptake and retention of metallic nanoparticles in the Mediterranean mussel (*Mytilus galloprovincialis*). *Aquat Toxicol* 140:89–97
- Jackson BP, Bugge D, Ranville JF, Chen CY (2012) Bioavailability, toxicity, and bioaccumulation of quantum dot nanoparticles to the amphipod *Leptocheirus plumulosus*. *Environ Sci Technol* 46:5550–5556
- Jang MH, Kim WK, Lee SK, Henry TB, Park JW (2014) Uptake, tissue distribution, and depuration of total silver in common carp (*Cyprinus carpio*) after aqueous exposure to silver nanoparticles. *Environ Sci Technol* 48(19):11568–11574

- Ji J, Torrealba D, Ruyra A, Roher N (2015) Nanodelivery systems as new tools for immunostimulant or vaccine administration: targeting the fish immune system. *Biology* 4:664–696
- Jiménez-Fernández E, Ruyra A, Roher N, Zuasti E, Infante C, Fernández-Díaz C (2014) Nanoparticles as a novel delivery system for vitamin C administration in aquaculture. *Aquaculture* 432:426–433
- Johari SA, Kalbassi MR, Soltani M, Yu JJ (2015) Study of fungicidal properties of colloidal silver nanoparticles (AgNPs) on trout egg pathogen, *Saprolegnia* sp. *Int J Aquat Biol* 3:191–198
- Johnston BD et al (2010) Bioavailability of nanoscale metal oxides TiO₂, CeO₂, and ZnO to fish. *Environ Sci Technol* 44:1144–1151
- Kandasamy K, Alikunhi NM, Manickaswami G, Nabikhan A, Ayyavu G (2013) Synthesis of silver nanoparticles by coastal plant *Prosopis chilensis* (L.) and their efficacy in controlling vibriosis in shrimp *Penaeus monodon*. *Appl Nanosci* 3:65–73
- Kamik BS, Davies SH, Baumann MJ, Masten SJ (2005) Fabrication of catalytic membranes for the treatment of drinking water using combined ozonation and ultrafiltration. *Environ Sci Technol* 39:7656–7661
- Karthikeyeni S, Siva Vijayakumar T, Vasanth S, Arul Ganesh MM, Subramanian P (2013) Biosynthesis of iron oxide nanoparticles and its haematological effects on fresh water fish *Oreochromis mossambicus*. *J Acad Indus res* 10:645–649
- Katuli KK, Amiri BM, Massarsky A, Yelghi S (2014a) Impact of a short-term diazinon exposure on the osmoregulation potentiality of Caspian roach (*Rutilus rutilus*) fingerlings. *Chemosphere* 31(108):396–404
- Katuli KK, Massarsky A, Hadadi A, Pourmehran Z (2014b) Silver nanoparticles inhibit the gill Na⁺/K⁺-ATPase and erythrocyte AChE activities and induce the stress response in adult zebrafish (*Danio rerio*). *Ecotoxicol Environ Saf* 106:173–180
- Khan FR, Paul KB, Dybowska AD, Valsami-Jones E, Lead JR, Stone V, Fernandes TF (2015) Accumulation dynamics and acute toxicity of silver nanoparticles to *Daphnia magna* and *Lumbriculus variegatus*: implications for metal modeling approaches. *Environ Sci Technol* 49:4389–4397
- Khan KU, Zuberi A, Nazir S, Fernandes JBK, Jamil Z, Sarwar H (2016) Effects of dietary selenium nanoparticles on physiological and biochemical aspects of juvenile *Tor putitora*. *Turk J Zool* 40
- Kim J, Park Y, Yoon TH, Yoon CS, Choi K (2010) Phototoxicity of CdSe/ZnSe quantum dots with surface coatings of 3-mercaptopropionic acid or tri-n-octylphosphine oxide/gum arabic in *Daphnia magna* under environmentally relevant UV-B light. *Aquat Toxicol* 97:116–124
- Klinkesom U, McClements DJ (2009) Influence of chitosan on stability and lipase digestibility of lecithin-stabilized tuna oil-in-water emulsions. *Food Chem* 114:1308–1315
- Krishnaraj C, Harper SL, Yun SI (2016) In vivo toxicological assessment of biologically synthesized silver nanoparticles in adult zebrafish (*Danio rerio*). *J Hazard Mater* 301:480–491
- Krysanov EY, Demidova TB, Pel'gunova LA, Badalyan SM, Rumyantseva MN, Gas'kov AM (2009) Effect of hydrated tin dioxide (SnO₂·xH₂O) nanoparticles on guppy (*Poecilia reticulata* Peters, 1860). In: *Doklady Biological Sciences*, vol 426, no. 1. MAIK Nauka/Interperiodica, USA, pp. 288–289.
- Lara HH, Ayala-Núñez NV, Turrent LCI, Padilla CR (2010) Bactericidal effect of silver nanoparticles against multidrug-resistant bacteria. *World J Microbiol Biotechnol* 26:615–621
- Lewinski NA, Zhu H, Ouyang CR, Conner GP, Wagner DS, Colvin VL, Drezek RA (2011) Trophic transfer of amphiphilic polymer coated CdSe/ZnS quantum dots to *Danio rerio*. *Nano* 3:3080–3083
- Libralato G (2014) The case of *Artemia* spp. in nanocotoxicology. *Mar Environ res* 101:38–43
- Libralato G et al (2013) Embryotoxicity of TiO₂ nanoparticles to *Mytilus galloprovincialis* (Lmk). *Mar Environ res* 92:71–78
- Libralato G et al (2016a) Phytotoxicity of ionic, micro- and nano-sized iron in three plant species. *Ecotoxicol Environ Saf* 123:81–88
- Libralato G, Prato E, Migliore L, Cicero A, Manfra L (2016b) A review of toxicity testing protocols and endpoints with *Artemia* spp. *Ecol Indic* 69:35–49
- Liu P-W, Guo T, Wei H (2009) Bactericidal effects of copper-bearing nanomontmorillonite on three aquatic pathogenic bacteria and two intestinal available bacteria in vitro. *J Shanghai Ocean Univ* 5:002
- Lofrano G et al (2016a) Polymer functionalized nanocomposites for metals removal from water and wastewater: an overview. *Water res* 92:22–37
- Lofrano G, Libralato G, Alfieri A, Carotenuto M (2016b) Metals and tributyltin sediment contamination along the Southeastern Tyrrhenian Sea coast. *Chemosphere* 144:399–407. doi:10.1016/j.chemosphere.2015.09.002
- Loh JW, Yeoh G, Saunders M, Lim L-Y (2010) Uptake and cytotoxicity of chitosan nanoparticles in human liver cells. *Toxicol Appl Pharmacol* 249:148–157
- Louis S, Gagné F, Auclair J, Turcotte P, Gagnon C, Émond C (2010) The characterisation of the behaviour and gill toxicity of CdS/CdTe quantum dots in rainbow trout (*Oncorhynchus mykiss*). *Int J Biomed Nanosci Nanotechnol* 1:52–69
- Lovern SB, Strickler JR, Klaper R (2007) Behavioral and physiological changes in *Daphnia magna* when exposed to nanoparticle suspensions (titanium dioxide, nano-C₆₀, and C₆₀HxC₇₀Hx). *Environ Sci Technol* 41:4465–4470
- Luo Y, Wang Q (2013) Recent advances of chitosan and its derivatives for novel applications in food science. *J Food Process Beverag* 1:1–13
- Lürling M, Tolman Y (2010) Effects of lanthanum and lanthanum-modified clay on growth, survival and reproduction of *Daphnia magna*. *Water res* 44:309–319
- Máková S, Babula P, Plhalová L, Žáčková K, Kizek R, Svobodová Z (2014) Acute toxicity of lanthanum to fish *Danio rerio* and *Poecilia reticulata*. *J Biochem Technol* 2:46–47
- Marcone GP, Oliveira AC, Almeida G, Umbuzeiro GA, Jardim WF (2012) Ecotoxicity of TiO₂ to *Daphnia similis* under irradiation. *J Hazard Mater* 211:436–442
- McEuen PL, Fuhrer MS, Park H (2002) Single-walled carbon nanotube electronics. *IEEE Trans Nanotechnol* 1:78–85
- Minetto D, Libralato G, Volpi Ghirardini A (2014) Ecotoxicity of engineered TiO₂ nanoparticles to saltwater organisms: an overview. *Environ Int* 66(0):18–27
- Minetto D, Volpi Ghirardini A, Libralato G, (2016) Saltwater ecotoxicology of nAg, nAu, nCuO, nTiO₂, nZnO and C₆₀. *Environ Int*
- Mohd Ashraf M, Aklakur R, Shabir A, Mujhid K (2011) Nanotechnology as a novel tool in fisheries and aquaculture development: a review. *Iran J Energy Environ* 2(3):258–261
- Mouneyrac C et al (2014) Fate and effects of metal-based nanoparticles in two marine invertebrates, the bivalve mollusc *Scrobicularia plana* and the annelid polychaete *Hediste diversicolor*. *Environ Sci Pollut res* 21:7899–7912
- Mühling M, Bradford A, Readman JW, Somerfield PJ, Handy RD (2009) An investigation into the effects of silver nanoparticles on antibiotic resistance of naturally occurring bacteria in an estuarine sediment. *Mar Environ res* 68:278–283
- Muralisankar T, Bhavan PS, Radhakrishnan S, Seenivasan C, Manickam N, Srinivasan V (2014) Dietary supplementation of zinc nanoparticles and its influence on biology, physiology and immune responses of the freshwater prawn, *Macrobrachium rosenbergii*. *Biol Trace Elem res* 160:56–66
- O'Rourke SA (2013) The environmental toxicology of zinc oxide nanoparticles to the oligochaete. Heriot-Watt University
- Osborne OJ, Lin S, Chang CH, Ji Z, Yu X, Wang X, Lin S, Xia T, Nel AE (2015) Organ-specific and size-dependent Ag nanoparticle toxicity in gills and intestines of adult zebrafish. *ACS nano* 9(10):9573–9584
- Pace HE, Leshner EK, Ranville JF (2010) Influence of stability on the acute toxicity of CdSe/ZnS nanocrystals to *Daphnia magna*. *Environ Toxicol Chem* 29:1338–1344

- Pati R, Mehta RK, Mohanty S, Padhi A, Sengupta M, Vaseeharan B, Goswami C, Sonawane A (2014) Topical application of zinc oxide nanoparticles reduces bacterial skin infection in mice and exhibits antibacterial activity by inducing oxidative stress response and cell membrane disintegration in macrophages. *Nanomedicine: NBM* 10: 1195–1208
- Peniche C, Howland I, Carrillo O, Zaldivar C, Argüelles-Monal W (2004) Formation and stability of shark liver oil loaded chitosan/calcium alginate capsules. *Food Hydrocoll* 18:865–871
- Perera TS, Han Y, Lu X, Wang X, Dai H, Li S (2015) Rare earth doped apatite nanomaterials for biological application. *J Nanomat* 1(2015):5
- Petersen EJ, Huang Q, Weber WJ Jr (2008) Ecological uptake and depuration of carbon nanotubes by *Lumbriculus variegatus*. *Environ Health Perspect* 116:496
- Podyacheva OY, Ismagilov ZR (2015) Nitrogen-doped carbon nanomaterials: to the mechanism of growth, electrical conductivity and application in catalysis. *Catal Today* 1(249):12–22
- Polettini A-E, Fortaner S, Farina M, Groppi F, Manenti S, Libralato G, Sabbioni E (2015) Uptake from water, internal distribution and bioaccumulation of selenium in *Scenedesmus obliquus*, *Unio mancus* and *Rattus norvegicus*: part A. *Bull Environ Contam Toxicol* 94(1):84–89
- Pradeep T (2009) Noble metal nanoparticles for water purification: a critical review. *Thin Solid Films* 517:6441–6478
- Pulavendran S, Chellan R, Asit B (2011) Hepatocyte growth factor incorporated chitosan nanoparticles augment the differentiation of stem cell into hepatocytes for the recovery of liver cirrhosis in mice. *J Nanobiotechnol* 9(1):1
- Pulkkinen K et al (2010) Intensive fish farming and the evolution of pathogen virulence: the case of columnaris disease in Finland. *Proc R Soc Lond B Biol Sci* 277. 1681:593–600
- Radhika Rajasree S, Ganesh Vumar V, Stanley Abraham L, Indabakandan D (2010) Studies on the toxicological effects of engineered nanoparticles in environment—a review. *Int J Appl Bioeng* 4
- Rafiee A et al (2014) Comparison of chitosan, alginate and chitosan/alginate nanoparticles with respect to their size, stability, toxicity and transfection. *Asian Pac J Trop Dis* 4:372–377
- Rajeshkumar S, Venkatesan C, Sarathi M, Sarathbabu V, Thomas J, Basha KA, Hameed AS (2009) Oral delivery of DNA construct using chitosan nanoparticles to protect the shrimp from white spot syndrome virus (WSSV). *Fish & Shellfish Immunol* 26:429–437
- Rajkumar KS, Kanipandian N, Thirumurugan R (2016) Toxicity assessment on haematology, biochemical and histopathological alterations of silver nanoparticles-exposed freshwater fish *Labeo rohita*. *Appl Nanosci* 6(1):19–29
- Ramesh R, Kavitha P, Kanipandian N, Arun S, Thirumurugan R, Subramanian P (2013) Alteration of antioxidant enzymes and impairment of DNA in the SiO₂ nanoparticles exposed zebra fish (*Danio rerio*). *Environ Monit Assess* 185:5873–5881
- Ramezani Z, Zarei M, Raminnejad N (2015) Comparing the effectiveness of chitosan and nanochitosan coatings on the quality of refrigerated silver carp fillets. *Food Control* 51:43–48
- Ramsden CS, Smith TJ, Shaw BJ, Handy RD (2009) Dietary exposure to titanium dioxide nanoparticles in rainbow trout (*Oncorhynchus mykiss*): no effect on growth, but subtle biochemical disturbances in the brain. *Ecotoxicology* 18:939–951
- Ramya VL, Sharma R, Gireesh-Babu P, Patchala SR, Rather A, Nandanpawar PC, Eswaran S (2014) Development of chitosan conjugated DNA vaccine against nodavirus in *Macrobrachium rosenbergii* (De Man, 1879). *J Fish Dis* 37:815–824. doi:10.1111/jfd.12179
- Rather M, Sharma R, Aklakur M, Ahmad S, Kumar N, Khan M, Ramya V (2011) Nanotechnology: a novel tool for aquaculture and fisheries development. A prospective mini-review. *Fisheries Aquaculture J* 16:1–5
- Rather MA, Sharma R, Gupta S, Ferozekhan S, Ramya V, Jadhao SB (2013) Chitosan-nanoconjugated hormone nanoparticles for sustained surge of gonadotropins and enhanced reproductive output in female fish. *PLoS One* 8:e57094
- Rather MA, Bhat IA, Gireesh-Babu P, Chaudhari A, Sundaray JK, Sharma R (2016) Molecular characterization of kisspeptin gene and effect of nano-encapsulated kisspeptin-10 on reproductive maturation in *Catla catla*. *Domest Anim Endocrinol* 56:36–47. doi:10.1016/j.domaniend.2016.01.005
- Ren X, Chen C, Nagatsu M, Wang X (2011) Carbon nanotubes as adsorbents in environmental pollution management: a review. *Chem Eng J* 170:395–410
- Romero J, Feijóo, CG, Navarrete P (2012) Antibiotics in Aquaculture – Use, Abuse and Alternatives, Health and Environment in Aquaculture. In: Carvalho E (ed), InTech. doi:10.5772/28157. Available from: <https://www.intechopen.com/books/health-and-environment-in-aquaculture/antibiotics-in-aquaculture-use-abuse-and-alternatives>
- Ross KA, Loyd H, Wu W, Huntimer L, Wannemuehler MJ, Carpenter S, Narasimhan B (2014) Structural and antigenic stability of H5N1 hemagglutinin trimer upon release from polyanhydride nanoparticles. *J Biomed Mat ResPart A* 102(11):4161–4168
- Rotruck J, Pope A, Ganther H, Swanson A, Hafeman DG, Hoekstra W (1973) Selenium: biochemical role as a component of glutathione peroxidase. *Science* 179:588–590
- Sabbioni E, Polettini A-E, Fortaner S, Farina M, Groppi F, Manenti S, Libralato G (2015) Uptake from water, internal distribution and bioaccumulation of selenium in *Scenedesmus obliquus*, *Unio mancus* and *Rattus norvegicus*: part B. *Bull Environ Contam Toxicol* 94(1):90–95
- Shaan M, Saleh M, El-Mahdy M, El-Matbouli M (2016) Recent progress in applications of nanoparticles in fish medicine: a review. *Nanomedicine: NBM* 12:701–710
- Sharma N, Rather MA, Ajima MNO, Gireesh-Babu P, Kumar K, Sharma R (2016) Assessment of DNA damage and molecular responses in *Labeo rohita* (Hamilton, 1822) following short-term exposure to silver nanoparticles. *Food Chem Toxicol* 96:122–132. doi:10.1016/j.fct.2016.06.020
- Shirazi MA, Shariati F, Ramezanzpour Z (2015) Toxic effect of aluminum oxide nanoparticles on green micro-algae *dunaliella salina*. *Int J Environ Res* 9(2): 585–594
- Smith CJ, Shaw BJ, Handy RD (2007) Toxicity of single walled carbon nanotubes to rainbow trout (*Oncorhynchus mykiss*): respiratory toxicity, organ pathologies, and other physiological effects. *Aquat Toxicol* 82:94–109
- Sonawane R, Hegde S, Dongare M (2003) Preparation of titanium (IV) oxide thin film photocatalyst by sol-gel dip coating. *Mater Chem Phys* 77:744–750
- Sonkusre P, Nanduri R, Gupta P, Cameotra SS (2014) Improved extraction of intracellular biogenic selenium nanoparticles and their specificity for cancer chemoprevention. *J Nanomed Nanotechnol*
- Strømme M, Brohede U, Atluri R, Garcia-Bennett AE (2009) Mesoporous silica-based nanomaterials for drug delivery: evaluation of structural properties associated with release rate *Wiley Interdisciplinary Reviews. Nanomed Nanobiotechnol* 1:140–148
- Swain P et al (2014) Antimicrobial activity of metal based nanoparticles against microbes associated with diseases in aquaculture. *World J Microbiol Biotechnol* 30:2491–2502
- Tedesco S, Doyle H, Redmond G, Sheehan D (2008) Gold nanoparticles and oxidative stress in *Mytilus edulis*. *Mar Environ Res* 66:131–133
- Trevisan R et al (2014) Gills are an initial target of zinc oxide nanoparticles in oysters *Crassostrea gigas*, leading to mitochondrial disruption and oxidative stress. *Aquat Toxicol* 153:27–38
- Twiddy D, Reilly P, Chatham K (1995) Occurrence of antibiotic-resistant human-pathogens in integrated fish farms. *FAO Fish rep* 514:23
- Vale G, Mehennaoui K, Cambier S, Libralato G, Jomini S, Domingos RF (2016) Manufactured nanoparticles in the aquatic environment-biochemical responses on freshwater organisms: a critical overview. *Aquat Toxicol* 170:162–174

- Vázquez-González M, Carrillo-Carrion C (2014) Analytical strategies based on quantum dots for heavy metal ions detection. *J Biomed opt* 19:101503–101503
- Vendramini T et al (2016) Effects of a blend of essential oils, chitosan or monensin on nutrient intake and digestibility of lactating dairy cows. *Animal Feed Sci Technol* 214:12–21
- Venkat K (2011) The climate change and economic impacts of food waste in the United States. *Int J Food Syst Dyn* 2:431–446
- Vijayan SR, Santhiyagu P, Singamuthu M, Kumari Ahila N, Jayaraman R, Ethiraj K (2014) Synthesis and characterization of silver and gold nanoparticles using aqueous extract of seaweed, *Turbinaria conoides*, and their antimicrofouling activity. *Sci World J*
- Völker C, Kämpken I, Boedicker C, Oehlmann J, Oetken M (2015) Toxicity of silver nanoparticles and ionic silver: comparison of adverse effects and potential toxicity mechanisms in the freshwater clam *Sphaerium corneum*. *Nanotoxicology* 9(6):677–685
- Wang H, Wick RL, Xing B (2009) Toxicity of nanoparticulate and bulk ZnO, Al₂O₃ and TiO₂ to the nematode *Caenorhabditis elegans*. *Environ Pollut* 157:1171–1177
- Wang D, Hu J, Irons DR, Wang J (2011) Synergistic toxic effect of nano-TiO₂ and As(V) on *Ceriodaphnia dubia*. *Sci Total Environ* 409:1351–1356
- Wang Y, Yan X, Fu L (2013) Effect of selenium nanoparticles with different sizes in primary cultured intestinal epithelial cells of crucian carp, *Carassius auratus gibelio*. *Int J Nanomedicine* 8:4007–4013
- Warheit DB, Hoke RA, Finlay C, Donne EM, Reed KL et al (2007) Development of a base set of toxicity tests using ultrafine TiO₂ particles as a component of nanoparticle risk management. *Toxicol Lett* 171:99–110
- Wen J, Chai D, Ding Y, Yu L, Huang J (2003) Summary report on experiment of strong nanometer 863 biological assistant growth unit in sea shrimp farming. *Modern Fisheries Inf* 18:12–15
- Wiench K, Wohlleben W, Hisgen V, Radke K, Salinas E, Zok S, Landsiedel R (2009) Acute and chronic effects of nano- and non-nano-scale TiO₂ and ZnO particles on mobility and reproduction of the freshwater invertebrate *Daphnia magna*. *Chemosphere* 76:1356–1365
- Xu P et al (2012) Use of iron oxide nanomaterials in wastewater treatment: a review. *Sci Total Environ* 424:1–10
- Yu JC, Tang HY, Yu JG (2002) Bactericidal and photocatalytic activities of TiO₂ thin films prepared by sol-gel and reverse micelle methods. *J Photochem Photobiol A Chem* 3:211–219
- Zhang X, Sun H, Zhang Z, Niu Q, Chen Y, Crittenden JC (2007) Enhanced bioaccumulation of cadmium in carp in the presence of titanium dioxide nanoparticles. *Chemosphere* 67:160–166
- Zhao D, Wang J, Sun B, Sun B, Gao J, Xu R (2000) Development and application of TiO₂ photocatalysis as antimicrobial agent. *J Liaoning Univ (Nat Sci Ed)* 2:173–174
- Zhao J, Wang Z, Liu X, Xie X, Zhang K, Xing B (2011) Distribution of CuO nanoparticles in juvenile carp (*Cyprinus carpio*) and their potential toxicity. *J Hazard Mater* 197:304–310
- Zhou X, Wang Y, Gu Q, Li W (2009) Effects of different dietary selenium sources (selenium nanoparticle and selenomethionine) on growth performance, muscle composition and glutathione peroxidase enzyme activity of crucian carp (*Carassius auratus gibelio*). *Aquaculture* 291:78–81
- Zhu X, Chang Y, Chen Y (2010a) Toxicity and bioaccumulation of TiO₂ nanoparticle aggregates in *Daphnia magna*. *Chemosphere* 78:209–215
- Zhu X, Wang J, Zhang X, Chang Y, Chen Y (2010b) Trophic transfer of TiO₂ nanoparticles from daphnia to zebrafish in a simplified freshwater food chain. *Chemosphere* 79:928–933
- Zhu X, Zhou J, Cai Z (2011) The toxicity and oxidative stress of TiO₂ nanoparticles in marine abalone (*Haliotis diversicolor supertexta*). *Mar Poll Bull* 63:334–338
- Zhu X, Tian S, Cai Z (2012) Toxicity assessment of iron oxide nanoparticles in zebrafish (*Danio rerio*) early life stages. *PLoS One* 7:e46286