Impacts of heavy metals on early development, growth and reproduction of fish – A review

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1. Introduction

Heavy metals pollution is a great concern to aquatic environments because they impart a wide range of toxicities with serious impacts to the aquatic faunal communities [1,2]. Most of the heavy metals accumulated in aquatic water bodies are originate from anthropogenic activities such as agricultural cultivation, erosions of landfills, docking and embarking activities, sewage from industrial and domestic wastewater and some natural processes [1,3]. The uncontrolled population growth, intensive agricultural activities and heavy industrialization result in a wide range of pollutants which eventually inflict serious consequences on aquatic ecosystems as well as associated faunal and floral communities [4–6]. Commonly, trace amount of heavy metals (non-degradable) cause serious difficulties in aquatic systems as a result of their assimilation, deposition and even incorporation at a specific concentration in abiotic substances and ultimately, accumulated into the body of associated aquatic organisms [7]. Heavy metals accumulate into the tissues of aquatic organisms throughout different aquatic food chains where they can be concentrated; bioaccumulated metals can result in substantial human health hazards upon consumption of these contaminated aquatic foods [8]. The rapid growth of industrialization across the cities results in the release of effluents contaminated with toxic metals including chromium (Cr), nickel (Ni), copper (Cu), lead (Pb), iron (Fe), and zinc (Zn). In broad, metals can be classified as biologically essential and nonessential. Metals like aluminum (Al), cadmium (Cd), mercury (Hg), tin (Sn) and lead (Pb) have no records of specific biological functions and therefore their toxicities rise with high concentration. On the other hand, essential metals (Cr, Zn, Ni, Cu, Co, Fe) have established biological functions and toxicities occur in response to either their deficiencies or excessive concentrations. Essential metals positively improved the growth and feed utilization of several species [9–15] but when maximum allowable/tolerable limit these metals are exceeded, they hamper the normal physiological and ecological systems in the aquatic environment [16,17], causing toxicity within the organisms and

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ultimately causing a substantial threat to human health [1,8]. Most of these heavy metals are highly carcinogenic in nature and in addition they can cause serious health complexities like liver disorders, cardiovascular difficulties, kidney dysfunctions and in extreme cases death. Heavy metal pollution severely disrupts the physiology of several aquatic organisms, especially fish [4,18,19]. Heavy metal contamination has been recorded by several studies [18]. Heavy metals contamination significantly hampers the reproductive performances of fish [22–24]. Investigations have reported several reproductive compromises including reduced GSI, fecundity, hatching rate, fertilization success, abnormal shape of reproductive organs, and finally overall reproductive success in response to a variety of heavy metals [25–30]. Moreover, heavy metals severely affected the embryonic and larval development of fish through resulting number of complexities such as increased heart rate, reduced cardiac activity, increased mortality rate, deformed shape, vertebral column deformities etc. in different developmental stages of embryo [11,31–35]. Despite the destructive impacts of several heavy metals on fish physiology and reproductive performance in fishes, few if any generalized or comprehensive patterns of these responses are available. The current review focuses on the aggregation of up-to-date information about the impacts of heavy metals on embryonic and larval development, growth, reproductive performance with an emphasis of the most commercially important aquaculture species.

2. Heavy metals effects on embryonic and larval development of fish

Early developmental stages of fish, specifically embryos and larvae, are more susceptible to pollutants such as heavy metals than juvenile and adult fish are, and are widely used as bio-indicators to determine the toxicity of such chemicals to the aquatic organisms [36,37]. Various endpoints such as developmental malformations (teratogenicity), physiological and biochemical alterations, behavioural and functional deformities are used to assess and predict the toxicity of heavy metals to fish population [35]. Fish embryos/larvae at each developmental stage respond differently to the intoxication and vary from species to species, types of metals and their mode of actions, concentration of heavy metals and their exposure time etc. [38,39]. For instance, hatching and embryo survival of African catfish (Clarias gariepinus) were unaffected by Cd exposure at a concentration ranging from 0.05–5 mg/L. Another study reported that embryo and larvae survival, hatching of Ide (Leuciscus idus) were significantly affected by Cd exposure (100 μg/L; [35,40]). The types of deformities in different fish species due to exposure to different heavy metals are summarized in Table 1.

Most of the literature reported reduced embryonic and larval survival, reduced and delayed hatching, stunted growth rate and morphological abnormalities such as skeletal deformities, vascular system abnormalities, retardation in pigmentation, eye anomalies etc. among different fish species exposed to lethal and sub-lethal doses of essential (Cu, Zn) and non-essential (Cd, Cr, Hg and Pb) heavy metals [32,38,40–42]. Cardiovascular endpoints such as hyper or hypotension, positioning abnormality, incomplete or abnormal heart looping, tubular heart, oedema, megalocardia etc. are important parameters to assess the toxicity of heavy metals in embryos and larvae, revealing species-dependent differences in the responses to various heavy metals. For example, Cu exposure significantly increased heart rate in zebrafish embryo [31], whereas cardiac activity is reduced in red sea bream [32] and zebrafish [43] embryos exposed to Cd. Larvae are less tolerant to heavy metals than the embryo since embryos have protective hard chorion layers and perivitelline fluid that can impede the entry of heavy metals [44,45]. Catalase (CAT, the enzyme which converts relatively toxic hydrogen peroxide to oxygen activity is significantly reduced in

| Species          | Dose       | Exposure period | Alterations/ type of deformities                                      | References |
|------------------|------------|----------------|---------------------------------------------------------------------|------------|
| Cyprinus carpio  | 0.2 mg/l   | 30 days        | Growth retardation                                                   | [56]       |
| Claris gariepinus| 0.50–5.00 mg/l | 5 days | Reduction of pigmentation, 100% mortality in 1.5 and 5.0 mg/l         | [40]       |
| Cyprinus carpio  | 5–50 mg/l  |                | Swelling of eggs with increasing concentration                        | [57]       |

(continued on next page)
### Table 1 (continued)

| Species                      | Dose          | Exposure period | Alterations/ type of deformities                                                                 | References |
|------------------------------|---------------|-----------------|---------------------------------------------------------------------------------------------------|------------|
| Melanotaenia fluviatilis     | 0.033–3.3 mg/1 | 2 h             | Spinal abnormalities                                                                             | [58]       |
| Cr                           | 1             |                 |                                                                                                   |            |
| Odontesthes bonariensis      | 4, 40 μg/l    | 10 days         | Reduced embryo and larval survivability, morphological alteration (C-shaped body)                 | [41]       |
| Danio rerio                  | 50, 500 mg/l  | 4 days          | Increased embryo mortality and heart rate of the hatched eggs                                     | [51]       |
| Clarias gariepinus           | 11–114 mg/l   | 5 days          | Abnormal body axis, reduced larval survivability and growth                                        | [40]       |
| Cu                           | 0.32 mg/l     | 7 days          | Skeletal and vascular system abnormalities (anemia, hemorrhage), reduction of pigmentation, absence of eye | [11]       |
| Oryzias melastigma           | 0.1 mg/l      | 21 days         | Vertebral curvatures, yolk sac deformities, shortened body length, body perimeter area, swim bladder perimeter area | [35]       |
| Pagrus major                 | 0.1–1 mg/l    | 24 h            | Scoliosis and tail curvatures                                                                     | [44]       |
| Oryzias latipes              | 6.95–23.1 μg/l| 10 days         | Spinal deformities (kyphosis and lordosis), yolk-sac mal-absorption, abnormal cardiovascular system | [47]       |
| Fundulus heteroclitus        | 0.0005–0.004 mg/l | 50 days    | Vertebral deformities and inflammatory masses                                                    | [59]       |
| Oncorhynchus mykiss          | 0.22 mg/l     | 4 days          | Increased mortality of embryos                                                                    | [48]       |
| Danio rerio                  | 0.068–0.244 mg/l | 120 haf     | Lateral line deformities (fewer functional neuromasts)                                           | [31]       |
| Danio rerio                  | 50–1000 μg/l  | 3 dpf           | Low hatching rate, higher heart rate, larger yolk sac                                             | [31]       |
| Cyprinus carpio              | 0.2 mg/l      |                 | First developmental retardation,                                                                | [60]       |

### Table 1 (continued)

| Species                      | Dose          | Exposure period | Alterations/ type of deformities                                                                 | References |
|------------------------------|---------------|-----------------|---------------------------------------------------------------------------------------------------|------------|
| Clarias gariepinus           | 0.15–2.5 mg/l | 5 days          | Reduction of pigmentation Larvae with axial and lateral curvatures of spine, C shaped larvae, eye anomalies, deformed yolk sac, cardiac edema | [40]       |
| Cyprinus carpio              | 2 mg/l        |                 | Abnormal fin, flexure of the posterior tail region                                                | [38]       |
| Pb                           | 0.1–0.5 mg/l  | 48–168 h        | Irregular head, notochord defects, yolk-sac edema, spinal curvatures etc.                         | [42]       |
| Zn                           | 211, 2110 μg/l| 10 days         | Cumulative embryo survival was significantly reduced to 40% at day 6 and 10% at day 2 respectively | [41]       |
| Danio rerio                  | 50, 500 mg/l  | 4 days          | Majority of eggs were dead within 48 hr because of its severe toxicity, the heart rate of the hatched eggs increased with increasing concentration | [51]       |
| Pagrus major                 | 0.3 mg/l      | 4 days          | Low hatching rate, high mortality, abnormal pigmentation, hooked tail, spinal deformity, pericardial edema, and visceral hemorrhage | [33]       |
| Melanotaenia fluviatilis     | 0.33–33.3 mg/ | 2 h             | Spinal deformities                                                                             | [58]       |

MN; micronucleus, NB; nuclear bud, BS; bi-nucleated

the larvae compared to embryos, which might contribute to the resistance of embryos to heavy metals.

Toxicity levels of heavy metals in embryos and larvae of freshwater fish are different from marine fish because of salinity differences. At higher salinity levels, the bioavailability of the toxic forms of heavy metals decreases, leading to lower toxicity. Furthermore, freshwater fish have different detoxification mechanisms compared to marine fish, which could affect the toxicity levels observed.
metals in water decreases. Information is limited about the toxic effects of heavy metals on marine fish embryos and larvae. Low hatchability, high mortality, morphological abnormalities etc. are reported in embryos and larvae of marine fish exposed to different heavy metals [11, 32]. Environmental cues especially high temperature is known to cause developmental deformities in fishes and it has been reported that combined application of high temperature (24-32°C) and heavy metal such as Cd causes intense increase in skeletal deformities in juvenile mosquito fish (Gambusia affinis) than Cd or temperature alone [46]. High temperature increases the metabolic activity of fish, increasing the potentiality of metal ion action (Cd in this case) on cellular enzyme and cell membrane.

The mode of action (especially changes in enzyme and DNA) of each heavy metal exposure in embryo and larvae are at early stage of investigation and gaining importance among the researchers investigating molecular mechanisms of their effects in fish. Superoxide dismutase (SOD) and catalase (CAT) enzymes are known to convert reactive oxygen species to non-toxic oxygen in the liver. It has been found that in embryos and larvae of goldfish (Carassius auratus), these enzymatic activities were significantly inhibited due to exposure of high Cu concentration (1.0 mg/L), causing oxidative stress responsible for lipid peroxidation [44]. Moreover, Cd and Cu exposure to 2 dph larvae of Japanese medaka (Oryzias latipes) induced significant DNA damage [47] determined by Comet assay (a reliable method to assess genotoxicity in all stages of fish).

There are numerous reports on the effect of single heavy metal on the ontogenic development embryos and larvae. Because most of the open water environment is contaminated with mixtures of heavy metals (from anthropogenic and geogenic sources), it is important to evaluate the combined effects of those heavy metals on embryonic and larval development. The combined effect of Cu-Zn and Cd-Zn has been investigated in Rainbow trout Oncorhynchus mykiss [48] and common carp Cyprinus carpio [49] embryos respectively, revealing increased embryonic mortality and physical deformities (e.g. vertebral column deformities). Hg and Pb toxicity resulted defects of important organs of fish such as abnormal and irregular fins, head, tails and several spinal difficulties [38,42]. Moreover, Zn contamination negatively affected the hatching success and survival of several fish species as well as hampered the normal formation and pigmentation of several organs [33,35,41,48].

Supplementation of vitamin C with the dry feed to the embryo and larvae of common carp (Cyprinus carpio) exposed to mixture of Zn and Cd increased the ontogenic development and quality and quantity of the larvae through the improvement of immune system [49]. It has been reported that Cd exposure under conditions of high alkalinity can significantly increase the hatching, survival rate and growth of larvae of Silver catfish Rhamdia quelen [50].

### 3. Impact of heavy metals on growth performance of fish

Nutritional adequacy is prerequisite sustainable aquaculture. The overall growth, health status and reproductive performances of various aquaculture species especially fish are dependant on appropriate nutrition [63-65]. Among the various candidates that contribute nutritional demand of various aquaculture species, heavy metals play important roles in this regard. Various types of trace metals significantly contribute to different physiological processes including growth of fish (Table 2). Several trace metals such as Mn, Fe, Co, Cu, Cr and Zn are known to be important minerals with positively influences on the physiology and metabolism of fish [9,10]. Cr has been regarded as very important trace element that improved the health status of several animals through upgrading the physiology as well as their metabolism [66,67]. Cd directly involved in nutrient (protein, lipid and carbohydrates) metabolism significantly influences the growth and feed utilization of several fish species [68,69]. Moreover, Cr also altered the fatty acid profile in blood through participating in fatty acid metabolism in various animals [70,71]. It has been found that Cr supplementation lowered the

### Table 2

| Species                        | Doses (mg/kg) | Exposure time (days) | Effects                                      | References |
|-------------------------------|--------------|----------------------|----------------------------------------------|------------|
| As                            | Oncorhynchus mykiss | 26-77 µg/kg | 30 | Growth reduced accompanied by slower feeding rate, reduced FCE | [105] |
| Cd                            | Mystus semghala | 1/3 of LC90 | 112 | Lowered average wet weight, body length and condition factor while higher FCR | [106] |
| Ichthala punctatus            | 0.5, 2, 6 µg/L | 180 | Negatively impacted on growth (length and weight) | [107] |
| Pelteobagrus fulvidraco       | 0, 50, 200 µg/L | 56 | Growth retardation; decreased WG and SGR in both 50 and 200 µg/L | [108] |
| Oreochromis niloticus         | 0, 25, 50 | 84 | Lowest BW and WG at 50 mg/kg | [109] |
| Danio rerio                   | 30 µg/L | 35 | Reduced growth and survival rate | [110] |
| Danio rerio                   | 30 µg/L | 35 | Inhibited body weight, SGR and survival rate | [111] |
| Oreochromis niloticus         | 0.5 | 56 | Reduced growth and feed intake | [112] |
| Oncorhynchus mykiss           | 1 and 3 µg/L | 30 | Condition Factor (K), SGR, BWG decreased, while FCR increased | [113] |
| Cynopharyngodon idella        | 0, 5, 500 µg/L | 56 | Reduction in growth | [114] |
| Pelteobagrus fulvidraco       | 0.25, 4.92, 48.57, 474.7 | 28 | WG, SGR, FI, PER declined with increasing dietary Cd | [115] |
| Cr                            | Pangasianodon hypophthalmus | 2, 4, & 8 | 60 | The growth and feed utilization increased significantly in the fish fed with 2 and 4 mg/kg supplemented diets | [10] |
| Labeo rohita                  | 0.4, 0.8 & 1.2 | 60 | Improved %WG, SGR, PER and %ANPU at 0.8 mg kg\(^{-1}\) | [116] |
| Oreochromis niloticus         | 4.57 mg/ L | 60 | WG, SGR reduced | [117] |
| Platichthys stellatus         | 0, 50, 100, 200, 400 ppb | 28 | DLG, DWG, CF, and HSI decreased | [118] |
| Megalobrama amblycephala      | 0.2, 0.4, 3.2 & 12.0 | 77 | Increased FW and SGR; lowest FCR in fish fed with 0.4 mg/kg | [119] |
| Sebastus schlegelli           | 0, 30, 60, 120 & 240 | 28 | Decreased growth performance | [120] |
| Lamichthys crecea             | 5, 10, 20, 40 & 80 | 70 | Higher survival and SGR in fish fed the diet with 5 mg/kg produced superior %WG, SGR, FCR and | [121] |

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Table 2 (continued)

| Species                  | Doses (mg/kg) | Exposure time (days) | Effects                                      | References |
|--------------------------|---------------|----------------------|----------------------------------------------|------------|
| Oreochromis niloticus    | 200, 400, 600 | 72                   | PER at a level 0.5 mg/kg increased FI at 400 ppb | [122]      |
| Cyprinus carpio          | 0.5, 1.0, 2.0 | 63                   | higher FBW, % WG, SGR and lower FCR at 0.5 mg/kg | [121]      |
| Ctenopharyngodon idella  | 0.2, 0.4, 0.8 | 70                   | improved WG, FER, PER and PR at 0.8 mg kg⁻¹ in fish exposed to 4 mg/L than the control | [123]      |
| Channa punctatus         | 2 & 4         | 60                   | BWG was comparatively less in fish exposed to 4 mg/L than the 2 mg/L control | [124]      |
| Cu                       | 0.05 & 0.1    | 90                   | Significantly reduced SGR, reduced WG, FER and increased FCR | [125]      |
| Megalobrama ambycephala  | 1.43 & 9.13   | 70                   | Increased growth performance                  | [126]      |
| Oreochromis niloticus    | 25, 50 & 75   | 90                   | Decrease in FW, WG, and HSI                   | [127]      |
| Cyprinus carpio          | 0, 1.5 & 3.0  | 60                   | Decrease in FG, length, CG and increase in FCR | [128]      |
| Poecilia reticulata      | 5 & 9 µg/L    | 365                  | Exposure to 9 µg/L Cu reduced fish body weight and length | [129]      |
| Pauts major              | 2             | 60                   | Increased FBW, WG, SGR, FER, PER, PG and PR   | [97]       |
| Pauts major              | 2, 4, 6, 8    | 60                   | Highest final body weight, WG, SGR, PG; and increase in FCR | [97]       |
| Channa punctatus         | 3.7, 4.7, 5.7, 7.7 & 8.7 | 84 | Fish fed with 6.7 mg kg⁻¹ copper had highest AWG, per, PG and best FCR | [130]      |
| Cyprinus carpio          | 20, 30, 40 & 70 | 28 | Decrease in FW, WG, and HSI and increase in HSI | [131]      |
| Carassius carassius      | 0.30 & 0.60   | 20                   | High-concentration (0.60 mg/L) hindered the growth | [132]      |
| Poecilia reticulata      | 0, 0.004, 0.013, 0.019, 0.029 | 56 | Decrease in FW, SGR, and increased in FCR | [133]      |
| Latosilurus japonicus    | 0 & 4         | 56                   | Higher FI, SGR, PER                           | [100]      |
| Huo huo                  | 1.1, 3.5, 7.1, 9.7, 13.1, 25.1, 49.9 & 195 | 84 | Weight gain of fish fed 10 and 13 mg/kg diets was higher than others | [96]       |
| Ctenopharyngodon idella  | 2.26, 3.75, 5.25 | 56 | increased %WG and FI at up to 3.75 mg/kg | [134]      |
| Poecilia reticulata      | 0, 0.004, 0.013, 0.019, 0.029 | 56 | Decrease in FW, SGR, and increased in FCR | [133]      |
| Lateolabrus japonicus    | 0 & 4         | 56                   | Higher FI, SGR, PER                           | [100]      |
| Huo huo                  | 1.1, 3.5, 7.1, 9.7, 13.1, 25.1, 49.9 & 195 | 84 | Weight gain of fish fed 10 and 13 mg/kg diets was higher than others | [96]       |
| Ctenopharyngodon idella  | 2.26, 3.75, 5.25 | 56 | increased %WG and FI at up to 3.75 mg/kg | [134]      |
| Ctenopharyngodon idella  | 2.26, 3.75, 5.25 | 56 | increased %WG and FI at up to 3.75 mg/kg | [134]      |
| Ctenopharyngodon idella  | 2.26, 3.75, 5.25 | 56 | increased %WG and FI at up to 3.75 mg/kg | [134]      |

Table 2 (continued)

| Species                  | Doses (mg/kg) | Exposure time (days) | Effects                                      | References |
|--------------------------|---------------|----------------------|----------------------------------------------|------------|
| Ctenopharyngodon idella  | 2.26, 3.75, 5.25 | 56 | increased %WG and FI at up to 3.75 mg/kg | [134]      |
| Ctenopharyngodon idella  | 2.26, 3.75, 5.25 | 56 | increased %WG and FI at up to 3.75 mg/kg | [134]      |
| Ctenopharyngodon idella  | 2.26, 3.75, 5.25 | 56 | increased %WG and FI at up to 3.75 mg/kg | [134]      |

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cholesterol, triglycerides level in blood and increased the high density lipoprotein (HDL) cholesterol level [72,73]. Dietary Cr significantly influenced the expression of several genes related to glucose metabolism, lipogenesis, apparently playing a key role in growth enhancement [74]. Cr supplementation in diet significantly improved the growth and feed utility of striped catfish (Pangasiodon hypophthalmus) upto 4 mg/kg but greater concentrations resulted in lower growth with higher micronucleus frequencies (Fig. 1) [10]. On the contrary, presence of Cr in excess level led to several toxicities and therefore, reduced the growth and feed palatability of several species [75–77]. Zn is an essential trace element that plays a significant role in the life processes of animals including fish [78–80]. Zn acts as a co-factor of several metallo-enzymes (carbonic anhydrase, alkaline phosphatase, alcohol dehydrogenase etc.) ensuring the availability and activities of those important enzymes to stimulate digestion and metabolism of nutrients [81–83]. Zn also regulates the nucleic acid metabolism, protein synthesis and anti-oxidative enzymes functionalities of fish [84]. The anti-oxidative roles of Zn were well demonstrated in several studies [85,86]. Dietary Zn supplementation considerably improved the growth of fish through upgrading muscle morphology [9]. Dietary Zn provisions also influence the whole body composition of fish muscle. Zn significantly enhanced the lipid content and lowered the moisture and ash level of fish carcass [87]. However, Zn deficiency hampers the nucleic acid and protein biosynthetic pathways [66,88], impairment of bone development [87] and various other pathological effects [89]. On the other hand, excess amount of Zn resulted various negative impacts such as growth and reproductive performance reduction [90], oxidative stress [91] and poor feed utilization [92–94]. Moreover, Zn toxicity resulted in delayed hatching, malformations in bone calcification and growth defects [95]. Cu is an essential element that plays a pivotal role in various physiological as well as biological systems such as hemoglobin and bone formation, control the activities of myelin in the nervous system and finally acts as an activists of many important enzymatic action including cytochrome oxidase, lysesl oxidase, dopamine hydroxylase ferrooxidase, tyrosinase and Cu-Zn superoxidase dismutate [93,96]. Various studies revealed that dietary Cu supplementation significantly improve the growth, oxidative status and immune system of several aquatic species [96–99]. In the very recent years, aquaculture nutritionists find out the outstanding role of Cu particles has caught the attention aquaculture personnel as potentially interesting feed supplement [100,101]. On the contrary, dietary Cu toxicity exhibited several adverse effects including reduced growth, greater FCR, lower feed efficiency [102,103]. Fe, an essential element that helps to maintain the normal activities of different organs and tissues of animals including fish because of its active role in physiological processes like oxygen gas transportation, cellular respiratory activities, and lipid peroxidation processes. Fe modulated the immune system of animals and thus protects against various infectious agents and also actively participates in the synthesis of steroid and DNA, drug metabolism and electron transportation [104].

### 4. Heavy metals effect on reproduction of fish

Reproduction is essential to all animals and successful reproductive performance among the most important determinants of survival at the species level [147–149]. Heavy metals pollution negatively affects the reproductive performance of fish resulting low quality gametes that may influence not only success rate of fertilization but also hatching as well as survival rate of the offspring (Table 3) [150]. Various types of heavy metals accumulated into the fish body from the environment and their continuous accumulation disrupt the formation and activities of various tissues and organs including reproductive organs [62]. Heavy metals caused anomalies in reproductive cell/organ development. Arsenic (As) pollution seriously affected the reproductive performances of fish through inhibition of spermatogenesis and oogenesis including reduced egg and sperm quality and quantity, hatching and fertilization rate [22–24]. Cd is a potent hazardous metal that resulted several dysfunctions of reproductive process of fish. Various studies demonstrated several difficulties in reproductive performance of fish such as abnormal oocytes structure, empty follicle and loosing follicular line, retraction as well as condensation of cytoplasm, total GSI reduced and so on [27]. Moreover, Cd toxicities cause shrinkage of spermatic lobules and fibrosis in testis, lower sperm motility and viability as well as reduced fertilization rate [26,150–153]. Cr has been regarded as one of the most biologically potent heavy metals due to its summative destructive effects on living organisms [154]. Long term exposure to Cr drastically reduced...
Table 3
Effects of heavy metals on reproductive performances of fish.

| Fish species | Doses | Exposure period (days) | Effects | References |
|--------------|-------|------------------------|---------|------------|
| Anguilla japonica | 0.1, 100 µM | 15 | Inhibited spermatogenesis via steroidogenesis suppression | [24] |
| Danio rerio | - | 68 | Reduced reproductive output, egg production, number of spawns, average number of eggs per spawn and hatching rate | [23] |
| Anguilla japonica | 10⁻³ M | 6 | Inhibited the spermatogenesis, necrosis of testicular fragments | [22] |
| Cd | Oryzias melastigma | 10 µg/L | 30 | Irregular oocytes, partly adhesion, empty follicle, and increased follicular atresia, cytoplasmatic retraction, cytoplasm condensate form, karyoplasm clumping, loose follicular lining | [27] |
| Gasterosteus aculeatus | 1 µg/L | 90 | GSI decreased in prolonged exposure | [161] |
| Odontesthes bonariensis | 0.25 µg/L | 14 | Testis showed fibrosis and shrinkage of the spermatogenic lobules, pyknotic cells, reduce of the length of the spermatogenic lobules | [26] |
| Cyprinus carpio | 50, 100, 150 & 200 ppm | 3 | Sperm quality (motility and viability) and fertilization rate decreased at 100 ppm or more | [153] |
| Acipenser baerii | 0-100 mg/L | 4 h | Percentage of motile sperm was reduced from 10 mg/l to higher conc. | [151] |
| Oncorhynchus mykiss | 10, 100 and 500 mg/l | 4 h | Altered sperm motility characteristics and hatching rates | [152] |
| Acipenser ruthenus | 0.1, 5.0 mg/L | 2 h | Sperm motility parameters (motility and velocity) inhibited in higher conc. | [150] |
| Cr | Oryzias melastigma | ½ of 96LC50 | 60 | After long-term exposure amount of spawning decreased | [155] |
| Odontesthes bonariensis | 4 µg/L | 14 | Testis showed fibrosis and shrinkage of the spermatogenic lobules, pyknotic cells in the testis | [26] |
| Oryzias latipes | 4 mg/L | 90 | Decrease in gonad weight, GSI and fecundity, reduced number of mature oocyte and mature spermatozoa in testes | [24] |

Table 3 (continued)

| Fish species | Doses | Exposure period (days) | Effects | References |
|--------------|-------|------------------------|---------|------------|
| Acipenser ruthenus | 0.1, 5.0 mg/L | 2 h | Sperm motility parameters (motility and velocity) inhibited in higher conc. | [150] |
| Channa punctatus | 4 mg/L | 30 | Decreased the percentage of vitellogenic oocytes | [124] |
| Cu | Poecilia reticulata | 0, 5, 10 mg/L | 56 | Lowest reproductive success, prolonged parturition time and highest mortality rate at 10 mg/l | [28] |
| Oreochromis niloticus | 1, 2, 4 mg/kg | 4 | Decrease in sperm motility rate, VCL, VAP, and VSL, Fibrosis and shrinkage of the spermatogenic lobules, pyknotic cells in the testis, reduce of the length of the spermatogenic lobules | [26] |
| Xiphophorus helleri | 0.04, 0.08, 0.12 & 0.16 ppm | 100 | Decreased GSI, gonad not developed in high concentrations (0.12 and 0.16 ppm) | [160] |
| Carassius auratus | 0.25, 0.05, 0.075 & 0.1 ppm | 100 | Decreased GSI, reduced the fecundity | [160] |
| Danio rerio | 100, 500 & 1000 µg/g | 260 | 1000 µg produce decrease in GSI but not significant. | [159] |
| Hg | Acipenser baerii | 0-100 mg/L | 4 h | Percentage of motile sperm reduced from 1 mg/l to higher conc and complete obstruction in 100 mg/l. | [151] |
| Oncorhynchus mykiss | 1, 10 & 100 mg/l | 4 h | Inhibition of sperm motility | [152] |
| Decentrarchus labrax | 0.01, 0.1, 3.93 µg/g | - | Exposure to100 ppm completely inhibited sperm motility | [158] |
| Oryzias latipes | 40 µg/L | 8 | Testicular atrophy and arrested spermatiation | [157] |
| Pimephales promelas | 0.87 ± 0.03, 250 | 3.93 µg/g diet | Lowered GSI,Reduced the reproductive success | [162] |
| goldfish | 1, 10 & 100 µg/L | - | Reduced curvilinear velocity, percentage of motile sperm, flagella length | [163] |
| Pimephales promelas | 0.88, 4.11 & 8.46 µg/g | - | Delayed spawning, and days to spawning Reduced the instantaneous rate of reproduction, GSI and reproductive efforts | [43] |
| Oreochromis niloticus | 0.08 to 0.54 µg/g | 210 | The normal morphology of the testes was altered, Decreased spermatozoa in testes | [164] |
| Pt | Oryzias melastigma | 50 µg/L | 30 | Irregular oocytes, partly adhesion, | [27] |

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Table 3 (continued)

| Fish species       | Doses                        | Exposure period (days) | Effects                                                                 | References |
|--------------------|------------------------------|------------------------|-------------------------------------------------------------------------|------------|
| Carassius gibelio  | 8, 13, 24 & 49 mg/kg         | 365                    | empty follicle, increased follicular atresia, loose follicular lining     | [30]       |
|                    |                              |                        | Decreased GSI, affected ovarian steroidogenesis, gametogenesis, ovulation | [30]       |
| Zn                 | 50, 200, 300 mg/kg           | 60                     | The highest GSI and fecundity at 50 mg/L                                | [25]       |
| Clarias magur      | 100 μg/L                     | 30                     | Irregular oocytes, partly adhesion, empty follicle, and increased         | [27]       |
|                    |                              |                        | follicular atresia, loose follicular lining                             |            |
| Odontesthes       | 211 μg/L                     | 14                     | Fibrosis and shrinkage of the spermatogenic lobules, pyknotic cells in | [26]       |
| bonariensis        |                              |                        | the testis, reduced the length of the spermatogenic lobules,           |            |
| Cyprinus carpio    | 10, 50, 100, 200, 500, 1000 and 2000 ppm |                        | Decreased the motility of sperm, inhibitory influence on VSL, low       | [165]      |
|                    |                              |                        | fertilization rate                                                      |            |

GSI; gonad-somatic index,

the spawning success [155], fibrotic and pyknotic testis [26], significantly reduced the GSI, fecundity, lowered number of oocytes and matured spermatooza [156], hampered the motility of sperm [150] and finally gradual decrease of vitellogenetic oocytes [124]. Various studies revealed that reduced GSI, fecundity, hatching rate, fertilization success, abnormal shape of reproductive organs, and finally overall reproductive success resulted from the toxicities created by Cu and Hg [28,29,151, 157–160]. Pd and Zn resulted similar deformities as well as negative impacts in Carassius gibelio [30], Odontesthes bonariensis [26]; Oryzias melastigma [27] and Clarias magur [25].

5. Conclusion and future perspectives

Heavy metals contamination is a serious threat to entire aquatic ecosystems including associated flora and fauna. The devastating impacts of heavy metals on aquatic organisms specifically fish result an irreparable loss in aquaculture industry. In this review, destructive effects of heavy metals on fish focusing the embryonic and larval development, growth and reproduction of commercially important species are discussed very concisely with a view to using it as a tool for further genotoxicity related experiments by the researchers of the associated areas. Heavy metals resulted in severe deformities in several aquatic organisms that will ultimately pose a substantial threat to associated consumers. To enlarge the sustainability of the aquaculture sector and to produce safe fish for human consumption, regular monitoring of the fish and associated environment should be done by the appropriate authorities at the local government, state, and national levels. A well-established framework should be developed as soon as possible to mitigate this great problem.

CRediT authorship contribution statement

Khanam Taslima: preparation of the first draft of the manuscript. Md Al-Emran, Mohammad Shadiqur Rahman, Jaber Hasan, Zannatul Ferdous and Md Fazle Rohani: data collection and preparation of the Tables. Md Shahjahan: conceptualization, edited the manuscript and final approval. All authors have read the final version and approved the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Sharing of data is not permissible for this article. The data that support the outcomes of this study are available on request from the corresponding author [M Shahjahan].

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