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REVIEW ARTICLE

Biomonitoring of aquatic pollution: status and trends from genomics to populations

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Abstract

Biomonitoring offers an appealing tool for the assessment of pollution in aquatic ecosystem. Biological processes, species, or communities of bioindicators are used to assess the quality of the environment and how it changes over time. Bioindicators include algae, macrophytes, zooplanktons, insects, bivalves, molluscs, gastropods, fish, amphibians, and others. Changes in aquatic ecosystems are often attributed to anthropogenic disturbances, including pollution. Major contributors to aquatic pollution include wastewater, metals and metalloids, industrial effluents, contaminated sediments, nutrients, polycyclic aromatic hydrocarbons, flame retardants, persistent organic pollutants, pharmaceuticals and illicit drugs, emerging contaminants (such as microplastics and engineered nanoparticles), pesticides, herbicides, and endocrine disruptors. In this review, we discuss categories of aquatic pollutants, status and trends of aquatic biomonitoring and approaches, from genomics to populations. We conclude by offering recommendations for research and regulatory testing.

Keywords: *Bioindicators, Pollution, Biomonitoring, Ecotoxicological tools*

Introduction

According to Adeyemo (2003), Nigeria's vast freshwater resources are among those most affected by environmental stress imposed by human population growth, urbanization, and industrialization. Fish and marine resources in the country face total collapse or extinction, due to over-fishing and destruction of marine life and natural habitats by pollution of water bodies. Unregulated and excessive use of pesticides for agriculture and the deliberate disposal and dumping of toxic and hazardous wastes into water bodies are significant causes of massive fish kills and loss of aquatic life and habitats in the country. Biomonitoring has been defined as the act of observing and assessing the state and ongoing changes in ecosystems, components of biodiversity and landscape, including the types of natural habitats, populations, and species. These has been said to lie at the core of environmental conservation, management, and restoration, albeit primarily in the developed world. In human studies, "exposomics" is an emerging area that falls between environmental monitoring and public health surveillance (Smith et al, 2015). The "exposome" is defined as the summation of environmental exposures for individuals, beginning *in utero*. Samples of human biospecimens such as blood, saliva, or urine are analyzed for chemical contaminants using advanced methodologies and looking for contaminants such as lead, phthalates, dioxins, or mercury, among others.

In aquatic ecosystems, biomonitoring studies are used to measure exposure, response, and recovery of aquatic communities to disturbances and provide an understanding of the relationship between physical, chemical, and biological components (Gurtz, 1994). Biomonitoring studies are important in assessing aquatic ecosystem health because organisms' function as sensors of the quality of their environment more than can be achieved with water quality measurements. Aquatic biomonitoring has become an essential task in most of the developed world because of strong anthropogenic pressures affecting the health of lakes, rivers, oceans, and groundwater. A typical assessment of the environmental quality status, such as is required by Europe, North America and other legislation, relies on matching the composition of assemblages of organisms identified using morphological criteria present in aquatic ecosystems to those expected in the absence of anthropogenic pressures. In developing countries like Nigeria, this assessment method is being utilized as well to evaluate the health status of aquatic ecosystems (Olaniran et al., 2019; Nwabueze et al., 2020). In this review/perspective paper, we provide an overview of aquatic biomonitoring, categories of aquatic pollutants, aquatic biomonitoring status and trends, aquatic biomonitoring approaches from genomics to populations and end with recommendations for research and regulatory testing.

Aquatic biomonitoring: would usually involve fish, macroinvertebrate, and algae. Rosenberg and Resh (1996) provided a comprehensive review of current biomonitoring approaches. These approaches span a range of scales:

1. Biochemical and physiological measurements, including metabolic studies and measures of enzyme activities.

2. Individual attributes such as morphological, behavioural, and life-history parameters, or the use of "sentinel organisms" that bioaccumulates toxic materials.

3. Population and assemblage level responses, such as using occurrence or abundance of indicator species as a measure of sensitivity to a pollutant.

4. Community-level approaches which synthesize many types of data into summary responses to a pollutant.

5. Ecosystem-level scales that assess effects of stressors on processes and function.

Categories of Aquatic Pollutants

Persistent Organic Pollutants: Persistent organic pollutants (POPs) are chemicals of global concern due to their potential for long-range transport, persistence in the environment, ability to bio-magnify and bio-accumulate in ecosystems, as well as their significant negative effects on human health and the environment. POPs have been the object of biomonitoring studies for more than 60 years. The most commonly encountered POPs are organochlorine pesticides, including, dichlorodiphenyltrichloroethane (DDT) and its metabolites and degradates; hexachlorocyclohexanes, including lindane; dieldrin; mirex; trans-nonachlor; polychlorinated biphenyls (PCBs); and several other POPs now listed in the Stockholm Convention. The same physical and chemical characteristics that lead to persistence in the environment lead to persistence in biological systems, with limited metabolism, slow elimination, and resulting bioaccumulation. Many of these pollutants have multiple effects on health. Some are potent endocrine disruptors, affecting development, reproduction and behaviour. Others are potent immune disruptors, lowering the natural defenses against disease. For example, p, p-DDE is both an anti-androgen and a weak estrogen and also affects immune parameters in fish exposed to this pesticide (Martyniuk et al, 2016).

Heavy metals: The term 'heavy metal' is used synonymously with 'trace metal' and includes both essential and non-essential trace metals. All of these have the potential to be toxic to living organisms if present or bioavailable above a threshold. Examples of heavy metals include mercury (Hg), cadmium (Cd), arsenic (As), chromium (Cr), thallium (Tl), and lead (Pb). Three measures of heavy metals level in aquatic habitats are usually carried out in pollution studies--namely concentrations in water, sediments, and biota. For example, A study (Adeyemo, 2007a) on lead levels in rivers, sediments and fishponds in the Ibadan metropolitan area, South-West Nigeria revealed that lead levels in surface waters ranged between 0.5–2.35 mg l^{-1} (mean: 0.76 mg l^{-1}) and 1.15–2.20 mg l^{-1} (mean: 1.34 mg l^{-1}) during the dry and rainy seasons, respectively. Lead levels in river sediments ranged between 0.9–4 mg kg^{-1} (mean 1.86 mg kg^{-1}) and 1.15–2.2 mg kg^{-1} (mean 1.49 mg kg^{-1}) during the dry and rainy seasons, respectively. Lead levels in fishponds were even higher, at 1.09–2.9 mg l^{-1} (mean 1.88 mg l^{-1}). The need for a detailed assessment of sources of lead in Nigerian aquatic ecosystems and further research into the distribution of lead in different biota (such as aquatic plants, invertebrates, and fish) in relation to the environment was recommended. Heavy metals are accumulated by many aquatic organisms to remarkably high tissue and hence body concentrations. These accumulated concentrations are easily measured, not liable to contamination, and provide a time-integrated measure of metal supply over weeks, months, or even years, according to the species analyzed. Many of these heavy metals cause kidney dysfunction and an assortment of other health issues such as gastrointestinal disorders, ataxia, paralysis, and death. Some heavy metals are carcinogens. Chronic exposure to these chemicals may be costly for the people involved (Omenka and Adeyi, 2016).

Pharmaceuticals, and Personal Care Products (PPCPs): The extensive use and misuse of antimicrobials for treatment and prophylaxis in livestock production generally and aquaculture is of great concern to environmental and public health. Other categories of PPCPs pollutants aside from antibiotics, including hormones, antimicrobial agents, synthetic musks, among others, have raised significant concerns about their persistent input and potential threat to the ecosystem and human health. As an important group of organic pollutants with intensive studies in recent years, PPCPs have been found to be ubiquitous in the aquatic environment throughout the world. They constitute a large and diverse group of organic compounds such as soaps, lotions, toothpaste, fragrances, and sunscreens, which are widely used in high quantities throughout the world, together with their metabolites and transformation products (Kummerer, 2010). In Nigeria, regulation and monitoring of aquaculture and other livestock production activities at best is lax. For example, in a study by Saka et al, (2017), all the isolates (100%) from fish muscle of live-fish obtained from a market in Nigeria had multiple antibiotic resistance (MAR) indices >0.2 to a wide range of antibiotics (ampicillin, cefixime, augmentin, ciprofloxacin, cefuroxime, nitrofurantoin, ofloxacin, ceftazidime and gentamycin), which portends potential source of resistant bacteria for humans. In a similar study carried out on Lafenwa effluents and its receiving water in Abeokuta, Ogun state, 31% Enterobacteriaceae and 66% Pseudomonas isolates were resistant to five antibiotics (Ceftazidime, Cefpodoxime, Cefotaxime, Ertapenem and Amoxicillin-clavulanate) and 77% of the isolates had MAR indices >0.2 to the same set of antibiotics (Akpan et al., 2020).

Endocrine-Disrupting Chemicals (EDCs): The occurrence of endocrine-disrupting chemicals (EDCs), including natural and synthetic estrogens, is well documented in the aquatic environment (Folmar et al, 1996, Yoon et al. 2010; Vidal-Dorsch et al. 2012, González et al, 2020). The understanding of EDCs and the effects that they have on aquatic biota has improved over the past two decades with increased precision of analytical methods and innovative assays designed to detect and quantify estrogenic responses. Baldigo et al, (2015) determined the levels of plasma vitellogenin (Vtg) and Vtg messenger ribonucleic acid (mRNA) in male fathead minnows (*Pimephales promelas*) exposed to wastewater effluents and dilutions of 17α-ethinylestradiol (EE2), estrogen activity, and fish assemblages in 10 receiving streams and reported that EE2, plasma Vtg concentration, and Vtg gene expression in fathead minnows, and 17β-estradiol equivalents (E2 Eq values) were highly related to each other (R 2 = 0.98–1.00). In Nigeria, several chemicals used in agriculture as pesticides and herbicides rank among these pollutants and have been proven to have deleterious effects in animals that are exposed to them in varying quantities and also pollution of air, soil, ground and surface water. For example, in the Ogun River, Nigeria, 15 PCB congeners, lindane, dieldrin, 4-isononylphenol and 4-tert-octylphenol analysed in fish muscle and sediments samples have been associated with 24% prevalence of intersex. This correlated with gonadal histopathological changes, significantly higher plasma estradiol-17β, luteinizing hormone, follicle stimulating hormones as well as hepatic transcript levels of Vtg, zona radiata and aromatase in male fish (Ibor et al., 2016).

Our study on carbendazim revealed significant decreases in testosterone and 11-ketotestosterone levels in exposed African Sharptooth Catfish (*Clarias gariepinus)*. Testicular histological and ultra-structural studies also revealed germinal and Sertoli cell degeneration and necrosis, displacement of Sertoli cysts, capillary endothelial wall necrosis and basement membrane disruption (Aina et al, 2019). In similar studies, catfish exposed to formalin had generalized massive vacuolations of the skin, multifocal necrosis of hepatocytes, massive lymphoid depleted spleen and seminiferous tubules (Adeyemo et al., 2011a). Malachite green exposed catfish (Adeyemo et al., 2011b) had disrupted and depleted seminiferous tubules, focal localized vacuolation of skin and generalized fatty degeneration of liver while copper sulphate exposure (Alarape et al., 2013) resulted in necrotic ovaries, matted lamellae of the gills and multifocal severe degeneration of the seminiferous tubules. All three (formalin, malachite green and copper sulphate) had significantly detrimental effects on egg, milt quality and hatchability.

Oil and Oil-Dispersing Agents: Oil pollution from exploration and production processes, natural seeps, atmospheric contribution, freight accidents, industrial discharge, and urban run-off is a significant hazard for the marine environment (Wilson and LeBlanc, 2000). Oil dispersants (chemical agents such as surfactants, solvents, and other compounds) are used to reduce the effect of oil spills by changing the chemical and physical properties of the oil. However, polycyclic aromatic hydrocarbons (PAHs) and other components of oil and the dispersant used in the clean-up process may persist in the marine environment for a long time thereby creating pathways for lingering biological exposure and associated adverse effects (Sogbanmu and Otitoloju, 2014). Our study (Adeyemo et al, 2015) on the effects of the exposure of inland silversides (*Menidia beryllina)* embryos at 30–48 h post-fertilization to water accommodated fractions of oil (WAF, 200 ppm, v/v), dispersants (20 ppm, v/v, Corexit 9500 or 9527), and mixtures of oil and each of the dispersants to produce chemically enhanced water accommodated fractions (CEWAFs) over a 72-h period revealed that that significantly more treated embryos were in a state of deterioration, with significantly more embryos presenting arrested tissue differentiation compared with controls (Figure 1), amongst other effects.

Figure 1: Some abnormalities observed in hatchlings of Menidia embryos exposed to dispersants and CEWAFs were (a) head malformation, (b) pericardial edema, and (c) Spinal deformities (Adeyemo et al, 2015).

Aquatic biomonitoring: Status and Trends

Environmental pollution due to anthropogenic activities is a major public health concern in Nigeria. Some studies have been conducted to determine the status of aquatic pollution in Nigeria. For example, seasonal variations in ecological parameters have been found to exert profound effect on the distribution and population density of both animal and plant species. Adeyemo (2008 a,b,c,d) conducted a field study to determine spatiotemporal pollution status of rivers in Ibadan, Nigeria. The metrics used were physicochemical parameters and nutrient load of rivers and their sediment. Habitat assessment was also conducted by evaluating the structure of the surrounding physical habitat that influences the quality of the water resource and the condition of the resident aquatic community. The results revealed that colour, total suspended solid, total solids and total nitrogen were generally higher during the dry season, which suggests that the run-offs have only a diluting effect on these parameters. The overall sensitivity of the watershed to physicochemical environmental pollution revealed that during dry season, of the 22 sample points, 3 (13.6%) were unpolluted; 6 (27.3%) were slightly polluted; 10 (45.4%) were moderately polluted; 2 (9.1%) were seriously polluted and 1 (4.5%) was exceptionally polluted.

In a similar field study on water quality parameters of one of the major rivers traversing an industrial estate in Ibadan to determine its suitability for aquatic life. It was revealed that the physico-chemical properties of the river were not within the World Health Organization standard and thus rendered unsuitable for aquatic life (Kupoluyi et al., 2018). Furthermore, the pollution status of other aquatic ecosystems in Nigeria such as the coastal waters of the Niger Delta, the Lagos lagoon, Lekki lagoon, among others have demonstrated the impact of anthropogenic pressures due to infrastructure development, exploitation of aquatic resources, shipping and other forms of water transportation, oil prospecting and extraction, sand mining and so on (Nwaichi and

Ntorgbo, 2016; Sogbanmu et al., 2016). The trend in aquatic biomonitoring in Nigeria is being driven towards hazard evaluation, integrated approaches and development of ecological risk indices targeting various priority and emerging pollutants and ecosystems (Benson et al., 2018; Edegbene et al., 2019; Sogbanmu et al., 2019).

Aquatic Biomonitoring approaches: from Genomics to Population

Genomic Markers: Since 1999, when the term "*toxicogenomics*" was coined to describe the application of genomics to toxicology, different genomic approaches have been available through a combination of advanced biological, instrumental, and bioinformatic techniques which can yield a previously unparalleled amount of data concerning the molecular and biochemical status of organisms. Ankley et al (2006) stated that "*among other applications, genomic information can be used to design microarrays or "gene chips" for some or all of the genes in an organism. These chips can be used to determine which genes are up- or down-regulated (as transcribed messenger RNA [mRNA]) in a cell, tissue, organ, or organism under specific physiological conditions or in response to an environmental perturbation, such as exposure to a toxic chemical".*

All responses to external stressors, including toxicants, have been linked to changes in normal patterns of gene expression (Ellwood and Foster, 2004, Grifiitt et al, 2012, Thomas and Meyer, 2012,). Different mechanisms of toxicity can generate specific patterns of gene expression reflective of mechanism or mode of action (MOA). The application of transcriptomics to toxicity research has become increasingly important because of the availability of many genes that can be queried with microarrays or RNAseq, which runs fifteen thousand to whole transcriptomes for some animal models (Hoffmann and Sgro, 2011, Marx, 2013, Qian et al, 2014).Proteomics also provides additional critical insights into biological pathways since not all mRNA sequences are transcribed, and many proteins are modified, for example, by phosphorylation, posttranslational cleavage) before becoming physiologically active (Dole-Olivier et al, 2009, Martyniuk et al, 2009, Unterseher et al, 2011). Consequently, alterations in protein profiles can be used, in conjunction with transcriptomics, to understand responses of an organism to toxicants (Wooley et al, 2010, Carter et al, 2012, Martyniuk and Denslow, 2012, Garcia et al, 2013), providing broad characterizations of the proteins expressed within cells, organs, or, in some instances, whole organisms. Methods typically include protein isolation and separation steps with techniques such as 2D gel electrophoresis or high-pressure liquid chromatography, followed by tandem mass spectrometry (MS/MS) analyses to identify peptide profiles or amino acid sequences as a basis for determining specific proteins (Whittaker, 1960, Yates et al, 2009, Wang et al, 2012, Wang et al, 2013a).

While transcriptomics and proteomics are excellent tools, metabolomics captures a more integrated assessment of the physiological state of an organism. Different high-resolution MS and nuclear magnetic resonance (NMR) techniques are the primary methods for generating metabolomic data. Transcriptomics, proteomics, and metabolomics measure responses at different biological levels of organization and thus provide different insights into the biochemical and molecular status of an organism. However, all three approaches have an excellent potential for defining toxicity pathways, particularly if used together (Carrigg et al, 2007, Gonzalez et al, 2011, Garcia et al, 2013, Mizrahi-Man et al, 2013, Davis et al, 2017). Adeyemo et al (2015), in their study which assessed developmental abnormalities and differential expression of genes induced in oil and dispersant exposed *Menidia beryllina* embryos quantified abundances of transcripts of target genes for sexual differentiation and sex determination (StAR, dmrt-1, amh, cyp19b, vtg and chg-L,), growth regulation (ghr)and stress response (cyp1a and Hsp90) concluded that molecular endpoints were most sensitive, especially the expression of star, cyp19b, cyp1a, hsp90 and recommended that these biomarkers could be used as early indicators of long term effects of Corexit 9500 and 9527 usage on *M. beryllina* in oil spill management and oil pollution events.

High-Throughput Cell Assays and Metagenomics

The application of high-throughput sequencing protocols in metagenomics (Thomas and Meyer, 2012) offers the opportunity for a cost-effective and comprehensive means of assessing biotic diversity and ecological relationships for many complex animal, plant and microbial ecosystems. However, addressing complex biological questions with metagenomics requires the interaction of researchers who bring different skill sets to problem solving. It is now possible to get one (1) litre of water from a location, extract the environmental DNA (eDNA), sequence this with high throughput sequencers and identify all the organisms present at a site (Deiner et al, 2017).

High-throughput cell assays that detect and integrate the response of multiple chemicals acting via a common mode of action enhances environmental monitoring practices (Wang et al, 2013b). In the United States, the Environmental Protection Agency has launched a large project using over 800 different in vitro assays to characterized contaminants into bins of similar modes of action. Results from these assays can be found at the CompTox Chemical Dashboard (https://comptox.epa.gov/dashboard) where, to date, they have tested over 875,000.

In Figure 2 below, we illustrate an example with p,p'-DDT. Plotted here is the AC50 of various assays as a function of the magnitude of the reaction as a scaled function (Scaled Top) to be able to represent all of the assays in one chart. Over 246 different assays were performed with this pesticide but only the 29 that are plotted here were active at AC50 concentrations below the cytotoxicity levels in the cells. Among the assays that were positive in this region, we find assays relating to cell cycle arrest, channels, cytochrome P450's, malformation, nuclear receptors, phosphatase, transferase and transporter activities. The most potent of all of the assays was a phosphatase assay with an AC50 of 0.16 uM. Among the nuclear receptors that are active, estrogen receptor 1 (ESR1) is the most active with an AC50 of 3.26. Other nuclear receptors include ESR2, PGR and NR112. These assays suggest that DDT is highly active with multiple endpoints.

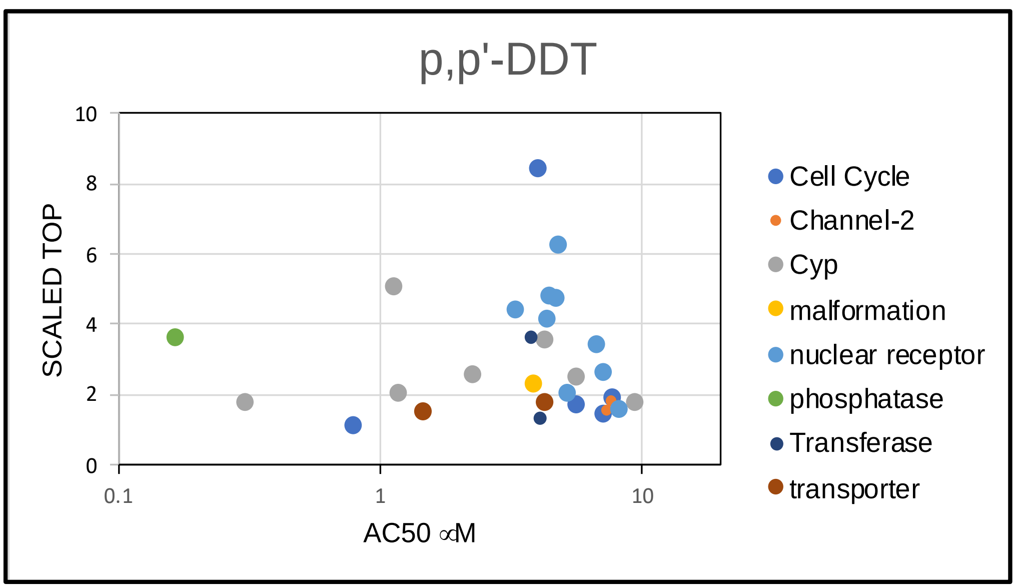

Figure 2: ToxCast bioanalytical plot for p,p'-DDT. The y-axis (scaled top) represents the highest response of each assay divided by the activity cutoff of the assay to be able to represent all assays in the same graph. The x-axis is the AC50 (uM) for each assay

These technologies are providing useful information to characterize environmental hazards. Additionally, it is important to complement high-throughput screening data with reliable in vivo effects data. Ultimately, this connection allows high-throughput screening data to be used to prioritize and predict effect thresholds for risk assessment. For example, Mehinto et al, (2018) reported that a linkage between in vitro and in vivo responses is key to demonstrating that in vitro cell assays can be predictive of ecologically relevant outcomes. Their study investigated the potency of 17β-estradiol (E2), estrone (E1), nonylphenol (NP), and treated wastewater effluent using the GeneBLAzer estrogen receptor transactivation assay and two life stages of the inland silverside (*Menidia beryllina*); and it was concluded that in vitro cell assays were more sensitive than live fish models, making it possible to develop in vitro effect thresholds which could be used to protect aquatic organisms.

Tissue responses: In chemical monitoring, the presence of pollutants in tissues are evaluated by chemical analysis, but biomonitoring methods evaluate not only the presence, but also the response of the organisms to these pollutants by the assessment of various physiological, cellular, biochemical and histopathological biomarkers. Detailed information can be obtained on general metabolism and physiological status of fish in different groups of age and habitat. For example, studies have shown that when the water quality is affected by toxicants, any physiological changes will be reflected in the values of one or more of the haematological and/or biochemical parameters (Adeyemo, 2007b; Nwabueze et al., 2020). Histopathology provides direct and reliable evidence by identifying cellular alterations in various organs because of environmental pollution. Sublethal levels of pollutants have been reported to cause biochemical or physiological effects at the subcellular level in an organism (Sogbanmu et al., 2018; Olaniran et al. 2019). A variety of pollutants and xenobiotics cause various gill lesions such as lamellar necrosis, epithelial lifting and hyperplasia (Sogbanmu et al., 2018), in response to a wide range of contaminants. Other tissues that could be used as biomarker of pollution include the liver, which is the site of metabolism and plays a key role in biochemical transformations of pollutants under detoxification processes; toxicant exposure, accumulation lesions and other histopathological alternations are therefore common in the liver.

Whole-organism responses: contaminants in aquatic systems usually remain either in soluble or suspension form and finally tend to settle down to the bottom or are taken up by the organisms. The progressive and irreversible accumulation of heavy metals in various organs of marine biota ultimately leads to metal-related diseases in the long run because of their toxicity. Badejo et al (2010) reported that fish and shrimp from Lagos Lagoon, Nigeria, bioaccumulated Zinc, Iron and Manganese in their tissues and linked this to the prevailing improper discharge of wastes from various human activities in the study area especially from industrial, oil sectors and municipal discharges. The result also showed that fish and shrimp significantly bioconcentrated Zinc, Iron and Manganese in comparison to their levels in the surface water. Similarly, developmental abnormalities, reduced hatching success, decreased heartbeat, embryo death have been observed in *Danio rerio* (zebrafish) embryos exposed to sediments from the Lagos lagoon (Sogbanmu et al., 2016; 2020) as well as environmentally relevant concentration of PAHs mixtures (Sogbanmu et al., 2016).

Population-level Responses: aquatic pollution has been established to have affected the normal function of aquatic ecosystems including reproduction, feeding, and have also affected the habitats of aquatic flora and fauna (Schmeller et al., 2018). Ola-Davies et al (2015) reported diazinon-induced clastogenity and pathological changes in ovaries and testes of *Clarias gariepinus*. Chemicals such as diazinon, an organophosphate pesticide, originating from agricultural activity enter the aquatic environment through atmospheric deposition, surface run-off or leaching. Pollutants enter the food chain through accumulation in soft bottom sediment and aquatic organisms.

The concept of Adverse Outcome Pathway has become important in both environmental and human toxicology. First proposed by Ankley for fish (Ankley et al, 2010), it is now used in human health as well. The idea behind this concept is that there is an initiating event which is called the molecular initiating event (MIE) where a toxicant binds to a protein or receptor to initiate a cascade of events that ultimately lead to adversity. These events start at the molecular level but increase in complexity as they alter cellular homeostasis, organ function and ultimately the organism and population to cause morbidity or mortality, considered adverse effects. The concept offers a way to organize effects from contaminants, with the idea that the effects must result in adversity if the contaminant is to be regulated. A lot of effort has gone into establishing these pathways for environmental organisms and humans and it has been used to develop a knowledge base that can be accessed through the AOP wiki https://aopwiki.org.

Recommendations for Research and Regulatory Testing

The protection of water quality and aquatic ecosystem as a vulnerable resource, essential to sustain life, development and environment is of utmost importance to prevent further pollution and degradation of Nigeria's aquatic resources A long-term research need involves relating the molecular and biochemical responses measured by toxicogenomic methods to specific toxicity pathways and to (adverse) alterations in survival, growth, and reproduction. Significant parallels exist between toxicogenomic data and the endpoints considered as potentially useful biomarkers (such as changes in CYP enzymes, metallothionein, heat shock proteins, vitellogenin). A database of pollutants or contaminant detection and levels in various aquatic ecosystems in Nigeria as well as biological effects elicited in aquatic organisms at environmental concentrations is imperative for future risk evaluations and guidelines development particularly for emerging environmental contaminants. These efforts in tandem with consistent monitoring and evaluation by relevant environmental regulators in Nigeria will support Nigeria' strides towards sustaining life below water (UNSDG 14).

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