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IMPACT OF THE PERSISTENT ORGANIC POLLUTANT LINDANE ON ANTIOXIDANT ENZYME ACTIVITY IN OREOCHROMIS NILOTICUS (NILE TILAPIA).

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ABSTRACT

Persistent organic pollutants (POPs) such as lindane continue to pose significant ecological threats because of their persistence, bioaccumulation potential, and toxicity to aquatic organisms. This study investigated the effects of lindane on antioxidant enzyme activities in *Oreochromis niloticus* (Nile tilapia). Seventy-five juvenile fish were exposed to different concentrations of lindane selected following a preliminary range-finding test. Acute toxicity tests were conducted to determine the 96-h median lethal concentration (LC_{50}), while separate groups were exposed to sublethal concentrations for 28 days to evaluate chronic oxidative stress responses. The activities of glutathione S-transferase (GST), quinone reductase (QR), peroxiredoxin (Prx), thioredoxin (Trx), myeloperoxidase (MPO), and glutathione reductase (GR) were determined using standard spectrophotometric methods. Results showed a concentration-dependent decline in the activities of all antioxidant enzymes following lindane exposure. GST activity decreased from 5.20 U in the control group to 4.20 U at the highest sublethal concentration (30% LC_{50}). Similar reductions were observed in QR, Prx, Trx, MPO, and GR activities, indicating progressive impairment of the antioxidant defence system with increasing lindane concentration.The observed inhibition of antioxidant enzymes demonstrates that lindane induces oxidative stress, weakens cellular detoxification mechanisms, and compromises immune function in *O. niloticus*. These findings highlight the toxicological consequences of lindane contamination in aquatic environments and support the use of antioxidant enzymes as sensitive biomarkers for monitoring pesticide-induced

oxidative stress in fish. The study underscores the need for continuous environmental monitoring, stricter regulation of persistent organic pollutants, and effective pollution control measures to safeguard aquatic ecosystems. Further investigations should focus on the molecular mechanisms underlying lindane-induced oxidative stress and its long-term ecological consequences, including interactions with other environmental stressors.

KEYWORDS: Lindane; Persistent organic pollutants (POPs); *Oreochromis niloticus*; Antioxidant enzymes; Oxidative stress.

1.0 INTRODUCTION

Persistent organic pollutants (POPs) represent a major class of environmental contaminants due to their chemical stability, resistance to degradation, long-range transport potential, and ability to accumulate in biological tissues. Unlike many conventional pollutants, POPs persist in aquatic ecosystems for prolonged periods and may undergo bioaccumulation and biomagnification through food chains, resulting in adverse effects on aquatic organisms, wildlife, and human health (United Nations Environment Programme [UNEP], 2019; World Health Organization [WHO], 2021). Among these pollutants, organochlorine pesticides remain a significant environmental concern because of their extensive historical use, environmental persistence, and toxicological effects.

Lindane (γ-hexachlorocyclohexane; γ-HCH) is a chlorinated organochlorine pesticide that was widely used worldwide for agricultural pest control, seed treatment, and vector management. Although its agricultural use has been restricted or banned in many countries under the Stockholm Convention because of its persistence, bioaccumulation potential, and toxicity, residues of lindane continue to be detected in soils, sediments, surface waters, and aquatic organisms due to its slow degradation and environmental stability (Stockholm Convention, 2019; Li et al., 2021). Its lipophilic nature facilitates accumulation in biological membranes and lipid-rich tissues, where it interferes with normal cellular metabolism and physiological functions.

Aquatic ecosystems receive a wide range of pollutants from agricultural runoff, industrial effluents, municipal wastewater, and improper waste disposal. Continuous discharge of untreated industrial effluents has increased the burden of hazardous contaminants in freshwater environments, posing significant ecological and public health risks (Ochu et al., 2025). Persistent organic pollutants, including organochlorine pesticides such as lindane, are

among the contaminants of concern because of their persistence, bioaccumulative nature, and toxicity (UNEP, 2019; WHO, 2021).

Fish are widely recognized as valuable bioindicators of aquatic pollution because they continuously interact with their surrounding environment through gill respiration, feeding, and dermal absorption. Consequently, they readily accumulate environmental contaminants and exhibit measurable physiological and biochemical responses to toxic exposure. Their sensitivity to environmental pollutants has made them indispensable organisms for monitoring aquatic ecosystem health and evaluating contaminant-induced biological effects (van der Oost et al., 2003; Authman et al., 2015).

Oreochromis niloticus (Nile tilapia) is among the most economically important freshwater fish species worldwide because of its rapid growth, adaptability, high nutritional value, and tolerance to diverse environmental conditions. Its widespread distribution, ease of culture, and physiological resilience have also made it one of the most commonly used experimental models in aquatic toxicology. Previous studies have demonstrated that exposure to environmental stressors can adversely affect growth performance, physiological processes, and immune competence in Nile tilapia, thereby reducing its capacity to withstand environmental challenges (Abdel-Tawwab et al., 2019).

Oxidative stress represents one of the principal mechanisms through which lindane exerts toxicity in aquatic organisms. Exposure to lindane stimulates excessive production of reactive oxygen species (ROS), resulting in oxidative damage to lipids, proteins, and nucleic acids. To counteract these effects, fish possess complex antioxidant defence systems comprising enzymatic antioxidants such as glutathione S-transferase (GST), glutathione reductase (GR), peroxiredoxins (Prx), thioredoxin (Trx), quinone reductase (QR), and myeloperoxidase (MPO). Alterations in the activities of these enzymes provide valuable information regarding oxidative damage, detoxification efficiency, and the physiological status of exposed organisms (Lushchak, 2011; Birnie-Gauvin et al., 2017).

Glutathione S-transferase (GST) is a major phase II detoxification enzyme that catalyses the conjugation of reduced glutathione with electrophilic compounds, facilitating their elimination from cells. Glutathione reductase maintains intracellular glutathione homeostasis by regenerating reduced glutathione, whereas the thioredoxin and peroxiredoxin systems regulate cellular redox balance and protect against oxidative injury. Quinone reductase contributes to the detoxification of reactive quinones, while myeloperoxidase plays an important role in immune defence through the generation of reactive oxidants. Disruption of these antioxidant systems compromises cellular defence mechanisms and increases

susceptibility to toxicant-induced oxidative damage (Halliwell & Gutteridge, 2015; Birnie-Gauvin et al., 2017).

Previous toxicological investigations have shown that lindane exposure induces oxidative stress, neurotoxicity, endocrine disruption, immunotoxicity, and metabolic dysfunction in aquatic organisms. These adverse effects arise largely from disruption of mitochondrial function, interference with cellular antioxidant systems, and excessive production of reactive oxygen species. Consequently, antioxidant enzymes have become widely accepted biomarkers for evaluating the toxicological effects of organochlorine pesticides and other environmental contaminants in fish (Lushchak, 2011; Li et al., 2021).

Acute toxicity assessment through determination of the median lethal concentration (96-h LC_{50}) remains an important approach for evaluating the immediate toxic effects of environmental contaminants. The LC_{50} provides a quantitative estimate of the concentration capable of causing mortality in 50% of exposed organisms within a specified period and serves as the basis for selecting environmentally relevant sublethal concentrations for chronic toxicity studies. The Organisation for Economic Co-operation and Development (OECD) has established standardized protocols to ensure consistency and reproducibility in aquatic toxicity testing (OECD, 2019).

Despite extensive investigations on pesticide pollution, information regarding the combined effects of lindane on multiple antioxidant defence enzymes in *Oreochromis niloticus* under both acute and prolonged sublethal exposure remains relatively limited. Understanding alterations in these enzymatic biomarkers is essential for elucidating the mechanisms of lindane-induced oxidative stress, improving ecological risk assessment, and strengthening biomonitoring programmes for contaminated aquatic ecosystems.

Therefore, this study investigated the impact of lindane exposure on antioxidant enzyme activities in *Oreochromis niloticus* by evaluating changes in glutathione S-transferase (GST), quinone reductase (QR), peroxiredoxins (Prx), thioredoxin (Trx), myeloperoxidase (MPO), and glutathione reductase (GR) following acute and sublethal exposure. The findings are expected to provide further insight into the oxidative stress mechanisms associated with lindane contamination and contribute to improved environmental monitoring, pollution management, and the protection of freshwater ecosystems.

MATERIALS AND METHODS

Materials Used

- Post-juvenile *Oreochromis niloticus* (Nile tilapia)
- Commercial fish feed (35% crude protein)
- Aerated plastic containers for transportation
- 120-liter glass aquaria
- Insulin syringes (for blood collection)
- Tricaine methanesulfonate (MS-222) for anesthesia
- Sterile collection tubes for blood
- Distilled and dechlorinated tap water

Reagents

- Lindane (technical grade for exposure)
- Sodium chloride (NaCl)
- Tris-HCl buffer (pH 7.4)
- Hydrogen peroxide (H_2O_2) for catalase assay
- Xanthine (for SOD assay)
- Glutathione (for GPx assay)
- Phosphate buffer saline (PBS)
- Superoxide dismutase (SOD) assay kit
- Catalase (CAT) assay kit
- Glutathione peroxidase (GPx) assay kit
- Trichloroacetic acid (TCA) for protein precipitation
- Bradford reagent (for protein concentration determination)

Equipment

- pH meter
- Dissolved oxygen meter
- Digital thermometer
- Water pump (for water circulation)
- Aquarium filters
- Centrifuge (for plasma separation)
- Spectrophotometer (for enzyme activity assays)
- Analytical balance (for weighing reagents and fish feed)
- Water bath (for incubation)
- Micropipettes and tips (for precise liquid measurement)

- Stirring hot plate (for reagent preparation)
- Analytical glassware (e.g., beakers, flasks, test tubes)

Evaluation of antioxidant enzymes activities in fish exposed to persistent organic pollutants

Experimental Fish and Acclimatization

Post-juvenile specimens of *Oreochromis niloticus* (Nile tilapia) were collected from a reputable private fish farm in Otuoke, Bayelsa State, Nigeria. The specimens exhibited a uniform length of 8.0 ± 1.2 cm and a weight of 20.0 ± 2.5 g. Seventy-five healthy fish were transported in aerated plastic containers to the Biology Department at the Faculty of Science, Federal University Otuoke. Upon arrival, the fish were introduced into 120-liter glass aquaria with dechlorinated tap water and allowed to acclimatise to laboratory conditions for 14 days. Throughout this period, the fish received feeding twice daily at 09:00 and 16:00 hours, utilising commercial fish feed with a composition of 35% crude protein. Feeding was suspended for 24 hours before chemical exposure to reduce metabolic waste.

Range-Finding Test and Exposure Concentrations

A preliminary range-finding test was performed to ascertain the suitable concentrations of lindane, a model persistent organic pollutant, for acute toxicity assessment. Five concentrations of lindane (1.0, 5.0, 10.0, 15.0, and 20.0 µg/L) were evaluated to determine the lower and upper thresholds for the acute test. Mortality data were collected after 96 hours to determine the concentrations for the definitive test. Three concentrations were chosen for the acute and sublethal tests based on these findings.

- **Control group**: No exposure to lindane
- **Acute test concentrations**:
- 5.0 µg/L
- 10.0 µg/L
- 15.0 µg/L
- **Sublethal test concentrations**:
- 10% of LC_{50} (1.5 µg/L)
- 20% of LC_{50} (3.0 µg/L)
- 30% of LC_{50} (4.5 µg/L)

A total of 75 fish were procured for the test, with 3 fish in each of the 4 test groups, including the control.

Acute Toxicity and LC_{50} Determination

In the acute toxicity assessment, *O. niloticus* were subjected to varying concentrations of lindane for a duration of 96 hours within a semi-static renewal system. The water in the exposure tanks was replaced every 24 hours, and deceased fish were removed and documented. Mortality data underwent probit analysis to ascertain the median lethal concentration (LC_{50}) employing the Finney method.

Sublethal Exposure Experiment

Following the acute test, fish were exposed to sublethal concentrations (10%, 20%, and 30% of the 96 h LC_{50} value) for 28 days. Each group consisted of 3 fish per tank in triplicate, totaling 48 fish for the sublethal exposure. Water quality parameters including temperature, dissolved oxygen, pH, and ammonia were monitored daily using standard protocols (APHA, 2017) and maintained within optimal limits for tilapia culture. Fish were fed twice daily as during the acclimation phase, and feeding was adjusted to 3% of body weight.

Sample Collection and Biochemical Analysis

On day 28, blood was collected via cardiac puncture to acquire a larger sample for biochemical analysis. Fish were anaesthetized with tricaine methane sulfonate (MS-222) before sampling. Blood samples underwent centrifugation at 3000 rpm for 10 minutes to facilitate plasma separation and were subsequently stored at –20°C until biochemical assays were performed.

The activities of antioxidant enzymes ; glutathione S-transferase (GST), quinone reductase (QR), peroxiredoxins (Prx), thioredoxin (Trx), myeloperoxidase (MPO), and glutathione reductase (GR) were determined using spectrophotometric methods as described by Habig *et al.* (1974) for GST, Siegel *et al.* (2000) for QR, Wood *et al.* (2003) for Prx, Holmgren (1979) for Trx, Kettle *et al*. (1994) for MPO, and Goldberg and Spooner (1983) for GR. Total protein concentration was also measured using the Biuret method for normalization of enzyme activities.

RESULTS

All of the physicochemical parameters observed in this study fall within the recommended limits for tilapia culture (Table 1)

- **Temperature**: 24°C–30°C (optimal range for tilapia)
- **pH**: 6.5–8.5 (tolerable range for tilapia)
- **Dissolved Oxygen**: 5.0 mg/L (minimum required for tilapia)
- **Ammonia**: < 0.5 mg/L (safe level for fish)

- **Salinity**: 0.1–15 ppt (acceptable for freshwater to brackish water tilapia)

Table 1: The Physico-Chemical Parameters of the test media in days.

	Day 7	Day 14	Day 21	Day 28
Parameter	**Mean ± SE)**	**Mean ± SE)**	**Mean ± SE)**	**Mean ± SE)**
Temp. (°C)	25.8 ± 0.2	26.0 ± 0.25	26.2 ± 0.3	26.4 ± 0.35
pH	7.6 ± 0.05	7.7 ± 0.05	7.8 ± 0.04	7.9 ± 0.03
DO (mg/L)	6.5 ± 0.2	6.3 ± 0.18	6.2 ± 0.2	6.1 ± 0.25
Ammonia (mg/L)	0.03 ± 0.005	0.05 ± 0.006	0.07 ± 0.007	0.09 ± 0.009
Salinity (ppt)	0.1 ± 0.02	0.2 ± 0.03	0.3 ± 0.04	0.4 ± 0.05

Antioxidant Enzymes

The activities of several antioxidant enzymes; glutathione S-transferase (GST), quinone reductase (QR), peroxiredoxins (Prx), thioredoxin (Trx), myeloperoxidase (MPO), and glutathione reductase (GR); were measured in fish exposed to varying concentrations of Lindane (Table 2)

Glutathione S-transferase

The control group exhibits peak GST activity at 5.2 units, signifying standard detoxification processes. The activity of GST exhibited a progressive decline with increasing Lindane concentration, measuring 4.8 units at 10% LC_{50}, 4.5 units at 20% LC50, and 4.2 units at 30% LC_{50}.

Quinone Reductase (QR)

In the control group, QR activity is within the normal range at 6.1 units. Groups Exposed to Lindane: The activity diminishes as Lindane concentration rises, decreasing from 5.7 units at 10% LC_{50} to 5.1 units at 30% LC_{50}.

Peroxiredoxins (Prx)

The control group exhibits a relatively high Prx activity of 4.5 units. The activity diminishes with heightened exposure, decreasing from 4.2 units at 10% LC50 to 3.8 units at 30% $LC_{50.}$

Thioredoxin (Trx)

In the control group, Trx activity is within the normal range at 5.3 units. In groups exposed to Lindane, Trx activity exhibits a slight decrease, from 5.0 units at 10% LC50 to 4.5 units at 30% LC_{50}.

Myeloperoxidase (MPO)

MPO activity is elevated at 7.2 units, indicating normal immune function in the control group. The activity exhibits a slight decline with rising Lindane concentration, decreasing from 6.9 units at 10% LC_{50} to 6.1 units at 30% LC_{50}. **Glutathione Reductase (GR)**

Glutathione Reductase (GR)

Control Group: GR activity is elevated at 6.8 units. The activity diminishes progressively as Lindane concentration increases, decreasing from 6.3 units at 10% LC_{50} to 5.7 units at 30% LC_{50}.

Table 2: Antioxidant Enzyme Activities mol/min/mg protein ± SE) in O.niloticus exposed to various concentrations of lindane in µg/L

Enzyme	Control	1.5	3.0	4.50
GST	5.2 ± 0.1	4.8 ± 0.15	4.5 ± 0.12	4.2 ± 0.14
QR	6.1 ± 0.2	5.7 ± 0.18	5.4 ± 0.17	5.1 ± 0.2
Prx	4.5 ± 0.1	4.2 ± 0.12	4.0 ± 0.13	3.8 ± 0.15
Trx	5.3 ± 0.15	5.0 ± 0.14	4.7 ± 0.16	4.5 ± 0.18
MPO	7.2 ± 0.2	6.9 ± 0.18	6.5 ± 0.17	6.1 ± 0.2
GR	6.8 ± 0.18	6.3 ± 0.16	6.0 ± 0.14	5.7 ± 0.19

DISCUSSION

The physico-chemical parameters of water are essential for the health and growth of aquatic organisms, influencing biochemical processes, behaviour, and overall well-being. This study measures parameters such as temperature, pH, dissolved oxygen (DO), ammonia, and salinity during the 28-day experimental period, alongside a comparison to established limits for aquatic environments.

Temperature (°C)

Temperature is a critical parameter in aquatic systems, as it influences metabolic rates and solubility of gases like oxygen. The temperature range observed in this study (25.8°C to 26.4°C) is within the optimal range for *Oreochromis niloticus* (Nile tilapia), which typically thrives in water temperatures between 24°C and 30°C (Popma & Masser, 1999). Higher temperatures can lead to increased metabolic rates but also decreased dissolved oxygen, which may stress the fish. The temperature is within the range for optimal tilapia growth, as per standard aquaculture practices.

pH: pH indicates the acidity or alkalinity of water. The observed pH values of 7.6 to 7.9 are slightly alkaline but still fall within the range suitable for *Oreochromis niloticus*, which prefers a pH of 6.5 to 8.5 (FAO, 2006). A pH outside this range could impair physiological

functions, including enzyme activities and oxygen utilization: The observed pH is ideal for tilapia culture, as it falls within the recommended range.

Dissolved Oxygen (DO): Dissolved oxygen is essential for cellular respiration in fish. The observed values of 6.1 to 6.5 mg/L are within the optimal range for tilapia, which requires at least 5.0 mg/L of DO for good health (De Silva & Anderson, 1995). DO levels below 3.0 mg/L can lead to hypoxia, causing stress or even death in fish. The observed DO levels are suitable for tilapia growth and are consistent with recommended aquaculture guidelines.

Ammonia (mg/L): Ammonia is toxic to fish at high concentrations, particularly in its un-ionized form (NH_3). The observed ammonia concentrations are very low and indicate that the water is relatively clean and free from excessive metabolic waste. However, concentrations exceeding 0.5 mg/L can be harmful to aquatic organisms (Eisler, 2000). The ammonia levels are well within safe limits for tilapia and other fish species, which suggests effective waste management and filtration in the experimental system.

Salinity (ppt): Salinity affects osmoregulation in fish. Nile tilapia can tolerate a range of salinities, from freshwater to brackish water (up to 15 ppt), although they are typically cultured in freshwater. The observed values of 0.1 to 0.4 ppt indicate that the water was close to freshwater, with only minor salinity fluctuations, which is not problematic for tilapia. The salinity levels are consistent with freshwater environments and do not pose any risk to the fish.

Antioxidant Enzyme Activities

Lindane is an organochlorine compound that has been utilized as an insecticide and acaricide. It is known for its effectiveness in pest control, particularly in agriculture and public health. However, concerns regarding its environmental persistence and potential health risks have led to regulatory restrictions in various countries.

The measurement of antioxidant enzyme activities in *O. niloticus* exposed to Lindane indicates a significant impairment of antioxidant defense mechanisms. The measured enzymes—glutathione S-transferase (GST), quinone reductase (QR), peroxiredoxins (Prx), thioredoxin (Trx), myeloperoxidase (MPO), and glutathione reductase (GR)—are essential elements of the cellular response to oxidative stress. The observed reduction in enzyme activities with increasing Lindane exposure indicates significant toxicological effects of this persistent organic pollutant on the antioxidant defense system in aquatic organisms.

Exposure to Lindane led to a progressive reduction in the activities of all measured antioxidant enzymes, signifying heightened oxidative stress. This indicates that Lindane exposure compromises the antioxidant defence system in fish, rendering them susceptible to

cellular damage. The fish's capacity to detoxify harmful compounds, neutralise peroxides, maintain redox balance, and respond to immune challenges is impaired. The findings underscore the toxic potential of Lindane as a persistent organic pollutant that interferes with the antioxidant defence mechanisms in aquatic organisms.

Glutathione S-transferase

GST functions as a phase II detoxification enzyme, facilitating the conjugation of glutathione (GSH) with xenobiotics, such as reactive oxygen species (ROS), which mitigates their toxicity (Hayes *et al*., 2005). This process enhances the water solubility of toxic compounds, facilitating their excretion. This study demonstrates a significant reduction in GST activity with escalating concentrations of Lindane, decreasing from 5.2 units in the control group to 4.2 units at the highest concentration (30% LC_{50}). This finding is consistent with earlier research indicating a decrease in GST activity following exposure to pesticides and other pollutants, suggesting a diminished capacity to detoxify harmful compounds (Cui et al., 2009). Lindane exposure inhibits GST activity, thereby diminishing the fish's capacity to conjugate and eliminate toxic metabolites, potentially resulting in the accumulation of harmful compounds in tissues.

Quinone Reductase

QR is essential for safeguarding cells against oxidative damage by converting quinones into less reactive forms, which helps to inhibit the generation of reactive oxygen species (ROS) and maintain cellular integrity (Siegel *et al.,* 2000). This study observed a reduction in QR activity from 6.1 units in the control group to 5.1 units at the maximum Lindane concentration. The reduction in QR activity indicates that Lindane exposure impairs the fish's capacity to mitigate toxic quinones, resulting in heightened oxidative stress. The reduction in QR activity may also lead to a decrease in the fish's antioxidant capacity, increasing its susceptibility to additional oxidative damage.

Peroxiredoxins

The findings indicate a reduction in Prx activity, decreasing from 4.5 units in the control group to 3.8 units at the maximum Lindane concentration. The decrease in Prx activity indicates that Lindane exposure hinders the fish's capacity to neutralise reactive peroxides, consequently enhancing oxidative damage to proteins, lipids, and DNA. Other studies have reported similar findings regarding pollutants, indicating that decreased Prx activity is associated with increased oxidative damage (Zhang *et al*., 2006).

Thioredoxin

Trx is a crucial protein that maintains redox homeostasis by reducing oxidised molecules, such as proteins, and regulating the activity of various antioxidant enzymes. The present study indicates a reduction in Trx activity from 5.3 units in the control group to 4.5 units at the maximum Lindane concentration. The observed decrease indicates that Lindane exposure interferes with the redox balance in fish by inhibiting Trx activity, essential for sustaining cellular antioxidant defences (Holmgren, 1979). Research indicates that environmental contaminants, such as heavy metals and pesticides, diminish Trx activity, resulting in compromised redox regulation (Petrakis *et al.,* 2017).

Myeloperoxidase

MPO plays a role in the production of reactive oxygen species (ROS) as a defence mechanism against pathogens. Excessive MPO activity may contribute to inflammation and oxidative damage. This study observed a reduction in MPO activity from 7.2 units in the control group to 6.1 units at the highest concentration of Lindane. The observed reduction in MPO activity indicates that Lindane exposure may compromise immune responses, thereby increasing the fish's vulnerability to infections and oxidative stress. MPO activity decreases in response to toxicants like pesticides, which impair immune function (Kettle *et al.,* 1994).

Glutathione Reductase

Glutathione reductase (GR) plays a vital role in the cellular antioxidant system by reducing oxidised glutathione (GSSG) to its reduced form (GSH), a primary antioxidant within cells. The findings indicate a reduction in GR activity, decreasing from 6.8 units in the control group to 5.7 units at the maximum Lindane concentration. The observed decrease indicates that Lindane exposure hinders the fish's capacity to regenerate GSH, consequently compromising its overall antioxidant defence system. The decrease in GR activity aligns with earlier research indicating comparable reductions in GR activity after exposure to different environmental pollutants, such as heavy metals and pesticides (Sarkar *et al*., 2008).

CONCLUSION

This study's results indicate that exposure to Lindane, a persistent organic pollutant, significantly disrupts the antioxidant defence system in Oreochromis niloticus (Nile tilapia). The activity of the measured antioxidant enzymes—glutathione S-transferase (GST), quinone reductase (QR), peroxiredoxins (Prx), thioredoxin (Trx), myeloperoxidase (MPO), and glutathione reductase (GR)—exhibited a progressive decline with increasing Lindane

concentration. The observed decline reflects oxidative stress caused by Lindane, surpassing the fish's capacity to neutralise harmful reactive oxygen species (ROS) and detoxify xenobiotics.

The reduction in antioxidant enzyme activities indicates that Lindane exposure impairs detoxification processes and immune functions in fish, resulting in heightened susceptibility to oxidative damage. The findings emphasise the toxicological effects of Lindane on aquatic organisms, indicating the necessity for rigorous environmental monitoring and regulation of pollutants in aquatic ecosystems.

Recommendation

Environmental Monitoring and Regulation: The substantial impact of Lindane exposure on fish health necessitates enhanced monitoring of persistent organic pollutants (POPs) in aquatic environments, particularly in areas characterised by intensive agricultural practices. Regulatory frameworks must be developed to restrict harmful chemicals in aquatic ecosystems, thereby safeguarding biodiversity and ensuring the sustainability of fisheries.

Additional Investigation into Mechanisms of Action: Additional research is required to investigate the mechanisms of Lindane toxicity at cellular and molecular levels, especially its interactions with other environmental stressors. Examining the interactions between Lindane and additional pollutants on the antioxidant defence system will enhance the understanding of the synergistic effects of pollutants in aquatic organisms.

Restoration and Conservation Efforts: To address the effects of pollutants such as Lindane, restoration and conservation initiatives must prioritise the rehabilitation of contaminated aquatic ecosystems. This involves the implementation of bioremediation strategies, the enhancement of water quality, and the establishment of conservation areas to limit exposure to toxic substances.

Raising awareness: Raising awareness among local communities, aquaculture farmers, and policy-makers regarding the risks associated with Lindane and other pesticides is crucial. Instruction on appropriate chemical usage, integrated pest management, and the significance of preserving clean aquatic ecosystems will aid in decreasing pollution levels in water bodies.

Alternatives to Harmful Chemicals: The detrimental impact of Lindane on aquatic life necessitates the exploration and promotion of safer alternatives in pest management practices.

Prioritising substitutes like biological control agents and eco-friendly pesticides in agricultural practices is essential for minimising the environmental impact of harmful chemicals

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