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Occurrence, Environmental Fate and Toxicological Effects of Nonylphenol Ethoxylates in Aquatic Organisms: A Comprehensive Review

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ABSTRACT:

Nonylphenol ethoxylates (NPEs) are one of the major non-ionic surfactants that have been used extensively in a wide variety of industries such as detergent manufacture, textile processing, pesticide manufacturing and cleaning products. The large-scale global use of NPEs is the main reason for their continuous and significant discharge into the water bodies through the effluents from the municipal and the industrial wastewater treatment plants. Environmental monitoring data show that the concentrations of total NPEs in untreated sewage are usually between 1 and 12 mg L^{-1}, while the levels of NPEs in surface waters that are discharged with treated effluents are between 0.05 and 5.0 µg L^{-1}. One of the major environmental concerns linked to NPEs is their partial biodegradation, where these substances are transformed only slightly by microorganisms producing lesser chain ethoxylates and eventually nearly nonylphenol (NP), a metabolite significantly more persistent and toxic than the parent compounds. Nonylphenol is a highly hydrophobic compound with octanol-water partition coefficients (log K_ow) of about 4.5 to 4.8, thus leading to strong bioaccumulation in aquatic organisms, which has been observed with bioconcentration factors of 1,000 to 10,000 depending on the species and environmental conditions. Long-term exposure to NPEs and their degradation products at environmentally relevant concentrations causes wide-ranging adverse effects like unpleasant smell, endocrine system disruption, reproductive failure, oxidative stress, and δ2H and δ18O ratios indicative of developmental abnormalities in fish and invertebrate populations. This in-depth review gives a critical analysis of the prevailing understanding of the environmental occurrence, fate processes, and bioaccumulation of NPEs and their transformation products in aquatic organisms, *particularly focusing on the endocrine-disrupting properties that are a risk even at very low environmental concentrations.*

Keywords: *Nonylphenol Ethoxylates, Substance, Environmental Fate, Aquatic Organisms*

1. INTRODUCTION:

Nonylphenol ethoxylates are those non-ionic surfactants, which comprise a huge class that has been utilized in industrial chemistry and commercial applications for quite a while. The share of these compounds in total global surfactant production is about 10 to 15%, which is quite a lot reflecting their use in many different industries. The historical records show that the yearly global demand for NPEs was more than 500,000 tons consistently, and the main areas of use were in industrial manufacturing processes, agricultural chemicals, cleaning in institutions, and textile processing. The usage of NPEs is so widespread because of their outstanding surfactant properties such as very good wetting, emulsifying, and chemical stability in different operational conditions. Even though regulatory restrictions and voluntary phase-out programs have been put in place in several areas such as the European Union, North America, and parts of Asia, NPEs are still found in aquatic ecosystems across the globe at such levels that their presence is a concern from an environmental point of view. NPE contamination is still a major issue because of both the previous use of NPE and the current use in areas where control is either weak or non-existent. NPEs are not like the easily biodegradable surfactants which include alcohol ethoxylates or linear alkylbenzene sulphonates in that they are not completely removed by microorganisms in both engineered treatment systems and natural environments. Eventually, the generated persistent metabolites include nonylphenol mono-, di-ethoxylates and ultimately free nonylphenol itself.

NPE degradation products, nonylphenol in particular, have significant environmental and toxicological implications and their importance is hard to downplay. The metabolites of the compound are extremely active in terms of mimicking the natural hormone estrogen and also very toxic to fishes and other aquatic life even at concentrations less than 1 μg L^{-1} which is the level commonly found in surface waters contaminated from wastewater discharges. Nonylphenol's estrogenic activity, which came to light in the early 90s, is a perfect example of how incomplete contamination reduction can paradoxically elevate rather than mitigate the environmental risk. This occurrence has had a profound effect on the regulation of surfactants and consequently on the necessity to evaluate both the parent compounds as well as their transformation products for ecological assessment has been brought out very clearly.

2. Occurrence of NPEs in Aquatic Environments

2.1 Wastewater Influents and Treatment Plant Effluents

NPEs are mainly introduced into aquatic ecosystems via municipal and industrial wastewater streams. The sewage from the different industries and the population's wastewater arriving at treatment plants usually contains NPE levels of 1 to 12 mg L^{-1}, where the differences in levels are due to the various factors such as the industries involved, the number of people served, and the extent of NPE usage in the watershed supplying the sewage. Through a combination of primary sedimentation, biological treatment in activated sludge systems, and secondary clarification, the conventional wastewater treatment processes facilitate significant reductions in total NPE concentrations by the combined actions of biodegradation, volatilization, and sorption to sewage sludge. However, the removal efficiencies are usually only between 60 and 85 percent, which indicates that a considerable amount of NPE and its degradation products escapes treatment and is discharged into the waters receiving treatment plant effluent.

Municipal wastewater treatment plants still release on the Gills and Pulp Mills NPE and nonylphenol in the range of 0.1 to 2.5 μg L^{-1}, thus these discharges are permanent relics of the past that are characterized by their high contaminating power for the aquatic ecosystems living downstream. The inadequacy of the removals points to both the slow rate of biodegradation processes under typical treatment plant hydraulic retention times and the strong resistance of shorter-chain ethoxylates and nonylphenol to further microbial transformation as the reasons. Consequently, on the one hand, large industrial establishments which make use of NPEs as part of their manufacturing process may discharge wastewaters with very high concentrations, especially in cases where no further treatment has been done before direct discharge, or when industrial wastewater is made to go through the municipal treatment plant during combined sewer overflow events.

2.2 Surface Water and Sediment Contamination

Urban/rural rivers, streams and lakes are contaminated with NPEs due to the the combination of all the influences of point source discharges, diffuse urban runoff and watershed inputs from upstream. Monitoring studies of surface water have been done in many different geographical places and the results indicate NPE concentration levels between 0.02 to 5.0 μg L^{-1}, although the most common measurements are the ones that show 0.2 to 1.0 μg L^{-1}. There is a marked spatial variability between the concentrations of surface water, where the highest concentrations can be found right downstream of the wastewater treatment plants' discharge points, and there is a decrease of concentration happening with the distance, which is mainly due to dilution and degradation processes in the water.

Sediment compartments are characterized by their nonylphenol and NPE concentrations that are significantly higher than those in the water column above them. This is a clear reflection of the very strong hydrophobic nature of these compounds and their selective partitioning to organic matter in the form of particles. Concentrations in the sediments are frequently described to be between 100 and 5,000 μg kg^{-1} dry weight; however, very polluted areas close to industrial outlets may have concentrations as high as 10,000 μg kg^{-1} or more. The deposition of these substances in sediments leads to the formation of a contamination reservoir that is difficult to eliminate and can therefore change the composition of the benthic community and be a long-term source of water column contamination through periodic resuspension and gradual desorption. The preferential sediment accumulation of contaminant also leads to extremely high exposure conditions for benthic invertebrates and bottom-feeding fish species, which are constantly in contact with the contaminated sediment surfaces.

2.3 Contamination in Aquatic Biota

Aquatic life forms habitually gather NPEs along with their degradation products from water and food, thus evolving tissue concentrations that are much higher than the water around them. Concentration ranges from 50 to 3,000 μg kg^{-1} wet weight depending on the species, duration of exposure, trophic position, and local pollution levels are common in the field monitoring studies that have been carried out to determine the amounts of NPE and nonylphenol in fish tissues, mollusks, and benthic invertebrates. The presence of these substances in aquatic organisms at such high levels raises not only the question of the health impact on the organisms that are directly exposed but also the issue of human dietary exposure through the consumption of contaminated fish and shellfish.

Table 1: NPE and NP concentrations in different compartments.

Environmental Matrix	Concentration Range	Typical Values	Key Characteristics
Untreated Wastewater	1–12 mg L^{-1}	3–6 mg L^{-1}	Primary source material
Treated Effluent	0.1–2.5 µg L^{-1}	0.5–1.5 µg L^{-1}	60–85% removal efficiency
Surface Waters (urban)	0.02–5.0 µg L^{-1}	0.2–1.0 µg L^{-1}	Continuous discharge impact
Sediments	100–5,000 µg kg^{-1}	500–2,000 µg kg^{-1}	Strong sorption accumulation
Aquatic Biota	50–3,000 µg kg^{-1}	200–1,000 µg kg^{-1}	Bioaccumulation in tissues

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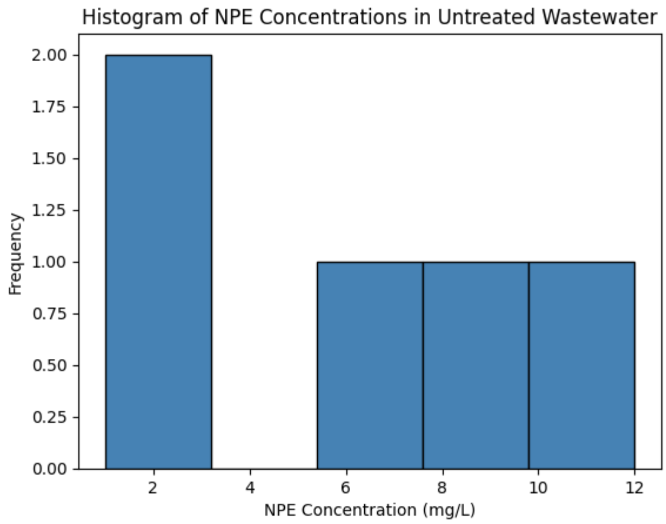


On the other hand, untreated wastewater is subdivided into classes.

3. Environmental Fate and Transformation Processes

3.1 Biodegradation Pathways and Kinetics

The microbial biodegradation processes are the primary reason for the environmental fate of NPEs, and they run through the sequential removal of ethoxylate units from the polyethylene oxide chain. In aerobic environments, such as well-operated wastewater treatment systems and oxygenated surface waters, NPEs are gradually shortened through an enzymatic process that is catalyzed by alcohol dehydrogenase and other enzymes made by the bacterial communities that have adapted to the environment. The microbial degradation of NPEs that have long chains of 9 to 15 ethylene oxide units goes on at a fairly fast pace, with half-lives of 1 to 7 days under favorable environmental conditions. When the alkyl chain becomes shorter, however, the degradation rate drops significantly and the route typically stops at nonylphenol mono- and di-ethoxylates rather than going on to complete mineralization.

The terminal degradation products that are hard to get rid of, especially the nonylphenol that is free and produced by breaking down the last ethoxylate units, behave in a very distinct manner in the environment when compared to the original NPE compounds. The nonylphenol which is produced during aerobic degradation has been found to be much less affected by the environment giving it a very long environmental half-life in some cases of 30 to 90 days if the sediments are not very well oxygenated. Aerobic conditions, which are found in deeper sediment layers, sewage sludge digesters, and oxygen-depleted hypolimnetic waters, NPE degradation through the slowest alternative microbial pathways is still very much alive. Parent NPE compounds have been estimated to have a half-life of 20 to 60 days under anaerobic conditions while nonylphenol has an even longer vegetable life under these conditions with its being degraded almost completely arrested in the absence of molecular oxygen.

The pattern of degradation not going to completion creates a toxicological paradox where the processes of wastewater treatment and natural attenuation do not eliminate the environmental risk but rather change the parent chemicals that are less toxic to the more toxic and more persistent metabolites. The environmental impact of this inversion is so great that nonylphenol, the transformed product, is immensely more hydrophobic, stronger in bioaccumulation and more damaging in endocrine activity than the original NPE surfactants. This occurrence has huge consequences for environmental risk assessment and regulatory decision-making, thus, it is required to take the transformation products along with the parent compounds while determining the environmental safety of chemical substances.

3.2 Sorption Behavior and Environmental Transport

Nonylphenol has shown an amazing power to cling to another hydrophobic nature and thus can be described as a very 'sticky' compound. Its octanol-water partition coefficients range from 4.5 to 4.8 in log K_ow values, indicating a strong preference for the organic phase over the aqueous one. This non-polar character is illustrated by the sediment-water partition coefficients of 2,000 to 20,000 liters per kilogram, which are exceedingly higher than the values of more polar surfactants, for instance, linear alkylbenzene sulphonates. It has been over found from the studies that nonylphenol has great impacts on the environment distribution because of its strong adsorption behavior; thus, the main part of its mass present in the aquatic system is located not in the dissolved aqueous phase but in sediment and suspended particle compartments.

The partitioning effect is a phenomenon that is capable of changing the ecosystem in number of ways. First and foremost, the organisms that are in direct contact with the sediment like those of the benthic community i.e., invertebrates and some fish species, get higher concentration of the substance than what water column measurement would suggest. Second, the sediment buildup acts as a source of contamination that is persistent and may still affect water quality long after the external inputs have been reduced or cut off. Thirdly, the strong particle association allows the nonylphenol to be transported over long distances through the movement of suspended sediments during high-flow events, possibly leading to the contamination areas being far away from the original source areas. Fourth, the potential for organisms that intake sediment particles or prey living in the sediments to be exposed through diet is greater than that of direct uptake from water.

4. Bioaccumulation and Biomagnification Potential

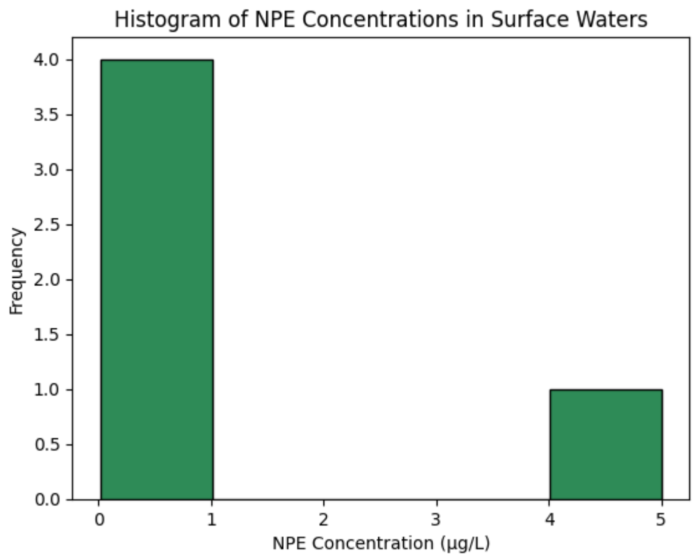
The bioaccumulation of nonylphenol, one of the NPE degradation products, is an ecological problem of mainly the things that cause it: very high hydrophobicity, long metabolic life, and constant exposure in the environment. Bioconcentration factors, which measure the concentration ratio of an organism's tissue to ambient water at equilibrium, are shown to be very different depending on the groups of organisms and environmental conditions. Fish species have been reported with BCF values for nonylphenol that are usually between 500 and 2,000, which implies a potential for moderate to high bioaccumulation. Invertebrate organisms, on the other hand, are already a step ahead in terms of the amounts they can accumulate, with the BCF values for mollusks (clams and mussels) and crustaceans (amphipods and crayfish) being 1,000 to 10,000 in most cases.

One of the most important issues regarding the ability of aquatic food webs to biomagnify is the differential bioaccumulation throughout the different trophic levels. The term biomagnification refers to the increase in the concentration of pollutants in the food chain as you go higher up the trophic levels and has been documented for nonylphenol in numerous studies of aquatic food webs. Reports have indicated that trophic magnification factors of above 1.2 to 1.8 are possible, which means that the predators that eat contaminated prey may end up having higher tissue concentrations than those in their food sources. This potential for biomagnification is indeed lower than that of persistent organic pollutants like PCBs and mercury, however, it still signifies that the highest predators like fish and birds that feed on fish may receive much larger doses through their diets.

The kinetics of bioaccumulation and depuration are factors that influence organism exposure profiles as well. Nonylphenol ingestion through both water and food is done in a relatively fast manner, and bioconcentration factors almost reach steady state in continuous exposure of 7 to 21 days which varies with species and environmental conditions. Depuration is slower after the transfer to clean conditions, and the half-lives for elimination range from 5 to 15 days. The difference between quick uptake and slow elimination creates a situation where net accumulation is possible under conditions of continuous or intermittent environmental exposure that are typical of systems impacted by wastewater.

Table 2: Cave sediment was revealingly a high-priority habitus for filling, and, importantly with negligible speed, Endeavor was on a trill to gather it.

Organism Group	BCF Range	Typical BCF	Primary Accumulation Tissues
Fish (various species)	500–2,000	1,000–1,500	Liver, adipose tissue, muscle
Mollusks (bivalves)	1,000–10,000	3,000–6,000	Digestive gland, gills
Crustaceans	1,000–8,000	2,000–4,000	Hepatopancreas, muscle
Aquatic Insects	500–3,000	1,000–2,000	Whole body



The possible reasons for the peak of enterococci at 1100 m, reflected in the rather high values of P31, is mainly due to: had killed cattle and sheep, dung, and drinking systems.

5. Toxicological Effects on Aquatic Organisms

5.1 Acute Toxicity Profiles

The performance of acute toxicity tests offers the first essential data on the lowest concentrations of nonylphenol and its derivatives which cause either instant harmful effects or the death of living organisms that have been subjected to its exposure. The laboratory standard 96-hour LC_{50} values for nonylphenol, potent enough to kill half of the fish in the specific species tested, are usually in the range of 0.2 to 1.0 mg L^{-1}, with the variation being the outcome of the sensitivity of the species, their life stage, and the conditions under which the test is performed. Sensitivity of invertebrate organisms is a little bit more than that of fish, with the 48-hour median effect concentrations (EC_{50}) for the water flea Daphnia magna lying between 0.1 and 0.3 mg L^{-1}. The primary producers, that is, the green algae and the diatoms, are found to have acute toxicity thresholds that are in the range of 0.05 to 0.2 mg L^{-1}, through the use of 72-hour growth inhibition trials as their method of testing.

Although these values for acute toxicity are important reference points, they are very far from the actual ecological risks of nonylphenol in the environment. In most cases, the environmental concentrations are between 0.02 and 5.0 µg L^{-1}, which are 100 to 10,000 times smaller than the thresholds for acute toxicity. Notwithstanding, chronic exposure to these sub-acute concentrations causes a variety of physiological and reproductive effects which may be of the same or even greater ecological importance than acute mortality. The parent NPE compounds, on the one hand, are less acutely toxic than nonylphenol; on the other hand, their environmental significance is mainly due to their being the precursors of the more toxic degradation product rather than being the less toxic ethoxylated forms.

5.2 Endocrine Disruption and Reproductive Impairment

The capacity of nonylphenol to mimic the natural estrogen hormones and disrupt the normal endocrines in the aquatic organisms at extraordinarily low concentrations is the most important environmental property of nonylphenol. The substance binds to the estrogen receptors of fish though with a significantly low affinity when compared to natural 17β-estradiol and then activates the signaling pathways that are responsible for reproduction which include stages like development, sexual differentiation, and gamete production. Even, the fish that are most sensitive to the chemical will show measurable endocrine responses to nonylphenol concentrations of just 0.01 to 0.1 μg L^{-1}, which are levels that typically occur in surface waters that receive wastewater discharges.

One of the most important and extensively studied markers of estrogenic exposure is the synthesis of vitellogenin in male fish. Vitellogenin is an egg yolk precursor protein which is generally synthesized only in adult females and only under the influence of estrogens. But, male fish that are subjected to the estrogenic substances such as nonylphenol synthesize vitellogenin in excess; the level in plasma of these males can be 5 to 50 times higher than in normal males. This disallowed vitellogenin production points out clearly the exposure to estrogens and also indicates a disruption of endocrine regulation. Nonylphenol exposure has been demonstrated to produce not only the above-mentioned biochemical marker but also functional reproductive impairments such as decreased gonadosomatic indices (gonad weight in relation to body weight) by 20 to 40 percent, which in turn indicates the gonadal development and the number of gametes produced have decreased.

Among the population-level effects of endocrine disruption are changed sex ratios which enhance the feminization of affected populations, resulting in an increase of phenotypic females and intersex individuals containing both male and female reproductive tissues. A long duration of exposure studies carried out through entire reproductive cycles have shown that the presence of nonylphenol at levels less than 1 μg L^{-1} can lead to a considerable decrease in reproductive output, a postponement of sexual maturation and a change in spawning behavior. It is overstated that these reproductive impairments, if continued for several generations, will result in lower recruitment of the population and changed demographic structure thus making chronic contamination systems an area of concern in terms of sustainability of the population.

5.3 Chronic and Sub-lethal Physiological Effects

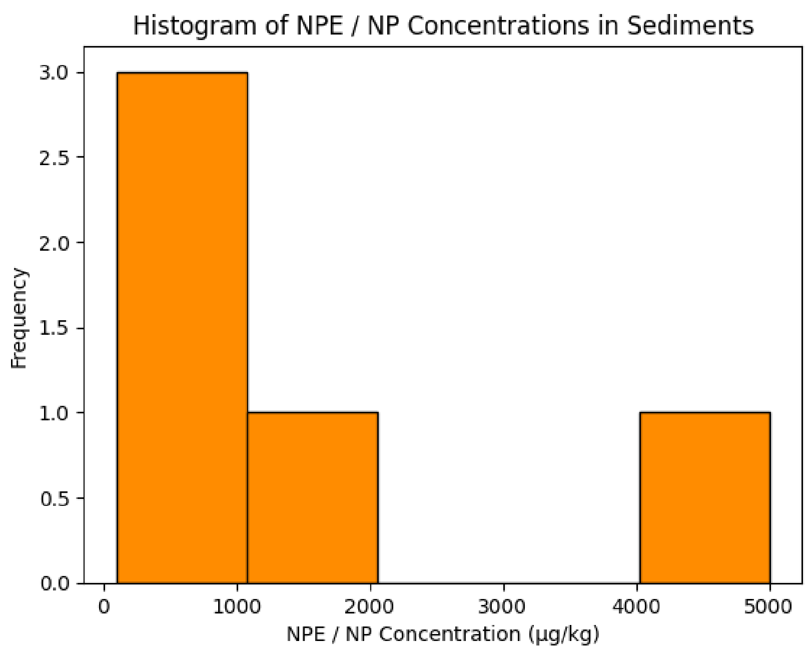
Aside from the endocrine disruptor part, continuous contact with nonylphenol at concentrations relevant to the environment has a variety of effects on fish growth, oxidative stress responses and immune function, all being sub-lethal. For instance, fish that were continually exposed to 0.005 to 0.05 μg L^{-1} of nonylphenol for 30 to 90 days, showed a decrease in weight and length of 15 to 30 percent when compared to the unexposed fish. The growth impairment is a sign of several mechanisms operating underneath, including reduced feeding efficiency, increased metabolic costs linked to detoxification process and likely disruption of growth hormone signaling pathways.

On the cellular level, the presence of nonylphenol causes oxidative stress by producing reactive oxygen species and disrupting the antioxidant defense mechanisms. Through biochemical analysis, it is disclosed that oxidative stress markers rise in the fish's liver and gill tissues by 40 to 70 percent and these markers are lipid peroxidation products, protein carbonyls, and DNA oxidation. At the same time, the responses of antioxidant enzyme activities differ, as some research indicates compensatory increases while others report depletion indicating overwhelmed defense capacity. Prolonged oxidative stress leads to cellular damage, faster aging processes, and even cancerous transformation as possible outcomes.

The chronic exposure to nonylphenol has been shown to affect the immune system's performance as the immune cell counts, antibody production, and disease resistance capacity have reduced by 25 to 35 percent. Such immune suppression causes bacteria, virus, and parasite infections to take place more easily and could even lower the survival chances in wild habitats where exposure to pathogens is constant. The exposure at early life stages during the embryo and larval development has the most severe consequences such as hatching time being one to three days delayed, 10 to 25 percent of larvae being malformed, and the swimming ability of larvae being reduced which thus making them more susceptible to predators.

Table 3: Aquatic Organism Effects: Toxicology of Nonylphenol

Effect Category	Effective Concentration	Effect Magnitude	Ecological Significance
Acute Toxicity (Fish LC_{50})	0.2–1.0 mg L^{-1}	50% mortality	Rare under environmental conditions
Vitellogenin Induction (males)	0.01–0.1 µg L^{-1}	5–50 fold increase	Endocrine disruption indicator
Gonadosomatic Index Reduction	0.1–1.0 µg L^{-1}	20–40% decrease	Reproductive capacity impairment
Growth Rate Reduction	0.005–0.05 µg L^{-1}	15–30% decrease	Population fitness reduction
Oxidative Stress Elevation	0.01–0.1 µg L^{-1}	40–70% increase	Cellular damage potential
Immune Response Suppression	0.05–0.5 µg L^{-1}	25–35% decrease	Disease susceptibility increase
Developmental Abnormalities	0.01–0.1 µg L^{-1}	10–25% larvae affected	Early life stage survival reduction



In order to quantify the distribution of different kinds of phosphorous in varied stages of sediments along the Jianyang canal, which beckons for further investigation.

6. Ecological Risk Assessment

A complete ecological risk assessment combines the data of environmental presence, organism exposure and toxicological effects to evaluate the risk and the impact of negative ecological situations. The risk characterization of nonylphenol applied to freshwater ecosystems usually employs the risk quotient approach, whereby the predicted environmental concentrations that are based on the monitoring data are compared with the predicted no-effect concentrations established from toxicity tests. Through extensive surface water monitoring in various geographical areas, the predicted environmental concentration of 1 μg L^{-1} can be taken as a reasonable estimate for urban rivers with moderate pollution. The predicted no-effect concentration, which is obtained by applying safety factors to chronic toxicity endpoints for sensitive species and life stages, is usually set at 0.1 μg L^{-1} or even lower.

The risk quotient derived as a fraction of predictive environmental concentration over predictive no-effect concentration gives a figure of 10 for common urban freshwater systems. Regular risk assessment frameworks assert that risk quotient values greater than 1 denote possible ecological issues that need to be assessed further, while values more than 5 imply high ecological risk that calls for management action. The computed risk quotient of 10 for nonylphenol shows enormous overshooting of the allowed exposure limits and reaffirms considerable risk to fish, mainly with respect to their reproductive ability and the development of the first stages of life.

The conclusion of the risk assessment receives additional backing from field evidence derived from persistently polluted systems where fish populations show disruption communication between the endocrine system and the ovaries, change in gender ratios, and reproductive problems that are in accordance with laboratory-derived predictions. The integration of laboratory toxicity data, environmental monitoring data, and field effects data for organisms provides strong and persuasive proof that nonylphenol contamination is an environmental concern which is large enough to warrant regulatory measures and clean-up operations. The extraordinary sensitivity of reproductive parameters, along with the possibility of low-level chronic exposure having an impact on population structure over many generations, makes nonylphenol an important substance that needs to be controlled in order to protect aquatic ecosystems.

Critical Risk Factors: The ecological risk associated with nonylphenol is increased by a number of factors: (1) the contradictory conversion of the parent compound to its less toxic metabolites during biodegradation, (2) the extremely low levels at which endocrine disruption occurs, (3) the global extent of occurrence in wastewater-impacted ecosystems, (4) the considerable capacity for bioaccumulation that leads to dietary exposure, and (5) the multigenerational reproductive effects that limit the population sustainability.

7. Conclusion

In all aquatic environments all over the world, nonylphenol ethoxylates and their environmental degradation products are still the most persistent and troublesome contaminants. In some places, there are laws to limit their use, and during the process of wastewater treatment, part of it gets biodegraded, but the formation of nonylphenol through incomplete microbial transformation paradoxically leads to increased ecological risk because it is more persistent, more easily accumulated in organisms, and more potent as an endocrine disruptor. Regular monitoring of the environment always shows that nonylphenol, even in concentrations of low microgram-per-liter or sub-microgram-per-liter, has a chronic toxic effect on aquatic organisms, especially by interfering with hormonal control, causing reproductive failure, altering sex ratios, and reducing population fitness.

The excellent hydrophobicity of nonylphenol contributes to its accumulation in sediments and the aquatic biota, hence, forming long-term contamination reservoirs that spread the effect of the nonylphenol pollution to the benthic organisms and the higher trophic levels long after the inputs have been reduced. The bioaccumulation factors for invertebrates and fish that soar to several thousand, along with the proof of trophic magnification, emphasize the danger of food-web transfer and the possible consequences for wildlife and human consumers of aquatic organisms. It is worth noting that traditional wastewater treatment processes, though quite efficient in lowering total NPE loads, cannot stop the generation and release of even more toxic transformation products, revealing a significant shortcoming in the existing pollution control strategies.

From a toxicological point of view, the pre-eminence of sub-lethal and endocrine-mediated effects over acute toxicity points out the traditional risk assessments based merely on mortality endpoints as insufficient. The induction of vitellogenin in male fish, gonadal degeneration, reduced fecundity, and developmental abnormalities at concentrations pertinent to the environment signify that the presence of nonylphenol in the water is a great risk for aquatic populations' long-term sustainability instead of causing an ecological disaster that happened suddenly. These chronic effects, though not very clear, could slowly lead to the loss of biodiversity and the weakening of ecosystem resilience.

This review reveals the dire need for a comprehensive management approach that takes into account the parent compounds as well as their transformation products in the safety evaluation of the environment. The complete mineralization of wastewater through advanced treatment technologies, the establishment of stricter regulatory frameworks in regions where NPE use is still allowed, and the continual monitoring of water and sediment are some of the measures that will be necessary to prevent future risks. It is likely that the ecological burden of NPE contamination will continue to be a considerable and underestimated threat to aquatic ecosystems globally unless the persistence and endocrine-disrupting property of nonylphenol are tackled.

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