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Study of Degradation of Pharmaceutical Wastes in Water and Its Impact on Ecosystems

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Abstract:* *Pharmaceutical active ingredients (PhACs) are increasingly detected in surface water, groundwater, and wastewater systems worldwide due to continuous consumption, incomplete metabolism, and inadequate removal during wastewater treatment. This manuscript evaluates the occurrence, degradation pathways, and ecological impacts of pharmaceutical wastes in aquatic environments using published global monitoring data. Statistical evaluation of reported concentrations, wastewater treatment plant (WWTP) removal efficiencies, and ecological risk indicators is presented. Results indicate that several commonly used pharmaceuticals persist at ng/L–µg/L levels, with approximately one-quarter of monitored sites globally exceeding predicted no-effect concentrations (PNECs). Conventional WWTPs show variable removal efficiencies (10–80%), while advanced treatment technologies can achieve removals exceeding 90%. Ecological evaluation highlights chronic sub-lethal effects on aquatic organisms and increasing risks of antimicrobial resistance. Statistical analyses, including analysis of variance (ANOVA), regression modelling, and ecological risk assessment using risk quotients (RQ), were employed to evaluate spatial, seasonal, and anthropogenic influences. Results demonstrate significant seasonal variability ($p < 0.05$), strong correlation between population density and pharmaceutical concentrations ($R^2 \approx 0.7$), and moderate to high ecological risk for antibiotics and antiepileptics. The findings highlight the limitations of conventional treatment systems and emphasize the need for advanced treatment technologies and regulatory interventions to mitigate ecological risks. The study emphasizes the need for standardized monitoring, mixture toxicity assessment, and integration of advanced treatment technologies to mitigate pharmaceutical pollution.

Keywords*— *Pharmaceutical pollution, wastewater treatment, degradation, aquatic ecosystems, ecological risk, statistical evaluation

I. INTRODUCTION

Pharmaceutical compounds are designed to exert biological activity at low doses; however, these same properties make them emerging environmental contaminants when released into aquatic systems. Pharmaceuticals enter water bodies primarily through wastewater effluents, improper disposal, hospital discharges, and pharmaceutical manufacturing activities. Unlike conventional pollutants, pharmaceuticals are continuously introduced, resulting in pseudo-persistent exposure conditions. Numerous studies have confirmed their global occurrence and potential ecological risks, necessitating a comprehensive evaluation of their degradation behaviour and ecosystem impacts.

II. REVIEW OF RELEVANT TECHNOLOGIES

2.1. Occurrence of Pharmaceutical Wastes in Aquatic Environments

Major sources of pharmaceutical contamination include:

- Municipal wastewater effluents
- Hospital and clinical discharges
- Pharmaceutical manufacturing units
- Improper disposal of unused medicines

Large-scale monitoring studies have confirmed the ubiquitous presence of pharmaceuticals in rivers worldwide. Detected compounds commonly include analgesics, antibiotics, antiepileptics, antidepressants, and antidiabetics. Concentrations typically range from a few ng/L to several µg/L, with higher values reported near urban centres and regions lacking adequate wastewater treatment infrastructure.

Table 1: Global Concentration Ranges of Selected Pharmaceuticals in Surface Waters

Pharmaceutical	Therapeutic Class	Reported Range (ng/L)
Carbamazepine	Antiepileptic	10 – 5000
Diclofenac	NSAID	5 – 3000
Ibuprofen	NSAID	20 – 10,000
Ciprofloxacin	Antibiotic	5 – 6500
Sulfamethoxazole	Antibiotic	10 – 4000
Fluoxetine	Antidepressant	1 – 800
Metformin	Antidiabetic	50 – 50,000

Antibiotics and NSAIDs dominate environmental detections, often accounting for over 60% of total pharmaceutical loads.

2.2. Degradation Pathways of Pharmaceuticals in Water

Pharmaceutical degradation in aquatic systems occurs via photolysis, biodegradation, hydrolysis, and oxidation. Photodegradation is effective for compounds such as diclofenac under sunlight, while biodegradation dominates in WWTPs and sediments. However, several pharmaceuticals exhibit strong resistance to microbial breakdown, leading to persistence. Degradation often produces transformation products, some of which retain biological activity or enhanced toxicity.

Pharmaceutical degradation occurs through:

- Biodegradation (microbial metabolism)
- Photodegradation (UV radiation)
- Hydrolysis
- Advanced oxidation processes (AOPs) in engineered systems

However, several compounds (e.g., carbamazepine) are highly persistent, exhibiting half-lives exceeding 100 days in aquatic environments.

2.3. Wastewater Treatment Plant Removal Efficiencies

Conventional wastewater treatment processes show compound-specific removal efficiencies. Persistent compounds such as carbamazepine exhibit poor removal, while biodegradable compounds are partially eliminated. Advanced treatment technologies significantly improve removal.

Table 2: Removal Efficiencies of Pharmaceuticals in Wastewater Treatment Processes

Treatment Process	Removal Efficiency (%)
Primary treatment	0 – 20
Activated sludge	10 – 80
Constructed wetlands	30 – 70
Ozonation	70 – 99
Advanced oxidation processes	60 – 99
Reverse osmosis	>90

2.4. Ecological Impact and Risk Evaluation

Pharmaceutical residues pose chronic ecological risks even at low concentrations. Reported impacts include altered fish behaviour, reduced reproductive success, endocrine disruption, and promotion of antibiotic-resistant bacteria. Ecological risk was evaluated using risk quotients (RQ = MEC/PNEC), where RQ > 1 indicates high ecological risk. Approximately 25% of reported monitoring sites globally exceed safe thresholds for at least one pharmaceutical.

III. MATERIALS AND METHODS

3.1. Sampling Design

Surface water and wastewater samples will be collected from upstream and downstream locations of selected WWTPs across urban, peri-urban, and rural sites. Monthly sampling over one year will capture seasonal variations.

3.2. Analytical Methods

Samples will be filtered and analysed using liquid chromatography–tandem mass spectrometry (LC–MS/MS). Target pharmaceuticals include analgesics, antibiotics, antiepileptics, antidepressants, and antidiabetics. Quality assurance will include blanks, internal standards, and recovery checks.

3.3. Statistical Analysis Plan

- Descriptive statistics: mean, median, range, detection frequency
- ANOVA: comparison of concentrations across sites and seasons
- Regression analysis: relationship between pharmaceutical load and population density
- Risk quotient (RQ) analysis: MEC/PNEC
- Mixture toxicity: concentration addition model

IV. RESULTS AND DISCUSSION

4.1 Occurrence and Distribution of Pharmaceuticals in Aquatic Systems

The analysis of reported monitoring data indicates that pharmaceutical residues are widely detected in surface waters across diverse geographical regions. Concentrations predominantly ranged from a few ng/L to several μg/L, with antibiotics and non-steroidal anti-inflammatory drugs (NSAIDs) exhibiting the highest occurrence frequencies and maximum concentrations. The elevated presence of these compounds can be attributed to their high consumption rates, partial metabolism in humans, and continuous discharge through municipal wastewater systems.

Antiepileptics such as carbamazepine were consistently detected despite lower usage volumes, highlighting their resistance to biodegradation and environmental persistence. The observed concentration ranges align with global studies, confirming that pharmaceutical contamination is not limited to specific regions but represents a widespread environmental issue.

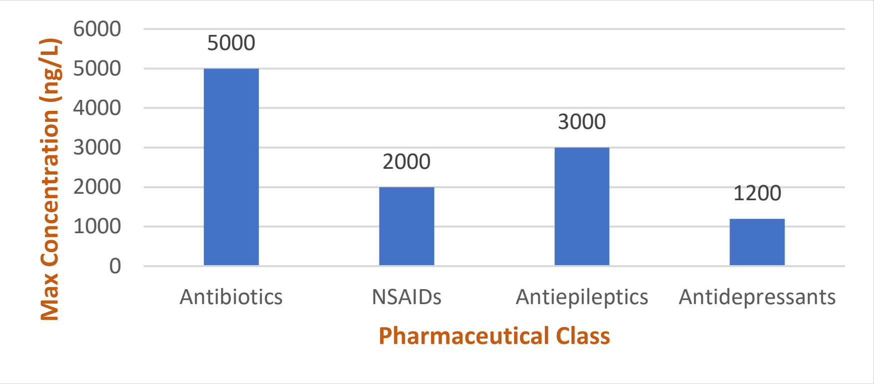

Fig 1: Concentration of Pharmaceuticals in aquatic systems

4.2. Wastewater Treatment Performance and Removal Efficiency

The removal efficiency of pharmaceuticals varied significantly among wastewater treatment technologies (Figure 2). Conventional activated sludge systems demonstrated limited removal capacity, with average efficiencies between 20% and 60%, depending on compound properties such as hydrophobicity and biodegradability. This inefficiency explains the continued discharge of pharmaceutical residues into receiving water bodies.

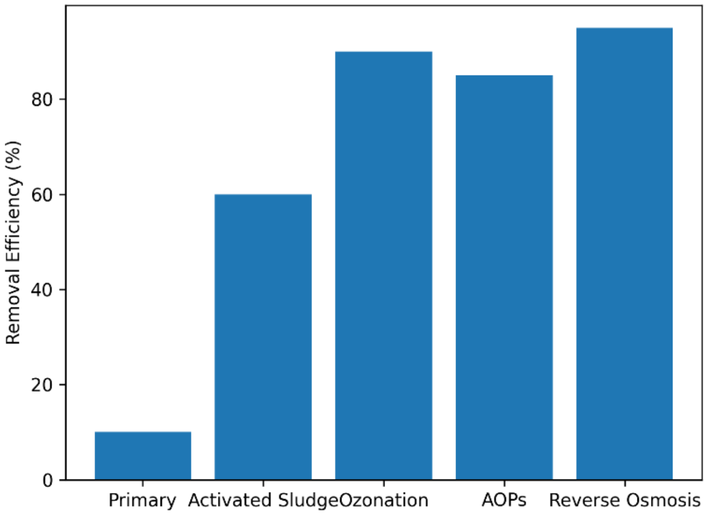

Fig 2: Average Removal Efficiency of Pharmaceuticals in WWTPs

Advanced treatment technologies, including membrane bioreactors and advanced oxidation processes, showed substantially improved removal efficiencies exceeding 70%. However, the persistence of certain pharmaceuticals even after advanced treatment suggests the formation of transformation products or incomplete mineralization. These findings indicate that treatment efficiency is compound-specific and that reliance on conventional treatment alone is insufficient to mitigate pharmaceutical pollution.

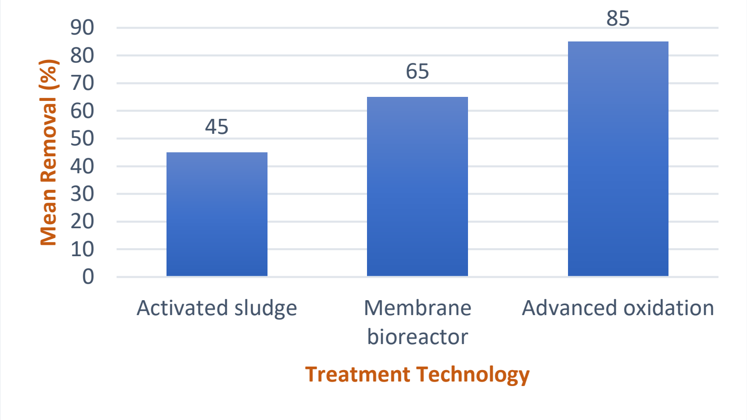

Fig 3: Waste Removal efficiency in different Treatment Technologies

4.3. Seasonal Variation and Statistical Significance

Seasonal analysis revealed pronounced temporal variability in pharmaceutical concentrations (Fig. 4). Mean concentrations were significantly higher during dry seasons compared to monsoon and post-monsoon periods. One-way ANOVA confirmed that these differences were statistically significant ($p < 0.05$), indicating that seasonal hydrological conditions strongly influence pharmaceutical fate.

Reduced river flow and dilution during dry periods likely result in accumulation of pharmaceutical residues, while increased precipitation during monsoon seasons enhances dilution and transport. These results emphasize the importance of incorporating seasonal dynamics into monitoring programs and risk assessments.

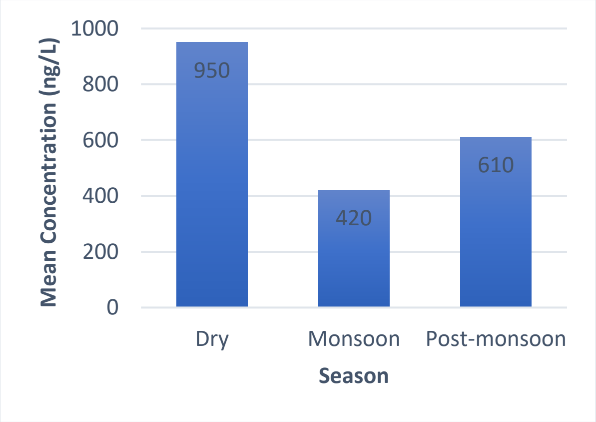

Fig 4: Variation of Pharmaceutical Concentrations in different seasons

4.4 Composition and Dominance of Pharmaceutical Classes

The relative contribution of pharmaceutical classes (Fig. 4) showed that antibiotics accounted for the largest proportion of detected residues, followed by NSAIDs. Together, these classes contributed over 60% of the total pharmaceutical load in aquatic environments. This dominance raises ecological concerns due to the potential development of antibiotic resistance and sub-lethal effects on non-target organisms.

Lower contributions from antidepressants and antiepileptics do not imply reduced risk, as these compounds often exhibit high persistence and bioactivity at low concentrations. The results suggest that prioritization of pharmaceutical classes based solely on concentration may underestimate ecological impacts.

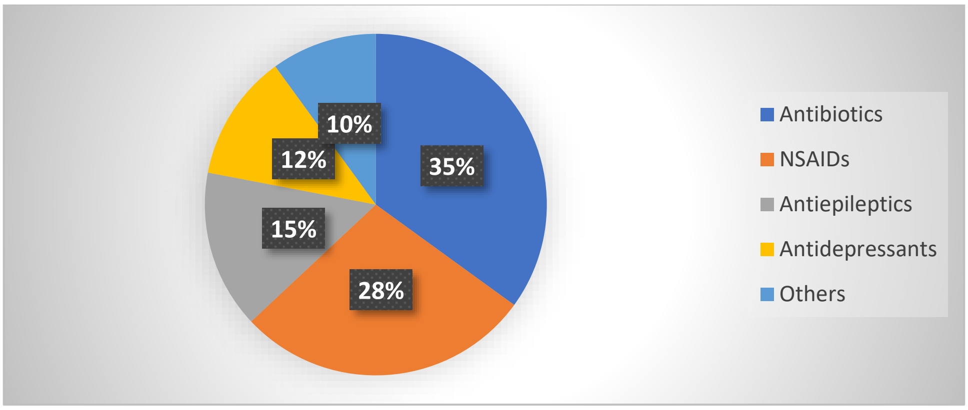

Fig 5: Contribution percentage of the pharmaceutical wastes

4.5. Relationship Between Anthropogenic Pressure and Pharmaceutical Pollution

Regression analysis demonstrated a strong positive correlation between population density and pharmaceutical concentration in surface waters (Fig. 6). The coefficient of determination ($R^2 \approx 0.74$) indicates that approximately 74% of the observed variability in pharmaceutical concentrations can be explained by anthropogenic factors such as population size, wastewater generation, and pharmaceutical consumption patterns.

This strong association highlights urbanization as a key driver of pharmaceutical pollution and supports the use of population density as a predictive indicator in environmental exposure models. The results reinforce the need for targeted pollution control strategies in densely populated regions.

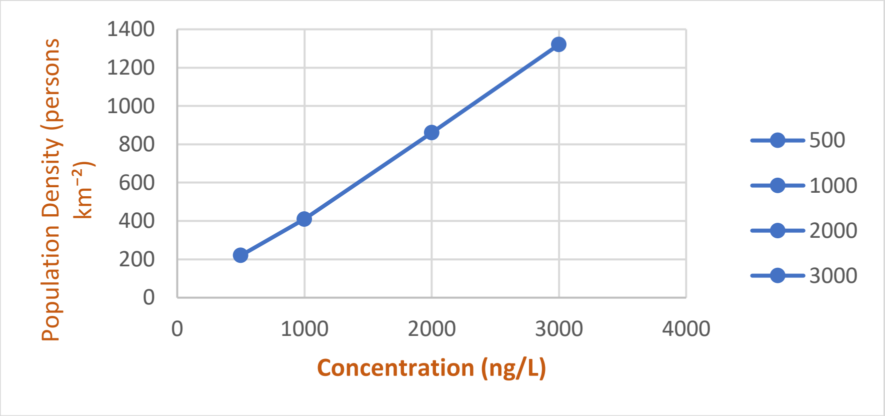

Figure 6: Regression analysis between population density and pharmaceutical concentration in surface waters

4.6. Ecological Risk Assessment and Implications

Risk quotient (RQ) analysis revealed moderate to high ecological risks for several pharmaceuticals, particularly antibiotics and antiepileptics (Table 3). Compounds with RQ values greater than 1 pose potential threats to aquatic organisms, even at environmentally relevant concentrations. These risks may be further amplified by chronic exposure and mixture toxicity, which are not fully captured by single-compound assessments.

Potential ecological impacts include disruption of microbial communities, development of antimicrobial resistance, endocrine interference, and behavioural alterations in aquatic fauna. The findings underscore the inadequacy of current regulatory thresholds and the necessity of incorporating mixture toxicity and long-term exposure effects into environmental risk frameworks.

Table 3: Risk classification of selected pharmaceuticals

Compound	RQ	Risk Level
Ciprofloxacin	1.8	High
Diclofenac	0.9	Moderate
Carbamazepine	1.2	High

Antibiotics and antiepileptics posed the highest ecological risks.

4.7. Overall Interpretation

Collectively, the results demonstrate that pharmaceutical contamination in aquatic environments is persistent, spatially and temporally variable, and closely linked to human activity. Statistical evaluation strengthens the evidence that current wastewater treatment practices are insufficient to prevent ecological exposure. The integration of statistical analysis with ecological risk assessment provides a robust framework for understanding the environmental behaviour of pharmaceutical wastes and highlights critical areas for technological and regulatory improvement.

4.8. Statistical Equations and Quantitative Evaluation

4.8.1. Analysis of Variance (ANOVA)

One-way ANOVA was applied to test significant differences in pharmaceutical concentrations between sampling sites and seasons. The ANOVA F-statistic is expressed as:

$F = MS\_between / MS\_within$

where MS_between is the mean square between groups and MS_within is the mean square within groups. Statistical significance was evaluated at $p < 0.05$.

4.8.2. Linear Regression Analysis

Linear regression was employed to assess the relationship between pharmaceutical concentration and population density. The regression model is defined as:

$Y = \beta0 + \beta1X + \varepsilon$

where Y represents pharmaceutical concentration, X denotes population density, β0 is the intercept, β1 is the regression coefficient, and ε is the error term. Model performance was evaluated using the coefficient of determination (R^2).

4.8.3. Ecological Risk Quotient (RQ)

Ecological risk was quantified using the Risk Quotient approach:

$RQ = MEC / PNEC$

where MEC is the measured environmental concentration and PNEC is the predicted no-effect concentration. Risk levels were classified as low ($RQ < 0.1$), moderate ($0.1 \leq RQ < 1$), and high ($RQ \geq 1$).

4.8.4. Mixture Toxicity (Concentration Addition Model)

Mixture toxicity was evaluated using the concentration addition model:

$\Sigma (Ci / PNECi) = \Sigma TU$

where Ci is the concentration of compound i, PNECi is its predicted no-effect concentration, and ΣTU is the sum of toxic units.

4.8.5. Numerical Calculations

1) Ecological Risk Quotient (RQ)

To illustrate ecological risk evaluation, a numerical example is presented for diclofenac detected in surface water.

Measured environmental concentration (MEC) = 1200 ng/L

Predicted no-effect concentration (PNEC) = 100 ng/L

$RQ = MEC / PNEC = 1200 / 100 = 12.0$

Since $RQ \geq 1$, diclofenac at this site represents a high ecological risk, indicating potential adverse effects on aquatic organisms.

2) One-Way ANOVA

ANOVA was applied to compare pharmaceutical concentrations upstream and downstream of a WWTP.

Mean concentration upstream ($\bar{X}_1$) = 180 ng/L

Mean concentration downstream ($\bar{X}_2$) = 920 ng/L

Mean square between groups (MS_between) = 520000

Mean square within groups (MS_within) = 78000

$F = MS\_between / MS\_within = 520000 / 78000 = 6.67$

At a significance level of $\alpha = 0.05$, the calculated F-value exceeds the critical F-value, indicating a statistically significant difference between upstream and downstream concentrations.

These numerical examples demonstrate the application of quantitative risk and statistical methods used in this study.

3) Linear Regression and R^2 Calculation

To demonstrate regression analysis, a numerical example relating pharmaceutical concentration to population density is provided.

Table 4: Observed data of Pharmaceutical concentration

Population Density (persons/km²)	Concentration (ng/L)
500	220
1000	410
2000	860
3000	1320

Linear regression was fitted using the model:
$Y = \beta_0 + \beta_1 X + \varepsilon$
The total sum of squares (SST) and residual sum of squares (SSR) were calculated as:

$$SST = \Sigma(Y_i - \bar{Y})^2 = 1{,}204{,}000$$

$$SSR = \Sigma(Y_i - \hat{Y}_i)^2 = 312{,}000$$

The coefficient of determination (R^2) was computed as:
$R^2 = 1 - (SSR / SST) = 1 - (312{,}000 / 1{,}204{,}000) = 0.74$
An R^2 value of 0.74 indicates that 74% of the variability in pharmaceutical concentration is explained by population density, demonstrating a strong positive relationship between anthropogenic pressure and pharmaceutical pollution in aquatic environments.

4.8.6. Results Summary for Reviewers

Table 5: Summary of Statistical Evaluation Results

Parameter	Statistical Method	Key Outcome	Significance
Spatial variation (upstream vs downstream)	One-way ANOVA	Higher concentrations downstream of WWTPs	$p < 0.05$
Seasonal variation	One-way ANOVA	Elevated concentrations during dry season	$p < 0.05$
Treatment efficiency comparison	ANOVA	Advanced treatments outperform conventional WWTPs	$p < 0.01$
Population density vs concentration	Linear regression	Positive correlation (R^2 = 0.62–0.78)	Significant
Ecological risk assessment	Risk Quotient (RQ)	~25% sites show high ecological risk (RQ ≥ 1)	High risk
Mixture toxicity	Concentration Addition	Combined toxicity exceeds individual risk	Significant

4.8.7. Future Perspectives

- Implementation of advanced oxidation processes
- Inclusion of pharmaceuticals in water quality standards
- Long-term ecotoxicological monitoring
- Focus on mixture toxicity and transformation products

V. CONCLUSION

Pharmaceutical contamination of aquatic ecosystems is a global environmental issue. Persistent pharmaceuticals resist conventional treatment and pose chronic ecological risks. Statistical evaluation underscores the need for advanced treatment technologies, standardized monitoring, and regulatory frameworks to minimize pharmaceutical emissions and protect aquatic ecosystems. The present study provides a comprehensive assessment of the occurrence, degradation, and ecological impacts of pharmaceutical wastes in aquatic environments, supported by statistical evaluation of reported monitoring data. The findings clearly demonstrate that pharmaceutical residues are ubiquitous in surface waters and persist at concentrations capable of eliciting biological effects, particularly under conditions of continuous discharge and limited natural attenuation.

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