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Artificial Intelligence-Based Detection of Antibiotic Residues in Urine-Derived Wastewater: Current Advances, Challenges, and Future Perspectives

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Abstract: *Antibiotic residues excreted through human urine constitute a major source of pharmaceutical contamination in wastewater systems. These contaminants persist in aquatic environments, promote antimicrobial resistance (AMR), and pose risks to ecosystems and public health. Conventional analytical methods such as high-performance liquid chromatography (HPLC) and liquid chromatography-mass spectrometry (LC-MS/MS) provide accurate measurements but are often expensive, labor-intensive, and unsuitable for real-time monitoring. Artificial Intelligence (AI), particularly Machine Learning (ML) and Deep Learning (DL), has emerged as a powerful tool for detecting, predicting, and managing antibiotic residues in wastewater. AI can analyze complex environmental datasets, improve contaminant identification, optimize sensor performance, and support wastewater treatment processes. This review discusses the occurrence of antibiotic residues in urine-derived wastewater, conventional detection techniques, AI-based monitoring approaches, current advancements, challenges, and future opportunities for intelligent wastewater surveillance systems.*

Keywords: Artificial Intelligence, Machine Learning, Antibiotic Residues, Urine-Derived Wastewater, Wastewater Surveillance, Antimicrobial Resistance, Environmental Monitoring

I. INTRODUCTION

The widespread use of antibiotics in human healthcare has resulted in increasing concentrations of pharmaceutical residues in the environment. A significant proportion of administered antibiotics is excreted unchanged or as active metabolites through urine. These compounds enter municipal wastewater treatment plants where conventional treatment systems are often unable to achieve complete removal. Consequently, antibiotic residues are discharged into rivers, lakes, groundwater, and agricultural systems, contributing to environmental pollution and antimicrobial resistance.

Urine contributes a substantial fraction of pharmaceutical compounds entering wastewater streams because many antibiotics are eliminated through renal excretion. The presence of these residues in wastewater creates selective pressure for resistant microorganisms and antibiotic resistance genes (ARGs). Wastewater surveillance has therefore become an important tool for environmental and public health monitoring.

Recent developments in Artificial Intelligence (AI) provide opportunities to improve detection and monitoring of antibiotic residues. AI-based systems can process large datasets from analytical instruments, sensors, and wastewater monitoring networks to provide rapid and accurate assessments.

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II. SOURCES AND OCCURRENCE OF ANTIBIOTIC RESIDUES IN URINE-DERIVED WASTEWATER

2.1 Human Excretion of Antibiotics

Following administration, antibiotics undergo varying degrees of metabolism. Depending on the drug, between 30% and 90% may be excreted through urine as unchanged compounds or active metabolites.

Common antibiotics detected include:

- Ciprofloxacin
- Amoxicillin
- Sulfamethoxazole
- Tetracycline
- Azithromycin
- Levofloxacin

2.2 Entry into Wastewater Systems

Major pathways include:

- Domestic sewage
- Hospitals and healthcare facilities
- Pharmaceutical industries
- Long-term care facilities

The accumulation of these compounds creates complex wastewater matrices that are difficult to monitor using conventional methods.

III. ENVIRONMENTAL AND PUBLIC HEALTH IMPACTS

3.1 Development of Antimicrobial Resistance

Continuous exposure of microorganisms to sub-therapeutic antibiotic concentrations promotes the selection and proliferation of resistant bacteria.

3.2 Ecotoxicological Effects

Antibiotic residues may:

- Affect aquatic microbial communities
- Alter nutrient cycling processes
- Impact fish and aquatic organisms
- Disturb ecosystem balance

3.3 Human Health Concerns

Potential consequences include:

- Increased antimicrobial resistance
- Contamination of drinking water sources
- Reduced effectiveness of therapeutic antibiotics

IV. CONVENTIONAL DETECTION METHODS

4.1 High-Performance Liquid Chromatography (HPLC)

Widely used for quantification of antibiotics but requires skilled personnel and expensive instrumentation.

4.2 Liquid Chromatography-Mass Spectrometry (LC-MS/MS)

Provides high sensitivity and specificity but has high operational costs.

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4.3 Gas Chromatography-Mass Spectrometry (GC-MS)

Suitable for certain antibiotic classes after derivatization.

4.4 Biosensors

Emerging biosensor technologies provide rapid detection but may suffer from limited sensitivity and selectivity.

V. RESULT AND DISCUSSION

The application of Artificial Intelligence (AI) in detecting antibiotic residues in urine-derived wastewater demonstrates significant improvements in sensitivity, prediction accuracy, and real-time monitoring compared to conventional analytical techniques. Machine learning (ML) models such as Random Forest (RF), Support Vector Machine (SVM), and Artificial Neural Networks (ANN) showed high efficiency in identifying antibiotic patterns from complex wastewater datasets. The integration of AI with sensor-based systems and analytical instruments enabled rapid detection and continuous monitoring of contaminants, reducing dependence on labor-intensive laboratory methods..

AI models trained on physicochemical and spectral datasets showed strong predictive capabilities.

Observed outcomes:

- Random Forest achieved high accuracy in classifying antibiotic presence due to its ability to handle nonlinear relationships.
- ANN models demonstrated superior performance in predicting antibiotic concentration levels.
- SVM models were effective in distinguishing between contaminated and non-contaminated samples.

Performance indicators:

High coefficient of determination ($R^2 > 0.90$ in many cases)

- Low Root Mean Square Error (RMSE)
- Improved sensitivity and specificity

These findings confirm that AI-based models can reliably detect and quantify antibiotic residues in complex wastewater matrices.

Limitations Observed

Despite promising results, several limitations were identified:

- Data dependency: AI models require large, high-quality datasets
- Model generalization issues: Models trained on specific datasets may not perform well across different regions
- Sensor calibration challenges: Variability in environmental conditions affects accuracy
- Black-box nature: Difficulty in interpreting deep learning outputs

These limitations indicate the need for improved data standardization and model transparency.

VI. CONCLUSION

The findings clearly demonstrate that AI is a transformative tool in the detection and monitoring of antibiotic residues in urine-derived wastewater. AI-driven systems provide enhanced accuracy, faster detection, and predictive insights that are not achievable with traditional methods alone. However, successful large-scale implementation requires addressing challenges related to data quality, model interpretability, and infrastructure development. With continued advancements, AI-based monitoring systems are expected to play a crucial role in combating environmental pollution and antimicrobial resistance.

Artificial Intelligence has emerged as a transformative technology for detecting antibiotic residues in urine-derived wastewater. AI-driven approaches enhance monitoring accuracy, enable real-time surveillance, support risk assessment, and optimize wastewater treatment processes. Although challenges remain regarding data quality, standardization, and

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regulatory acceptance, future integration of AI with biosensors, IoT platforms, and advanced analytical techniques is expected to revolutionize environmental monitoring and antimicrobial resistance management. AI-based wastewater surveillance systems will play a critical role in protecting environmental sustainability and public health.

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