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Transformation Mechanisms of Antibiotics in Aquatic Sediments: study review

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ABSTRACT

The environmental stability and movement of antibiotics depend on physical, chemical, and biological reactions that produce transformation products (TPs). These transformation products of antibiotics show different levels of toxicity and potency compared to their parent compounds. The environmental contamination of aquatic sediments with antibiotics has become a major environmental concern because these substances retain their toxic properties and resistance-promoting abilities while harming benthic ecosystems. Sediments function as lasting storage sites that release antibiotics into water over time while enabling the spread of antibiotic-resistant bacteria and their genetic information. The underwater environments transform substances through the natural processes of water interacting with sediments. The speed of transformation depends on four main factors, which include oxygen levels (aerobic or anaerobic), temperature, light exposure, pH values, matrix effect, and sediment composition. The analysis of sediments faces ongoing difficulties because of their diverse nature, the minimal amounts of antibiotic residues, and insufficient standardized laboratory procedures. The identification and quantification of antibiotics and their transformation products TPs depend on LC–MS/MS systems, which provide superior sensitivity and accuracy. The review demonstrated practical applications of these systems via case studies, which prove analytical methods work and demonstrate their environmental value. The current state of knowledge lacks essential information about the transformation products TPs, and there is no standardized controlling system in place. Scientists need to combine new chemical methods with various environmental monitoring systems and global research partnerships to combat antibiotic contamination while enhancing environmental risk assessment and protecting water sources from antibiotic resistance and long-term contamination.

Keywords: antibiotics, pollution, chemistry analysis, environmental monitoring, biosensors, extraction techniques, antimicrobial resistance.

Introduction

The long duration of antibiotics in aquatic sediments creates environmental threats because these substances stay active for long periods while harming water ecosystems and developing antimicrobial resistance (AMR) [1, 2]. The environment receives antibiotic compounds through multiple wastewater streams which include urban sewerage systems and hospital waste and agricultural runoff and aquaculture discharge [3]. The environmental stability of antibiotics combined with their slow degradation process allows them to attach to suspended particles which then settle into sediments where they persist for extended periods [4, 5]. Sediments serve as antibiotic storage sites yet they create additional contamination problems which release their accumulated pollutants into water systems when environmental conditions change thus extending the duration of ecological harm [2, 6]. Scientists study antibiotics in aquatic sediments by research to route environmental substance movement and estimate their effects on natural eco-systems. The identification of environmental pollutants in the environment demands advanced analytical methods for their detection [7]. The sediments matrix composition which including organic matter, metals and colloids create many difficulties for extracting and detecting for those components. The analysis of antibiotic residues (at low concentrations) needs highly sensitive analytical methods because these compounds had existed in trace and ultra-trace amounts [4, 8]. The combination of LC–MS/MS with HPLC and capillary electrophoresis provided perfect methods to detect antibiotics for both identification and concentration measurement. The extraction process requires supplemental work because sediment analysis of antibiotics needs optimal recovery and analytical accuracy [9–12]. The monitoring of water samples alone leads to the omission of sediment-based antibiotic contamination [6]. The dense microbial communities in sedimentary environments function as an effective antibiotic reservoir because they allow antibiotics to bind and accumulate. The sedimentary matrix contains both original compounds and transformation products (TPs) which result from microbial and photochemical and chemical decomposition processes. The environmental stability and toxic potential of these degradation products exceeds that of their parent compounds while extending their availability to benthic organisms which increases the risk of long-term environmental and health problems [13–15]. The high microbial density and biofilm formation and mobile genetic elements in sediments create an optimal environment for horizontal gene transfer (HGT) between different microbial species which drives the spread of antimicrobial resistance (AMR). The extended exposure of bacteria to antibiotics and toxin-producing agents (TPs) at reduced levels selects resistant bacterial strains while it increases resistance gene abundance which can reenter the water column or spread through food chains [16, 17]. Benthic organisms experience elevated toxicity from Ciprofloxacin N-oxide and Anhydrotetracycline and 4-nitro-sulfamethoxazole metabolites which exceed the toxic effects of their original compounds. The compounds create damage to biological systems while producing increased oxidative stress and they disrupt normal growth and reproductive processes. The compounds can move through the food chain which might trigger health problems in humans through hormonal imbalances and liver damage and kidney problems and immune system changes [17–20]. The analysis of NDMA (N-Nitrosodimethylamine) and its antibiotic degradation products in environmental samples faces challenges because of insufficient standardized analytical methods and matrix interference and poor extraction yields [21, 22]. The analysis of antibiotics in sediments requires analytical chemistry methods to evaluate and measure these compounds. The identification of antibiotic groups from multiple novel antibiotic substances becomes possible through qualitative analysis. The use of quantitative methods for concentration measurement allows scientists to establish environmental risk thresholds. The advanced analytical technique LC-MS/MS stands as the current best method for sediment analysis because it provides high sensitivity and selectivity [23]. The following discussion evaluates current methods for detecting antibiotics in aquatic sediments through qualitative and quantitative approaches [11]. The review examines sediment collection methods and preparation techniques and extraction protocols and detection instruments and their operational characteristics including sensitivity and selectivity and reproducibility. The review evaluates practical applications through specific examples and various suitable case studies to determine essential analytical restrictions and knowledge deficiencies and proposes methods for improving sediment-based antibiotic detection [16].

Sources and Environmental Behavior of Antibiotics in Aquatic Sediments

The environment receives antibiotics from human activities through wastewater treatment plant (WWTP) effluents and agricultural runoff and aquaculture discharges and industrial waste which accumulate in aquatic sediments as long-term storage sites [9]. The chemical characteristics of antibiotics enable them to attach to particles which then settle in sediments where they stay and undergo changes during extended periods. The process of antibiotic entry and accumulation and transformation in sedimentary environments requires scientific study to determine their potential harm to ecosystems [24, 25]. The treatment process fails to eliminate all antibiotics which enter surface waters through different pathways. The treatment process produces remaining substances which attach to suspended particles before they settle into sediment deposits [2]. The mixture of manure with sludge and veterinary antibiotics enters agricultural environments through agricultural practices before water runoff occurs from rainstorms or irrigation events. Aquaculture operations that use antibiotics to control fish diseases result in major environmental contamination because non-absorbed feed waste and fish excrement accumulate in sediments [13, 26]. The detection methods for antibiotics in sediments use different analytical techniques which provide varying levels of sensitivity and selectivity and operational range (Table 1). The figure 1 demonstrates that agricultural runoff and aquaculture discharges produce the most sediment contamination because they will generate the highest amount of pollution.

Table 1: Analytical Techniques Used in Antibiotic Sediment Detection[4, 9, 23]

Method	Sensitivity	Selectivity	Suitability
LC–MS/MS	Very high	Excellent	Multi-class quantification at trace levels
HPLC–UV	Moderate	Moderate	Cost-effective for targeted antibiotics
UV–Vis Spectroscopy	Low	Poor	Limited use, affected by sediment background
Biosensors	Fast, portable	Currently experimental	Promising for on-site detection, needs validation

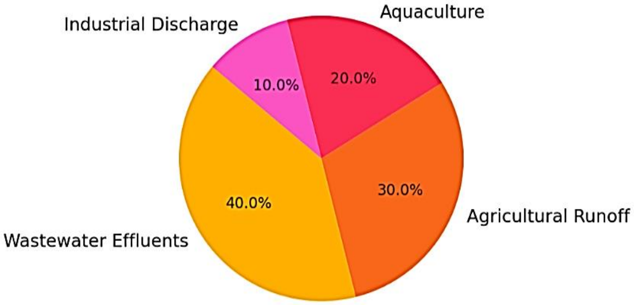

Figure 1: Estimated Contribution of Antibiotic Sources to Sediment Contamination

Accumulation and Partitioning in Sediment Matrices

Sedimentary matrices operate as active systems which determine the final destinations of environmental pollutants and antibiotics. Two fundamental processes affect the distribution and environmental impact of substances that reach river and lake bottoms through accumulation and partitioning. The accumulation process leads to permanent substance embedding which becomes an essential part of sedimentary rock formations. Sediments function as permanent storage facilities which maintain compounds from several weeks to multiple years. The substance properties together with its ability to attach to organic matter and clay determine its accumulation process. The process of compound distribution between water and sediment happens through partitioning. The distribution of water solubility and organic matter and clay particle binding capacity determines this process. The availability of compounds for biological decomposition and their possibility to form bacterial resistance and environmental toxicity depends on their distribution between water/sediment. The study of accumulation and partitioning in sedimentary matrices enables scientists to understand better how chemicals move through aquatic systems and how they affect ecosystems in the long run (see figure 2) [27–29]. The remaining substances bond to floating particles before they settle into the sediment layer. The antibiotic will follow different paths after release into aquatic environments because it can either settle into sediment or remain suspended in water. The antibiotic's properties together with the sediment properties determine how the substance will distribute between the two phases. The sediment particle binding of tetracyclines and fluoroquinolones antibiotics to sediment particles occurs through their chemical bonds with organic matter and divalent cations. The sorption process depends on three main factors which include sediment grain size and pH levels and total organic carbon (TOC) content [26, 30]. The distribution of antibiotics between water and sediment phases depends on sediment–water partition coefficients (K_d) which show different patterns between antibiotic groups and specific sediment characteristics. The high antibiotic retention in TOC-rich fine-grained sediments might result from their strong attraction to sorbent materials. The long duration of sediment stay in stagnant or low-flow systems creates contamination worries because these systems exchange sediment at a slow rate [29, 31]. The organic carbon-normalized partition coefficient (K_{OC}) (see eq.1) served as a fundamental point in environmental modeling and toxicity assessments and mobility predictions and binding assessments of complex carbon to sediment or soil fibers [32, 33].

$$K_{OC} = \frac{K_d}{f_{TOC}} \qquad (1)$$

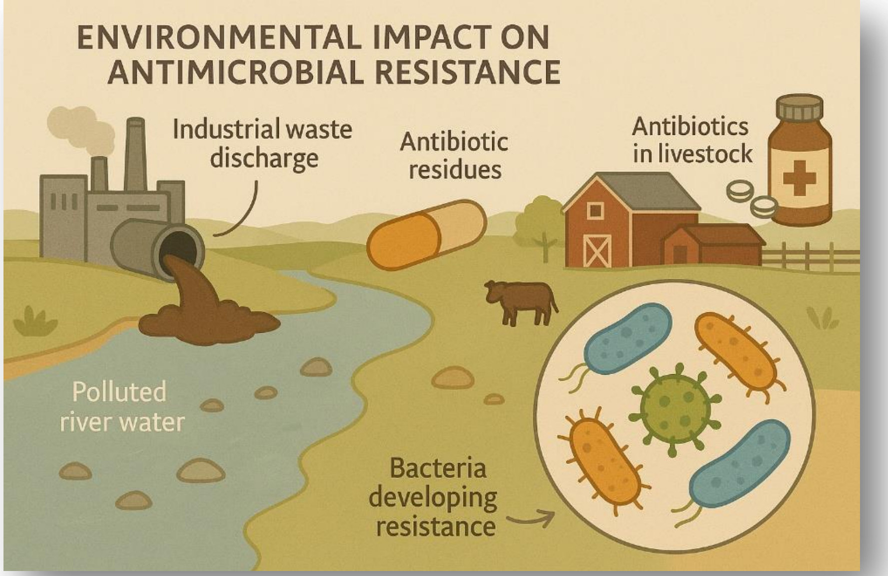

Figure 2: Antibiotic Sources to Sediment Contamination.

Transformation and Environmental Fate

Antibiotics in the environment undergo a complex series of physical, chemical and biological process that determine their survival, mobility and the metabolites they form, and these metabolites may be less or more potent or toxic than original compound[34]. In the environment the antibiotics undergo three main types of transformation that work together in the interconnected manner, the processes often being with a physical, chemical and biological transformation and these processes are not separate from each other [35]. As a result, the decomposition of antibiotics in sediments is a gradual and intricate process that greatly varies based on variables like temperature, photolysis, metabolism, bioactivity, and redox potential[26] . The adsorption of a drug onto the clay surface[35] a physical transformation may indeed protect it from photolysis or enzymatic degradation, thus prolonging its survival in the sediment for extended periods. On the other hand, the photolysis is important mechanism to break down and removal some of antibiotics cause without enough light some photolysis mechanism would not work effetely, those the sediments' water column in an area that receives light is usually low, and under anoxic or anaerobic conditions, microbial degradation of antibiotics is limited [36]. In contrast, the changing in chemical conditions, such as pH changes or exposure to light, could change the degree of adsorption/decompose mineral complexes and returning the molecules to a more biodegradable state. Thus, the final environmental fate of an antibiotic was determined by a continuous dynamic interaction between physical, chemical, and biological processes within the environment. The tetracyclines[37] such as Tetracycline, Doxycycline and Oxytetracycline are antibiotics that difficult to degrade in the environment due to their ability to form strong complexes with minerals (such as Ca^{2+}, Mg^{2+} and Fe^{3+}) like 4-epi-tetracycline and anhydrotetracycline. These increases their adsorption onto sediments and prolongs their persistence. Adsorption partially protects them from photodegradation and biological degradation, and they undergo transformations such as epimerization and produce stable anhydrous metabolites, give them a persistent source of selective pressure on resistant bacteria. Sulfonamides [38](includes: Sulfamethoxazole (SMX), Sulfadiazine (SDZ) and Sulfapyridine (SPY)), by side, they are more soluble and biodegradable, but they remain stable in anaerobic environments and undergo transformations like N-acetylation and photodegradation. Some of the degradation products remain biologically active, which means they maintain an environmental impact despite their higher bioavailability compared to tetracyclines. Also, recent studies[31, 39, 40] shown that some bacterial communities possess enzymes capable of breaking down antibiotics. However, this breakdown is often complex, specific, and incomplete, resulting in the formation of TPs. The products may stay active in living things. In some cases the products may even be more toxic, to the environment than the antibiotics. The complex mix of chemical stuff, in sediment makes it hard to find and measure the products. I think we need to know the transformation pathways and the environmental fate of the antibiotics and the transformation products. Knowing the transformation pathways and the environmental fate of the antibiotics and the transformation products helps us see the risks. Knowing the transformation pathways and the environmental fate of the antibiotics and the transformation products also helps us create the measures that can lower the long-term impacts of the antibiotic sediment contamination. pH is one of the most important factors controlling the behavior of antibiotics within sediments, as it determines the ionization state of the antibiotic and thus alters the type of surface interactions that can occur between the molecule and the sediment. It is also an important chemical factor in explaining the K_{OC} and K_d Most antibiotics are polyfunctional molecules, meaning they contain acidic ($-COOH$), basic ($-NH_2$), and phenolic or cyclic groups. Therefore, their charge changes with the pH of the medium at a low (acidic) pH, protonation increases, and many antibiotics become positively charged (cationic); at a high (basic) pH, deprotonation occurs, and the molecules become negatively charged (anionic) or neutral. This is important because the precipitates themselves often carry a charge: negative at a pH above the zero point of charge (PZC), and less negative at a low pH. Due to the difference in charges, changes occur in the type of bonds, including electrostatic interactions and hydrogen bonding. The electrostatic interactions depend on (charge and opposite charge), where at a low pH, antibiotics are often positively charged and precipitates are usually negatively charged, so strong adsorption occurs through electrostatic attraction. The opposite occurs at a high pH. While hydrogen bonding depends on the availability of protons ($H - donors$) and the availability of electron sites that can accept bonds ($H - acceptors$). Raising or lowering the pH can change the ability of groups such as $-NH_2$ or $-OH$ to donate or accept, and thus affect the strength and number of possible hydrogen bonds with organic carbon in precipitates, clay minerals, and metal-organic surfaces[41, 42]. The importance of pH influence becomes even clearer when considering some practical examples, such as tetracyclines, which have three dissociation values ($pKa \approx 3.3, 7.7, and\ 9.7$), making their charge highly sensitive to any change in pH. At a near-neutral pH ($pH \approx 7$), these compounds tend to acquire a negative charge, causing repulsion from clay surfaces and sediments, which are also negatively charged. The compounds keep up of their binding strength through their ability to form complexes with clay minerals and sediment minerals which produced multiple environmental effects. The sulfonamide compounds(SAs) with their pK_a approximately equals to 6 evolve negative charges when the solution reaches a pH above this point which decreases their ability to bind to sediments while making them more mobile in water. When the compounds exhibit higher mobility in water and reduced environmental stability, they do not bind as strongly to organic carbon or mineral surfaces as other antibiotics bind [43, 44].

Analytical Challenges in Sediment Matrices

The analysis of antibiotics in sediment encounters many difficulties [8,13] because of:

❶ The complicated composition of antibiotic contaminants.

❷ The low levels of antibiotic contaminants present.

❸ The interference of detection processes with other pollutants that impact both extraction techniques and detection instruments.

The three major challenges in sediment analysis came from matrix effects, sensitivity constraints and inadequate standardization techniques.

Matrix Complexity and Interference

The analysis of samples becomes difficult because spectroscopic measurements and chromatography with mass spectrometry (LC-MS/MS and GC-MS/MS) observation of signal suppression or enhancement due to matrix effects from substances other than the target compound. The analysis of antibiotics in sediment samples faces difficulties because their irregular non-uniform matrix structure creates analysis challenges. The matrix contains organic substances together with clay fragments and heavy metal contaminants and humic compounds. The detection process for quantification becomes difficult because these additives create problems during extraction and purification and affect the detection methods. The mass spectrometer experiences ionization suppression when antibiotics co-elute with other compounds from the chromatographic column which results in poor quantification accuracy [8, 11]. The wide range of antibiotic properties including polarity and stability and chemical structure makes it difficult to create a single method for detecting multiple antibiotic classes. The extraction recovery process shows significant differences between compounds because different analytes tend to bind strongly to sediment particles while others become trapped in small fractions less than 63 µm [14]. The exact processes which enhance signals in figure 3 have not been determined but scientists believe gas-phase interactions and modifications in charge transport efficiency are essential factors. The measurement accuracy and normative validity and sensitivity will experience substantial changes when the analyzer emits interfering compounds together with the analyzed substances. LC-MS method validation in forensic toxicology requires matrix effect evaluation as a basic requirement because it handles intricate sample types. The selection of suitable analytical techniques will reduce sample contamination effects to produce dependable analytical data [48].

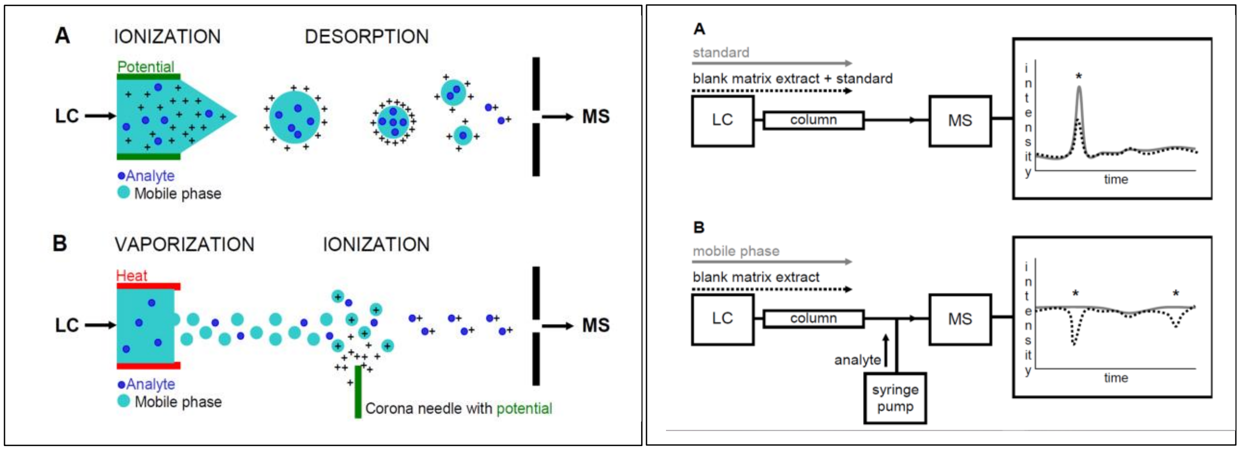

Figure 3: Matrix effect and interference[48]

Trace-Level Concentrations and Sensitivity

The analysis of sediments faces a major challenge because antibiotics exist at extremely low concentrations which range from nanograms to micrograms per kilogram. The EDS system needs to detect samples with high precision because it requires particular sample preparation techniques. The detection methods with low sensitivity produce false negative results because they cannot detect small antibiotic concentrations and remaining drug residues [15]. The required sensitivity for analysis antibiotics became possible through LC–MS/MS techniques but these methods still encounter challenges with matrix interference when measuring samples. The combination of sample dilution with matrix effect correction using calibration standards and isotope ratio–labeled internal standards helped to minimize signal suppression and improve measurement accuracy [13, 21]. The deployment of these methods leads to analysis difficulties which drive up operational costs and increase power consumption.

Standardization and Methodological Limitations

Sediment monitoring faces a major restriction because there are no established standardized methods for obtaining and storing and processing and measuring antibiotics in environmental samples. The results of antibiotic recovery tests depend heavily on the specific pretreatment methods used for drying and sieving and homogenizing sediment samples, which makes it difficult to compare different studies. The quantitative methods developed for laboratory field work, but may not work effectively with environmental samples cause sediment properties differ from laboratory and field environment [22]. The results between laboratories became disagreeing for differences in instrument precision and calibration methods with quality confidence protocols. Organizations be faced with a challenge in creating environmental standards and tracking environmental changes between different time periods for the reason that they had not established measurement methods. Therefore, the international organization for standardization (ISO) needs to set standardized analytical methods for sediment antimicrobial contaminant detection, it would improve toxicological risk assessments globally [23, 40]. Table 2 show the required steps for methodological standardization and better environmental monitoring.

Table 2: Identified Research Gaps and Recommendations [9, 11]

Research Gap	Proposed Recommendation
Lack of standardization	Develop internationally harmonized protocols
Limited study on transformation products	Integrate non-targeted screening and high-resolution MS
Insufficient risk assessment	Apply ERA models using PNEC and MEC values
Poor inter-laboratory reproducibility	Encourage proficiency testing and quality assurance programs
Limited policy linkage	Incorporate findings into sediment quality guidelines

Sample Preparation and Extraction Techniques

The detection of antibiotics in sediment needs two major factors to achieve successful results:

❶ Particular sample pre-treatment methods

❷ Extraction techniques

The optimization of pre-treatment and extraction conditions remains definitive cause sediment matrices contain complex block which reduce analyte recovery and produce interfering compounds [26]. The following topics explains sediment pre-treatment techniques besides their extraction methods with focus on solid-phase extraction, ultrasound-assisted and microwave-assisted extraction methods [12, 14].

Pretreatment of Sediment Samples

The accuracy of antibiotic test results depends on exact sediment sample preparation methods. The analysis of samples requires four established procedures which include drying and grinding and sieving and homogenization. Scientific research shows that freeze-drying methods should be used for heat-sensitive antibiotic materials instead of air-drying methods [31]. The measurement of antibiotic concentrations requires dry weight normalization because water content in samples affects water distribution which decreases extraction efficiency [49]. The normalization of results to dry weight serves two essential functions because it enables both exact measurements and enables researchers to match their findings. The homogenization process produces uniform analyte distribution which results in dependable results during both subsampling and extraction procedures. The sieving process with mesh sizes below (2 mm) separates large particles from smaller particles which contain most organic matter and antibiotic binding sites. The extraction process needs moisture control because it determines the success of sample extraction [15, 50].

Extraction Techniques

Scientists used various extraction methods to extract antibiotics from sediment samples according to the text. The solid-liquid extraction method stands as the preferred choice because it effectively retrieves different types of analytes. New extraction methods achieve superior extraction results by using reduced amounts of solvent. The ultrasonic energy in UAE treatment technology both fragments sediment particles and extracts antibiotics from the soil. The extraction method UAE proves effective for tetracyclines and sulfonamides and fluoroquinolones because it requires minimal solvent and short extraction duration. The extraction process of MAE achieves better heating and penetration because of its fast extraction rate which makes it suitable for compounds that bind strongly to the matrix and those that have non-polar characteristics. The extraction method Microwave-Assisted Extraction (MAE) allows for efficient macrolide antibiotic extraction from sediment samples because of their complex structures. The extraction process concludes with Solid Phase Extraction (SPE) which functions to clean and concentrate the extracted analytes from samples. The selection of SPE cartridges depends on the polarity of the target compounds because researchers use Oasis HLB or C18 commercial cartridges. The selection of elution solvents and SPE cartridge conditioning procedures determines the effectiveness of extraction methods to recover samples and preserve their results [11,51]. The extraction methods in Table 3 show their effectiveness for antibiotic extraction from sediments but researchers encounter three primary analytical obstacles which impact both experimental reliability and detection precision. The recovery rates of different extraction methods appear in Figure 4 which demonstrates that UAE and MAE outperform SLE methods in terms of extraction efficiency according to research findings [9].

Table 3: Common Challenges in Analyzing Antibiotics in Sediment Matrices[7, 9]

Challenge	Description	Impact
Matrix Interference	Presence of organic matter, clay, metals	Inaccurate detection, ion suppression
Trace-Level Concentrations	Nanogram-level residues	Requires ultra-sensitive instruments
Non-Standardized Protocols	Variability in sample collection/extraction methods	Low reproducibility, inter-study gaps
Incomplete Extraction	Strong adsorption of analytes	Low recovery rates
Diverse Antibiotic Properties	Variations in polarity and stability	Difficult multi-class detection

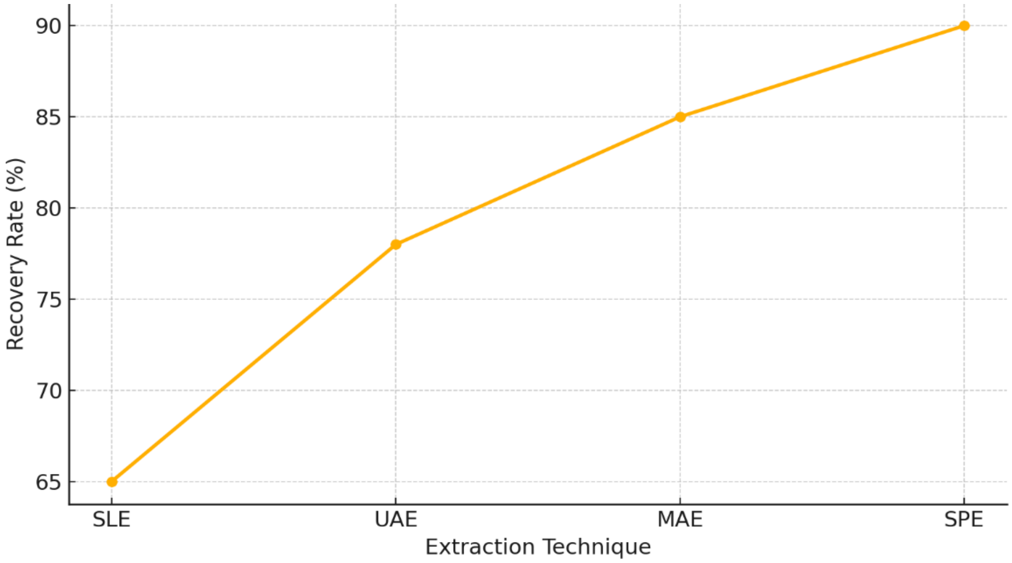

Figure 4: Recovery Rates of Extraction Techniques

Optimization and Method Performance

The extraction process requires optimization of extraction parameters including pH and organic solvent concentration and extraction duration and temperature to achieve high recovery rates with minimal matrix interference. Basic and amphoteric compounds require extraction solutions at pH levels between neutral and slightly alkaline but acidic antibiotics need extraction solutions at pH 3–5. The evaluation of methods uses three main performance metrics which include recovery rates and accuracy measurements through coefficient of variation and RSD% and detection limit (LOD) [17]. The recovery rates for antibiotic analysis in sediment samples produced results between 70% and 120% based on the specific compound group and sample complexity. The matrix complexity level can be determined through two methods which involve calculating its impact (eq.2) or by studying its dependence on co-eluting species [52, 53].

$$ME\% = \left(\frac{B}{A} - 1\right) \times 100 \qquad (2)$$

Where: ME% refers to the percentage of matrix effect, (B) the peak area for the blank matrix extract and (A) the corresponding peak area for the blank, respectively. If, ion suppression will result in $(-) values$ then, ion enhancement will cause $(+)\, values$. Precision, accuracy and ME% are key parameters, often ensured through internal standard (IS) validation of samples and spiked sample analysis to enhance measurement repeatability among different research investigations[21, 54].

Analytical Methods for Qualitative and Quantitative Detection

The detection of antibiotics in sediment requires methods that can identify these compounds at very low concentrations because they appear only in small amounts. The detection of antibiotics in sediment needs highly sensitive methods because these compounds appear at very low levels throughout complex environmental samples. The evaluation of method performance and quality requires basic validation standards and new technologies and contemporary analytical software according to [23, 55].

Chemical Techniques

The two primary methods for detecting antibiotics in sediment samples use high-performance liquid chromatography (HPLC) and liquid chromatography–tandem mass spectrometry (LC–MS/MS). The HPLC–UV method produces excellent separation results but lacks sensitivity to detect extremely small amounts of substances. The analytical method LC–MS/MS provides excellent selectivity and sensitivity which makes it an ideal choice for detecting different types of antibiotics. However, the high-resolution mass spectroscopy (HRMS) as Quadrupole time of flight mass spectrometry (QTOF) and Orbitrap are a necessary and more advanced technique than LC–MS/MS, where, its deal with a more complex TPs, high interaction matrixes and non-targeting screen with very low complexes [9]. The analysis of sediments through LC–MS/MS represents the most common method according to Figure 4 because scientists prefer this technique for its ability to detect multiple antibiotic classes at very low concentrations [8, 56].

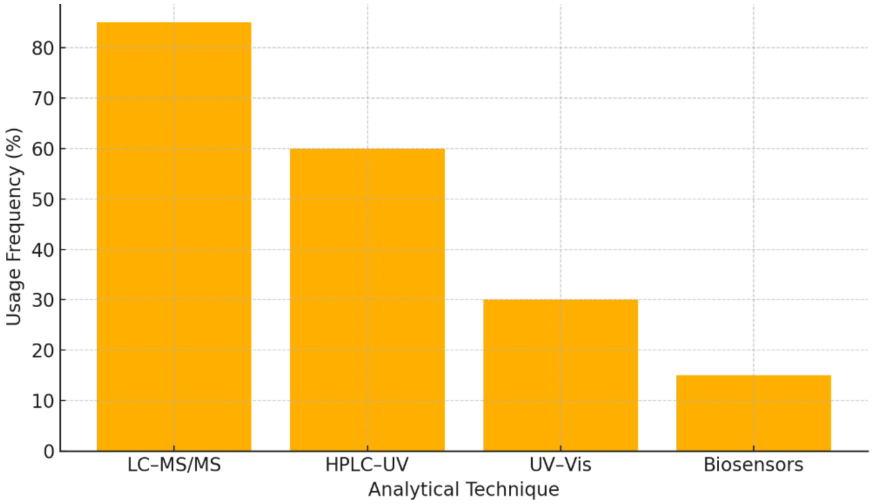

Figure 5 the distribution of analytical methods which scientists apply to study sediments according to [8][9][21].

The methods allow scientists to identify antibiotics through their retention time and m/z values when the samples contain nanogram per kilogram amounts. The combination of solid-phase extraction (SPE) with chromatographic resolution enables both analyte concentration and matrix effect reduction [4]. The combination of internal standards with isotopically labeled substances produces more accurate and reproducible results for quantitative analysis. The extraction methods in Table 4 show different benefits and drawbacks based on the physical characteristics of antibiotics. The extraction methods UAE and MAE enable fast antibiotic recovery but MAE works better than UAE while solid–liquid extraction serves as an affordable method for initial antibiotic screening [11, 56].

Table 4: Comparison of Extraction Techniques for Antibiotics in Sediments [11, 23]

Technique	**Advantages**	**Limitations**	**Suitable Antibiotics**
Ultrasound-Assisted (UAE)	Rapid, moderate solvent use	May not extract strongly bound compounds	Tetracyclines, Fluoroquinolones
Microwave-Assisted (MAE)	High efficiency, short extraction time	High temperature may degrade labile compounds	Macrolides, Hydrophobic antibiotics
Solid-Phase Extraction	Purification and concentration, low matrix effects	Cartridge-dependent performance, higher cost	Broad spectrum with prior extraction
Solid-Liquid Extraction	Simple and low-cost	Low selectivity, higher solvent consumption	General screening

Spectrometric and Sensor-Based Methods

Sediment analysis depends on chromatographic methods for analysis but spectrometric techniques such as UV–Vis and fluorescence spectroscopy function for qualitative screening and confirmation tests. The sediment matrix produces strong interference effects which prevent these techniques from working because they fail to select specific components. The use of electrochemical and biosensors for antibiotic detection in situ becomes more popular as a new sensor technology. The systems produce quick results while requiring little sample preparation but need further validation to work with conventional sediment testing methods. The use of these sensors for sediment research exists only in experimental stages according to [12, 57].

Method Validation and Comparative Performance

The established principles of method validation exist but new analytical methods need to demonstrate their quality and reliability through validation tests to achieve long-term credibility. The evaluation of linearity and detection limits (LOD and LOQ) and recovery rates and matrix effects must be performed. The LOD values for LC–MS/MS methods used to detect mixed antibiotic compounds in sediments range from 0.1 to 10 ng/kg depending on the analyte and sediment characteristics [11,58]. Research studies show that LC–MS/MS provides better analytical results because it detects samples with higher precision. The method needs specialized equipment and trained operators to operate which creates barriers for its use in resource-limited settings. The screening process becomes possible through HPLC–UV and immunoassays after optimization of extraction and clean-up methods [40].

Case Studies and Applications

The detection of antibiotics in sediments requires analytical methods which become more understandable through the study of actual field situations. The methods enable scientists to check laboratory testing procedures for environmental samples and evaluate analytical techniques for sample evaluation and identify contamination patterns that help with ecological risk assessments. The following examples show current environmental detection methods which demonstrate their operational ranges and particular restrictions. The environmental distribution and persistence of antibiotics in sediments depends on multiple environmental factors which include sediment grain size and total organic carbon content and pH levels and redox conditions and divalent cations according to Table 5 [14, 15].

Table 5: Parameters Influencing Antibiotic Sorption in Sediments [21, 54]

Parameter	Influence on Sorption
Sediment Grain Size	Fine particles increase surface area and binding
Total Organic Carbon (TOC)	High TOC enhances adsorption of hydrophobic compounds
pH	Affects ionization of antibiotics and sediment reactivity
Redox Conditions	Influence degradation potential and microbial activity
Divalent Cations	Promote complexation with antibiotics like tetracyclines

Field Monitoring Studies

Field case studies show that laboratory-tested methods work as expected when deployed in actual field settings. A research study investigated the impact of antibiotic residues on urban lake sediment which receives agricultural waste from surrounding farms. The study showed that sulfonamides and fluoroquinolones and macrolides accumulated at higher levels in the sediment which proved their persistence in the environment. The research showed that antibiotic distribution patterns between different areas followed regional patterns because of different pollution sources and sediment characteristics [14, 58].

Evaluating Method Performance in Real Samples

The described method successfully extracted environmental samples through an efficient and proper process. The method used solid-phase extraction followed by LC–MS/MS analysis to detect tetracyclines, macrolides and fluoroquinolones in benthic samples collected from aquaculture contaminated sites. The method produced recovery results between 80% and 95% while it successfully measured ng/kg levels in complex sample types. The results showed that the method proved effective through these findings. The implementation of these techniques faced technical problems because of matrix suppression effects and sediment property changes that occurred during the testing process [22, 55].

Implications for Environmental Risk Assessment

Scientists perform field studies to support their analytical techniques while they collect vital information about antibiotic contamination risk in sediment layer. The water samples contain activated antibiotic concentrations due to the antibiotic resistance genes (ARG) that tied throughout of diffusional water flow. The review demonstrates how sediment matrixes distribute resistance between them which results in long-lasting environmental risk. The review provides essential data about environmental contaminant behavior and pollutant distribution and regulatory standards [14, 51]. The risk quotient (RQ) (the normal levels $RQ < 1 \geq 0.1$) could be considered as an important reference to observe the contaminate in an environmental system [54].

Conclusion

The slow degradation of antibiotics in aquatic sediments creates environmental issues because these substances persist in the environment while generating antimicrobial resistance and scientists have not determined their permanent ecological impact. The review assesses sediment matrix problems by analyzing current monitoring systems to prove that better detection systems are required. The combination of improved sample preparation techniques with extraction methods and LC–MS/MS instrumentation has enhanced analytical results but researchers continue to face problems with matrix effects and detecting small amounts of pollutants and achieving consistent results between laboratories. The application of advanced analytical methods in field-based studies demonstrates their practical value through their ability to detect different sediment properties and pollutant distribution patterns. Scientists need to perform additional scientific studies to confirm the accuracy of risk assessment techniques for transformation product (TP) fate in sediment environments. Scientists must use advanced analytical methods together with suitable monitoring instruments to evaluate antibiotic contamination in sediments for future pollution assessment.

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