



Research Article

Identification and Quantification of Emerging Contaminants in Pharmaceuticals Wastewater

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Abstract

Pharmaceutical wastewater is a major source of emerging contaminants (ECs), which include pharmaceutical residues, personal care products, endocrine-disrupting compounds, and other biologically active substances that are not completely removed by conventional wastewater treatment processes. The continuous discharge of these contaminants into aquatic environments poses significant risks to ecosystems and human health due to their persistence, bioaccumulation potential, and biological activity. This study focused on the identification and quantification of emerging contaminants present in pharmaceutical wastewater collected from a pharmaceutical manufacturing facility. Wastewater samples were collected and subjected to physicochemical characterization prior to contaminant analysis. The identification and quantification of target contaminants were carried out using advanced analytical techniques, Gas Chromatography-Mass Spectrometry (GC-MS) and ICP-OES for Organic and Inorganic emerging contaminants respectively. Common pharmaceutical compounds detected included analgesics, antibiotics, anti-inflammatory drugs, anti-malaria drugs and other active pharmaceutical ingredients. The concentrations of these contaminants varied depending on the nature of the manufacturing processes and wastewater characteristics. The physicochemical results revealed a pH of 2.73, turbidity of 11.95 NTU, dissolved oxygen (DO) of 6.80 mg/L, biochemical oxygen demand (BOD) of 14.24 mg/L, chemical oxygen demand (COD) of 12.41 mg/L, total dissolved solids (TDS) of 1,200 mg/L, chloride (Cl^-) of 882.28 mg/L, and sulphate (SO_4^{2-}) of 37.14 mg/L. The inorganic contaminants detected include arsenic (As) at 0.011 mg/L, cadmium (Cd) at 0.001 mg/L, mercury (Hg) at 0.007 mg/L, and lead (Pb) at 0.007 mg/L. and organic emerging contaminants are paracetamol (4.390), dichlofenac (6.131), tetracycline (0.698), and ampiclux (0.389). While some contaminants exceeded recommended environmental thresholds, highlighting the inadequacy of conventional treatment systems in completely removing these pollutants. The study provides essential baseline data on the occurrence and levels of emerging contaminants in pharmaceutical wastewater and underscores the need for effective treatment technologies to prevent environmental contamination. The results also support the development of sustainable remediation strategies, including the application of nanoparticle-based adsorption systems for the efficient removal of pharmaceutical pollutants from wastewater.

Keywords

Pharmaceutical Wastewater, Emerging Contaminants, Identification, Quantification, GC-MS, Pharmaceutical Residues, Environmental Pollution

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1. Introduction

Pharmaceutical wastewater is a complex industrial effluent generated during the manufacture, formulation, packaging, and cleaning operations associated with pharmaceutical production. These effluents often contain a mixture of active pharmaceutical ingredients (APIs), intermediates, solvents, reagents, by-products, and other chemical substances, that may pose environmental risks if discharged without adequate treatment [1-3]. The discharge of such wastewater into aquatic environments has become a growing environmental concern due to the presence of emerging contaminants that may persist in the environment and adversely affect both ecosystems and human health [4, 5]. The composition of pharmaceutical wastewater is highly variable and depends on the type of pharmaceutical products manufactured, production processes employed, and operational practices within the facility. Consequently, pharmaceutical effluents are frequently characterized by high chemical oxygen demand (COD), biological oxygen demand (BOD), total dissolved solids (TDS), and elevated concentrations of biologically active compounds that are resistant to conventional treatment methods [6, 7]. Among the pollutants present in pharmaceutical effluents, emerging contaminants (ECs) have attracted significant global attention because of their widespread occurrence, persistence, and biological activity. Emerging contaminants refer to naturally occurring or synthetic chemicals that are not routinely monitored but have the potential to cause ecological and health-related risks even at very low concentrations [8, 9]. Globally, the pharmaceuticals most commonly detected in water samples include antibiotics such as erythromycin, sulfamethoxazole, and trimethoprim; antiepileptic drugs, particularly carbamazepine; nonsteroidal anti-inflammatory drugs (NSAIDs) such as ibuprofen; and analgesics such as acetaminophen (paracetamol). Their frequent occurrence is attributed to their extensive consumption, incomplete metabolism in humans and animals, continuous discharge into aquatic environments, and insufficient removal by conventional wastewater treatment systems [10-13]. In the United States, the Environmental Protection Agency (EPA) has released guidelines for establishing national water quality criteria using aquatic toxicological data. These guidelines facilitate the assessment of the hazards posed by pharmaceuticals and personal care products to aquatic life. Although, these guidelines do not specify priority compounds, they suggest the need for increased attention to identify the ecotoxicological risks associated with pharmaceuticals and personal care products [14-16]. In Sweden, data on environmental hazard, persistence, bioaccumulation, and toxicity of marketed pharmaceuticals have been publicly available through the FASS environmental classification system since 2005/2006. The framework has undergone continuous improvement since its enhancement in 2010 [17-19]. In 2015, the European Union's Watch List for emerging pollutants included pharmaceuticals for the first time, recognizing their potential ecological relevance. This list served as a starting point

for many countries and regions to develop their own monitoring programs. Between 2015 and 2022, the watch lists for pharmaceuticals have evolved significantly, reflecting an increasing concern about their presence in the environment. Their continuous release into aquatic environments, coupled with their resistance to conventional wastewater treatment processes, has led to their widespread detection in wastewater, surface water, groundwater, sediments, and drinking water sources worldwide [16, 20]. The environmental implications of emerging contaminants are substantial. Unlike conventional pollutants, many pharmaceutical compounds are specifically designed to produce biological effects at low concentrations. Their continuous introduction into aquatic environments may affect non-target organisms, alter ecosystem functions, disrupt ecological processes, and contribute to biodiversity loss. The pharmaceutical industry represents one of the most important point sources of emerging contaminants in aquatic ecosystems. During pharmaceutical manufacturing processes, significant quantities of active pharmaceutical ingredients (APIs) and their metabolites may enter wastewater streams through raw material losses, equipment cleaning operations, production residues, formulation activities, and accidental discharges [21, 22]. Pharmaceutical manufacturing wastewater is often characterized by elevated concentrations of pharmaceutical active compounds, organic solvents, inorganic salts, and other hazardous substances that can be released into receiving water bodies if not adequately treated [23]. Consequently, pharmaceutical production facilities are recognized as significant contributors to the occurrence and dissemination of emerging contaminants in aquatic environments worldwide [24, 25]. One of the most critical concerns associated with pharmaceutical contaminants is the development and dissemination of antimicrobial resistance (AMR). The continuous release of antibiotics into wastewater environments creates selective pressure that promotes the proliferation of antibiotic-resistant bacteria and antibiotic resistance genes [26, 27]. The presence of antibiotic residues in wastewater facilitates the selection, enrichment, and horizontal transfer of resistance genes among microbial communities, thereby accelerating the emergence and spread of antimicrobial resistance in aquatic environments and posing significant threats to public health and ecosystem integrity [27, 28]. The World Health Organization has recognized antimicrobial resistance (AMR) as one of the most serious global public health threats of the twenty-first century, with increasing resistance compromising the effectiveness of antibiotics and other antimicrobial agents worldwide. Recent reports indicate that AMR is associated with millions of deaths annually and continues to pose substantial challenges to healthcare systems, food security, and sustainable development [29, 30]. Consequently, monitoring antibiotic residues in pharmaceutical wastewater has become an important component of environmental surveillance and risk assessment programs.

Wastewater systems serve as critical reservoirs and transmission pathways for antibiotic-resistant bacteria and antibiotic resistance genes [31, 32]. Wastewater surveillance is increasingly being adopted within the One Health framework to track antimicrobial residues, antibiotic-resistant bacteria, resistance genes, and emerging public health risks across human, animal, and environmental interfaces [28, 30]. This approach recognizes wastewater treatment systems as critical convergence points where human, animal, and environmental health interact. Thereby providing valuable information for monitoring the occurrence, dissemination, and evolution of antimicrobial resistance within communities and ecosystems. Despite advances in wastewater treatment technologies, conventional treatment methods such as activated sludge systems, coagulation-flocculation, sedimentation, filtration, and biological oxidation often fail to achieve complete removal of emerging contaminants [33, 34]. Many pharmaceutical compounds exhibit high chemical stability, low biodegradability, and complex molecular structures that enable them to persist through conventional wastewater treatment processes. As a result, these contaminants are only partially removed during treatment and may remain in treated effluents at concentrations capable of causing environmental concern [6, 35]. Consequently, residual contaminants may be discharged into receiving water bodies where they continue to exert ecological effects, which include chronic toxicity, endocrine disruption, bioaccumulation, and the promotion of antimicrobial resistance in aquatic ecosystems [36, 37]. Accurate identification and quantification of emerging contaminants are essential for understanding their occurrence, distribution, environmental fate, transport mechanisms, and potential risks. The identification process involves determining the specific contaminants present in wastewater, while quantification provides information on their concentration levels. These data are critical for evaluating pollution loads, assessing treatment efficiency, conducting environmental risk assessments, establishing regulatory guidelines, and designing suitable remediation technologies [38, 39]. Furthermore, contaminant profiling enables researchers to prioritize pollutants of concern and develop targeted management strategies for pollution control [40-42]. Accurate monitoring and analytical characterization of contaminants of emerging concern are increasingly recognized as indispensable components of sustainable wastewater management and environmental protection programs [43, 44]. The analysis of emerging contaminants in pharmaceutical wastewater requires highly sensitive and selective analytical techniques because many contaminants occur at trace concentrations ranging from nanograms per litre (ng/L) to micrograms per litre (µg/L). Recent developments in analytical chemistry have significantly improved the detection and quantification of pharmaceutical residues in environmental matrices [45, 46]. Advanced techniques such as Gas Chromatography-Mass Spectrometry (GC-MS), Liquid Chromatography-Mass Spectrometry (LC-MS/MS), Ultra-Performance Liquid Chromatography (UPLC), High-Performance Liquid Chromatography (HPLC),

and high-resolution mass spectrometry have become indispensable tools for emerging contaminant analysis [47, 48]. Sample preparation techniques including solid-phase extraction (SPE), liquid-liquid extraction (LLE), and membrane filtration are commonly employed to improve analytical sensitivity, increase extraction efficiency, and minimize matrix interferences during the determination of emerging contaminants in environmental samples. These procedures are particularly important for wastewater analysis because contaminants are often present at trace concentrations within highly complex matrices. Effective sample preparation enhances analyte recovery, lowers detection limits, and improves the accuracy and precision of subsequent instrumental analyses [49, 50]. Consequently, these analytical approaches provide reliable qualitative and quantitative information required for environmental monitoring, contaminant risk assessment, and regulatory compliance [51, 52]. The increasing occurrence of emerging contaminants in pharmaceutical wastewater has stimulated research into advanced treatment technologies capable of achieving higher removal efficiencies. Technologies such as adsorption, advanced oxidation processes, photocatalysis, membrane filtration, electrochemical oxidation, and nanoparticle-based remediation have demonstrated considerable potential for contaminant removal [53, 54]. Among these approaches, adsorption using engineered nanoparticles synthesized from waste-derived materials has attracted growing interest because of its high efficiency, environmental sustainability, regeneration potential, and cost-effectiveness. Nanoparticle-based adsorbents possess large surface areas, abundant active sites, and enhanced adsorption capacities, making them promising materials for the removal of pharmaceutical pollutants and other emerging contaminants from wastewater [54, 55]. Advanced treatment systems that integrate adsorption with photocatalysis, membrane separation, or electrochemical processes have also demonstrated improved contaminant removal efficiencies compared with conventional treatment methods [56]. The application of copper nanoparticles and copper-iron composite nanoparticles synthesized from mine tailings represents a promising strategy for the removal of pharmaceutical contaminants from wastewater while simultaneously promoting resource recovery and waste valorization [57]. Mine tailings contain significant quantities of recoverable metals that can be transformed into functional nanomaterials, by converting mine waste into value-added products for environmental remediation applications [58, 59]. Copper-based and bimetallic copper-iron nanoparticles have attracted considerable attention due to their high surface area, catalytic activity, adsorption capacity, and redox properties enhances the removal and degradation of pharmaceutical pollutants and other emerging contaminants in aqueous systems [60, 61]. The utilization of mine tailings as precursor materials for nanoparticle synthesis further supports circular economy principles by reducing waste disposal challenges and promoting sustainable resource management [58, 62]. Therefore, the identification

and quantification of emerging contaminants in pharmaceutical wastewater are fundamental steps toward understanding the extent of environmental contamination and developing effective remediation strategies. The information generated from such investigations provides valuable baseline data for environmental monitoring, risk assessment, treatment process optimization, and policy formulation. Accurate characterization of emerging contaminants enables the assessment of pollutant occurrence, environmental exposure pathways, ecological impacts, and treatment performance, thereby supporting evidence-based decision-making and sustainable wastewater management practices [41, 63]. Furthermore, comprehensive monitoring and quantification of contaminants of emerging concern are essential for establishing regulatory frameworks, prioritizing pollutants for control measures, and advancing the development of innovative treatment technologies for environmental protection. Accurate monitoring data provide critical information for environmental risk assessment, contaminant prioritization, policy development, and the implementation of sustainable wastewater management strategies [64-66]. The integration of advanced analytical methods and monitoring programs is increasingly recognized as a prerequisite for evidence-based environmental regulation and the effective management of emerging contaminants in aquatic systems [67]. This study therefore focuses on the identification and quantification of emerging contaminants present in a pharmaceutical wastewater discharged from a point source of pharmaceutical industry in Ikeja, Lagos State, Nigeria. It is a prerequisite for evaluating the effectiveness of synthesized copper and copper-iron composite nanoparticles in the adsorption-based treatment of pharmaceutical effluents.

2. Materials and Methods

2.1. Sample Collection and Sampling

Pharmaceutical wastewater samples were collected from the effluent discharge point of the selected areas of a pharmaceutical manufacturing facility in Ikeja, Lagos, Nigeria. To ensure the target analytes are captured, two separate wastewater samples were collected simultaneously following standard procedures for emerging contaminant monitoring [68]. The first sample was collected in a clean high-density polyethylene (HDPE) plastic container. Immediately after collection, the sample was acidified on-site with concentrated nitric acid (HNO_3) to reduce microbial activity, minimize chemical degradation, and preserve the stability of inorganic contaminants during transportation and storage [69]. The acidified sample was used for heavy metal analysis. The second sample was collected in a pre-cleaned amber glass bottle. The amber bottle was selected to protect light-sensitive pharmaceutical organic emerging contaminants (OECs) from photodegradation, thereby maintaining the original composition of the wastewater sample before analysis [70]. Following collection,

both samples were properly labeled and transported to the laboratory in an ice-filled cooler at approximately 4°C. Upon arrival, the samples were stored under refrigerated conditions until analysis. Prior to instrumental determination, the samples were filtered through a 0.45 μm membrane filter to remove suspended particulate matter that could interfere with analytical measurements [69]. The use of both acidified plastic containers and amber glass bottles provided adequate preservation of the wastewater samples and enhanced the reliability of the identification and quantification of emerging contaminants present in the pharmaceutical wastewater [68, 70].

2.2. Chemicals and Materials

All chemicals and reagents used in this study were of analytical grade to ensure accuracy and reliability of the analytical results. The materials used for sample collection included high-density polyethylene (HDPE) plastic containers and amber glass bottles. Concentrated nitric acid (HNO_3 , analytical grade) was used for on-site preservation of samples collected in plastic containers. Amber glass bottles were used to protect light-sensitive contaminants from photodegradation during transportation and storage. Additional materials included 0.45 μm membrane filters, filter holders, glassware (beakers, graduated cylinders, volumetric flasks, and sample bottles), micropipettes, syringes, and ice-filled coolers for sample transportation. Samples were stored in a refrigerator at 4°C prior to analysis. Analytical instruments used for the identification and quantification of emerging contaminants included a pH meter, analytical balance, filtration apparatus and an Inductively Coupled Plasma - Optical Emission Spectroscopy (ICP-OES). These instruments facilitated the detection and quantification of pharmaceutical contaminants present in the wastewater samples at trace concentrations.

2.3. Preparation of Solution

The collected wastewater samples were filtered through a 0.45 μm membrane filter to remove suspended solids. The filtered samples were subjected to solid-phase extraction (SPE) for concentration of organic contaminants. The extracts were subsequently analyzed using appropriate analytical instruments such as ICP-OES for metals and GC-MS for pharmaceutical residues and other emerging contaminants.

2.4. Physicochemical Analysis

The physicochemical properties of the pharmaceutical wastewater were analyzed to evaluate its quality and characteristics. Parameters including pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, dissolved oxygen (DO), and temperature were measured using a Hanna HI98494 multiparameter meter. Biochemical oxygen demand (BOD_5) was determined using a Hach BODTrak™ II system, while chemical oxygen demand (COD) was measured using

the dichromate reflux method. Total suspended solids (TSS) were determined using a Hach SOLITAX sc Sensor. All analyses were performed according to standard methods for water and wastewater examination (APHA, 2023)[70], and the results were used to characterize the pharmaceutical wastewater and support the identification and quantification of emerging contaminants. The results obtained were compared with the National Environmental Standards and Regulations Enforcement Agency (NESREA) effluent discharge limits for Chemicals, Pharmaceuticals, Soaps and Detergent Manufacturing Industries (NESREA, 2009) [71].

2.5. Digestion of Pharmaceutical Wastewater

For sample digestion required for elemental analysis, nitric acid and hydrochloric acid in ratio 3:1 was used as the digestion reagent. All prepared solutions were stored in clean polyethylene containers and stored in a refrigerator until use.

2.6. Solid Phase Extraction

Solid Phase Extraction (SPE) was employed as a pre-concentration and clean-up technique for the isolation of emerging contaminants (ECs) from pharmaceutical wastewater prior to instrumental analysis. The method was adopted to enhance analytical sensitivity, reduce matrix interferences, and improve detection limits for trace-level contaminants.

The disposable Stationary Phase Extraction (SPE) cartridges used in this study were Agilent octadecyl silica (ODS) C₁₈ (a hydrophobic silica-based sorbent, 200 mg, 3 mL). The extraction was conducted using Agilent vacuum manifold to aid the liquid flow right below the pressure of 20 mmHg at all times and flow rate approximately within the range of 5-7 mL/min.

The extraction commenced with the SPE columns conditioned using 2 x 1 mL of methanol and then 1 x 1 mL of distilled water. The cartridges were further conditioned using 1 mL of 2 mM sodium acetate buffer pH 4.0. The cartridges were not allowed to dry before loading 5 x 5 mL samples. The cartridges were washed with 3 x 0.5 mL sodium acetate buffer containing 15% acetonitrile (ACN). These were then vacuum dried for about 5mins, after which the analytes were eluted using 3 x 1 mL solution of 3% ammonia (NH₃) in methanol (MeOH) controlled using stop-cock valves. Prior to HPLC analysis, the extracted analytes were reconstituted by evaporating the extracts in an Ultra wave thermostat water bath.

2.7. Quantification of Emerging Contaminants in Digested Pharmaceutical Wastewater

The quantification of emerging contaminants present in the pharmaceutical wastewater was carried out using ICP-OES and GC-MS following sample collection, preservation, filtration, and extraction procedures. The concentrations of the tar-

get contaminants were determined by comparing the instrumental responses of the samples with those obtained from calibration standards of known concentrations. For pharmaceutical residues and other organic contaminants, quantification was performed using GC-MS. Calibration curves were established using a series of standard solutions prepared at different concentrations. The peak areas obtained from the chromatograms were plotted against the corresponding standard concentrations, and the resulting calibration equations were used to determine the concentrations of contaminants in the wastewater samples. For inorganic emerging contaminants, including heavy metals and trace elements, quantification was carried out using ICP-OES. Multi-element calibration standards were used to generate calibration curves, and the concentrations of metals in the samples were calculated from the measured emission intensities. The concentration of each contaminant was expressed in milligrams per litre (mg/L), depending on the detected levels. Quantitative data obtained from the analysis were used to evaluate the occurrence and distribution of emerging contaminants in the pharmaceutical wastewater and to assess their potential environmental impact.

2.8. Experimental Techniques

The experimental procedure involved systematic steps of sample collection, preservation, preparation, extraction, and instrumental analysis. Pharmaceutical wastewater samples were collected from the effluent discharge point using high-density polyethylene (HDPE) containers and amber glass bottles, with appropriate preservation using nitric acid and protection from light, respectively. Physicochemical parameters were determined using standard methods, while samples were filtered through a 0.45 µm membrane prior to analysis. Emerging contaminants were extracted and concentrated using solid-phase extraction (SPE) with Oasis HLB cartridges. Identification and quantification of pharmaceutical compounds were performed using Gas Chromatography Mass Spectrometry (GC-MS), based on retention times and mass spectral data. Trace metals were analyzed using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) with calibration standards and quality control procedures to ensure accuracy and precision. All analyses were conducted in accordance with standard QA/QC protocols, including blanks, duplicates, and calibration verification.

3. Results and Discussion

3.1. Physicochemical Analysis

The physicochemical analysis of the pharmaceutical wastewater is presented in Table 1 and Figures 1 and 2. Physicochemical characterization of the pharmaceutical wastewater revealed that most of the investigated parameters were within the permissible limits specified by the National Environmental Standards and Regulations Enforcement

Agency [71]. However, the wastewater exhibited total solids (TS), total suspended solids (TSS), electrical conductivity (EC) and chloride concentrations above the applicable regulatory limits. The lower-than-permissible pH indicates an acidic nature of the effluent, while elevated TS and TSS suggest increased solids loading. The higher chloride concentration may be associated with the use of chloride-containing process materials and cleaning agents during pharmaceutical production.

Despite compliance of the other physicochemical parameters, these observed exceedances indicate that the wastewater requires further treatment prior to discharge. The findings therefore demonstrate the need for an effective treatment approach capable of reducing both conventional pollutants and pharmaceutical contaminants in the effluent [72].

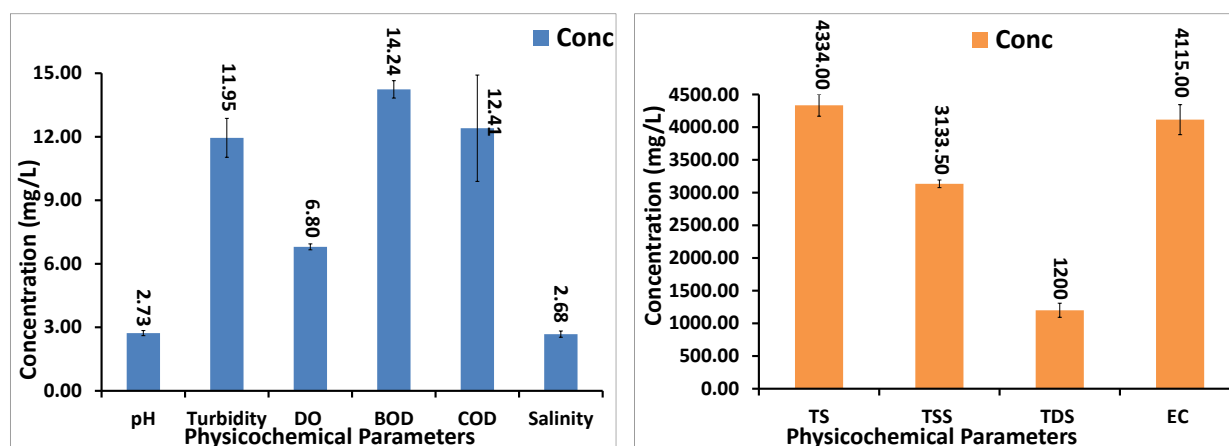


Figure 1. Physicochemical Analysis of Pharmaceutical wastewater.

Table 1. Physicochemical WHO standard permissible limits for pharmaceutical wastewater.

PARAMETER	NIS -WHO STANDARD
pH	6.5-8.5
Turbidity	NTU 30 max
Dissolved Oxygen (DO)	15 mg/L max
Biochemical Oxygen Demand (BOD)	30 mg/L max
Chemical Oxygen Demand (COD)	80 mg/L max
Salinity	1000 mg/L (max)
Total Solid (TS)	1500 mg/mL (max)
Total Suspended Solid (TSS)	2000 mg/L (max)
Total Dissolved Solids (TDS)	2000 mg/L (max)
Conductivity	2500 μ S/cm (max)
Chloride ion (Cl^-)	250 mg/L (max)
Nitrate (NO_3^-)	45 mg/L (max)
Phosphate (PO_4^{3-})	4.5 mg/L (max)
Sulphate (SO_4^{2-})	250 mg/L (max)

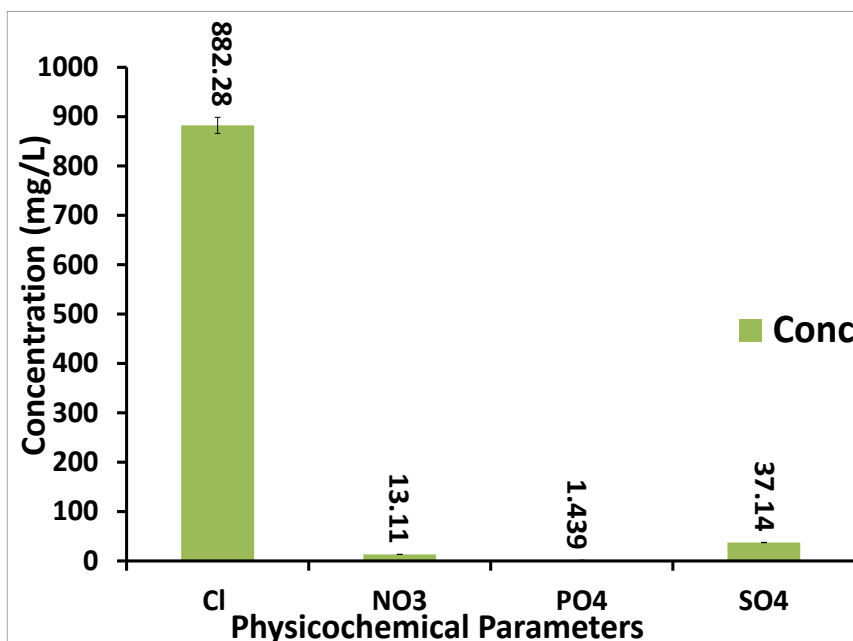


Figure 2. Physicochemical Analysis of Pharmaceutical wastewater.

3.2. Identification and Quantification

The identification and quantification of emerging contaminants is classified into two categories (Inorganic and Organic emerging contaminants) presented in Figures 2-3.

3.2.1. Inorganic Emerging Contaminants

Inorganic emerging contaminants (IECs) comprise inorganic pollutants of increasing environmental concern, including toxic metals and metalloids such as cadmium (Cd), lead (Pb), mercury (Hg), chromium (Cr), arsenic (As), and barium (Ba), as well as certain engineered nanomaterials. These contaminants are persistent and non-biodegradable, and even at

low concentration; some may accumulate in aquatic systems and pose significant risks to human health and ecosystems. Conventional wastewater treatment processes may not achieve complete removal of these contaminants, necessitating advanced treatment technologies for their effective removal [73]. The concentrations of all investigated inorganic emerging contaminants were below the applicable NESREA permissible limits, indicating 100% compliance with the regulatory requirements for the inorganic parameters analyzed. Thus, the untreated pharmaceutical wastewater did not exhibit significant inorganic contamination based on the parameters assessed. However, the presence of other emerging contaminants necessitates further treatment before discharge.

Table 2. Inorganic emerging contaminants WHO standard permissible limits for pharmaceutical wastewater.

PARAMETERS	WHO Standard permissible limit
Arsenic (As)	0.2
Barium (Ba)	5.0
Cadmium (Cd)	0.02
Chromium (Cr)	0.5
Mercury (Hg)	0.01
Manganese (Mn)	0.08
Lead (Pb)	0.1

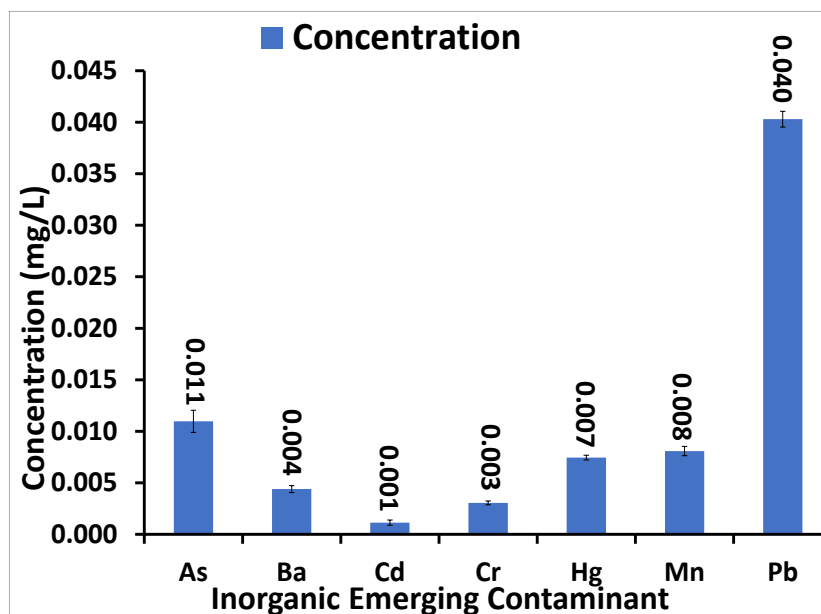


Figure 3. Inorganic emerging contaminants in pharmaceutical wastewater.

3.2.2. Organic Emerging Contaminants

Organic emerging contaminants (OECs) are carbon-based chemical substances that are not traditionally monitored or regulated but are increasingly detected in the environment, particularly in wastewater and surface water. They include pharmaceuticals, antibiotics, hormones, personal-care products, pesticides, and industrial chemicals. In pharmaceutical wastewater, compounds such as diclofenac, paracetamol, ibuprofen, ampiclox, tetracycline, and trimethoprim are important OECs because they can persist in water, resist conventional wastewater treatment, and potentially cause ecological and human-health effects even at low concentrations [74]. The

assessment of organic emerging contaminants in the pharmaceutical wastewater revealed varying degrees of compliance with the applicable WHO limits. Among the compounds analysed, ibuprofen and Ampiclox were within the permissible limits, whereas diclofenac, paracetamol, tetracycline, and trimethoprim exceeded the prescribed limits. The elevated concentrations of these pharmaceutical residues indicate potential contamination of the wastewater by active pharmaceutical ingredients and antibiotics. Their occurrence above regulatory thresholds highlights the inadequacy of conventional wastewater management practices for completely eliminating pharmaceutical contaminants and underscores the need for effective advanced treatment.

Table 3. Organic emerging contaminants WHO standard permissible limits for pharmaceutical wastewater.

PARAMETERS	WHO Standard permissible limit
Dichlofenac	0.0005
Paracetamol	0.0092
Ibuprofen	0.0071
Amplicus	0.6000
Tetracycline	0.0010
Trimethropin	0.0005

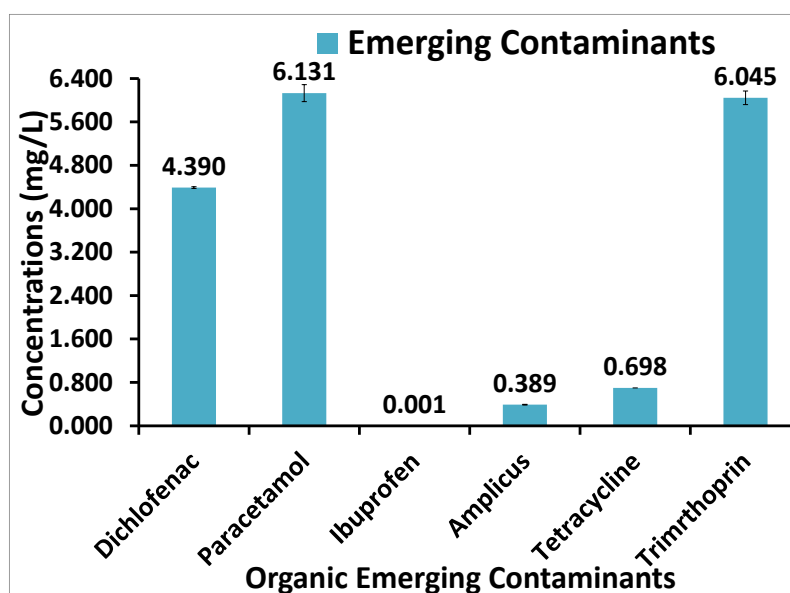


Figure 4. Organic Emerging contaminants in pharmaceutical wastewater.

4. Conclusion

The study confirms that the pharmaceutical wastewater contains both organic and inorganic emerging contaminants, making it a complex environmental pollutant. Organic contaminants include pharmaceutical residues such as antibiotics, analgesics and anti-inflammatory drugs, while inorganic contaminants include heavy metals and other inorganic constituents. Therefore, comprehensive identification and quantification of both contaminant groups are necessary to properly assess wastewater quality, potential environmental risks and the treatment requirements. The findings also highlight the need for advanced treatment technologies capable of effectively removing these contaminants from pharmaceutical wastewater.

Abbreviations

ECs	Emerging Contaminants
Cu-Fe NPS	Copper-Iron Nanoparticles Tailing
IECs	Inorganic Emerging Contaminants
OECs	Organic Emerging Contaminants
ICP-OES	Inductively Coupled Plasma–Optical Emission Spectrometry
GC-MS	Gas Chromatography–Mass Spectrometry
SPE	Solid Phase Extraction
HNO ₃	Nitric Acid
HCl	Hydrochloric Acid
COD	Chemical Oxygen Demand
BOD	Biochemical Oxygen Demand
EC	Electrical Conductivity Salinity,
TDS	Total Dissolved Solids
DO	Dissolved Oxygen

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Author Contributions

Okpala-Chinonso Angela: Fund acquisition, Investigation, Project administration

Moronkola Bridget Adekemi: Data curation, Project administration, Supervision

Alegbe Monday John: Conceptualization, Methodology, Supervision

Conflict of Interest

The authors declare no conflicts of interest.

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