Detection of Illicit Drug Metabolites in a Nairobi Wastewater Influent: A Wastewater-based Epidemiology Study

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ABSTRACT

Wastewater-based epidemiology (WBE) is a powerful analytical tool for determining community-level exposure to legal and illicit chemicals by analysing parent materials and human metabolites in sewage influent. In this work, liquid chromatography-tandem mass spectrometry (LC-MS/MS) was utilised to quantify seven drug biomarkers in weekly influent samples collected over a 16-week period (February-May) from a major wastewater treatment facility in Nairobi, Kenya. The target analytes were amphetamine (AMP), methamphetamine marker (MAMP), benzoylecgonine (BE), cocaine (COC), morphine (MOR), codeine (COD), and 11-nor-9-carboxy-tetrahydrocannabinol (THC-COOH). Concentrations were measured in the ng L^{-1} range and analysed using descriptive statistics and short-term temporal trends. BE was regularly found at moderate levels (mean 15.3 ng L^{-1}), while AMP and THC-COOH had the highest mean concentrations (31.9 and 19.8 ng L^{-1}, respectively). The pooled standard deviations (0.46-2.72 ng L^{-1}) showed low week-to-week variability. Linear regression indicated mostly stable temporal patterns, with very small positive trends in AMP and MAMP. Overall, the findings illustrate the analytical feasibility of LC-MS/MS-based WBE in an urban African setting, taking into account population normalisation, influent flow variability, analytical recovery, and in-sewer transformation.

KEYWORDS

environmental analytical chemistry, wastewater-based epidemiology, LC-MS/MS analysis, wastewater monitoring, illicit drugs.

Received: 26 January 2026 Revised: 17 March 2026 Accepted: 6 April 2026

INTRODUCTION

The use of both illegal and legal psychoactive chemicals continues to be a major public health concern around the world, with far-reaching consequences for health systems, social stability, and economic productivity.[1] Accurate data on community-level drug use is critical for developing prevention efforts, harm reduction programs, and policy responses. However, traditional drug surveillance tools—such as demographic surveys, hospital records, law-enforcement statistics, and seizure data—are usually limited by reporting bias, social desirability effects, insufficient coverage, and delayed data availability.[2] These limitations are especially evident in low- and middle-income countries (LMICs), where monitoring infrastructures are frequently fragmented and underfunded, resulting in significant uncertainty in national and sub-national drug-use estimates.[3]

Over the last decade, wastewater-based epidemiology (WBE) has developed as a reliable, complementary method for monitoring population-wide exposure to pharmaceuticals and other chemical stressors.[4] By quantifying parent substances and human metabolites excreted into sewage systems, WBE allows for an objective, anonymous, and near-real-time assessment of community-level consumption that is not dependent on individual self-reporting.[5] The approach combines analytical chemistry, environmental engineering, and epidemiology, resulting in high temporal resolution and scalability at the wastewater catchment level handled by treatment plants.

WBE has been widely used worldwide, especially in Europe, North America, and Australia, to monitor stimulants (such as amphetamine, methamphetamine, and cocaine), opioids (such as morphine and codeine), and cannabinoids.[6,7] The effectiveness of WBE for identifying weekly, seasonal, and event-driven variations in drug consumption as well as for comparing spatial patterns across urban centres has been shown by coordinated multi-city monitoring programs run by the European Monitoring Centre for Drugs and Drug Addiction.[8] Wastewater-derived indicators are susceptible to policy changes, societal disturbances, and public health measures, such as those seen during the COVID-19 pandemic.[9,10] When taken as a whole, this research has proven that WBE is a reliable part of contemporary drug surveillance systems.

On the other hand, despite rising urbanisation, population expansion, and changing drug markets throughout the area, Sub-Saharan Africa is still glaringly under-represented in the WBE literature. Stimulants, opioids, and cannabis have been found to travel through and be used in Kenya, and Nairobi in particular, a major commercial and transportation hub in East Africa.[11] The majority of Kenya's national drug-use data comes from household surveys and law enforcement records, which have a limited temporal resolution and probably underreport actual consumption because of stigma and underreporting.[12] Because of this, there is a glaring lack of data on objective, population-level drug-use indicators in metropolitan Kenya.

From an analytical standpoint, the choice of suitable biomarkers that are stable, specific, and mostly of human metabolic origin determines the dependability of WBE. Because of its high rate of excretion and relative durability in sewer systems, benzoylecgonine (BE), the main metabolite of cocaine, is considered a reliable diagnostic.[13] Although they may show more temporal variability, amphetamine (AMP) and methamphetamine-related markers (MAMP) are frequently employed to measure stimulant usage. Although morphine (MOR) and codeine (COD) are useful indicators of opioid exposure, their valid therapeutic use necessitates careful interpretation.[14] The most accurate biomarker for cannabis is still 11-nor-9-carboxy-tetrahydrocannabinol (THC-COOH), which reflects human metabolism rather than direct disposal.[15] These substances may now be sensitively and reliably quantified at nanogram-per-liter quantities in complicated wastewater matrices thanks to developments in liquid chromatography–tandem mass spectrometry (LC–MS/MS).

However, the interpretation of WBE data is complicated by a number of sources of ambiguity, especially in LMIC environments. These include population normalisation uncertainties, wastewater flow temporal variability, in-sewer transformation processes, and analytical recovery efficiency. According to recent methodological evaluations,

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ISSN 1996-840X Online / South African Chemical Institute / http://saci.co.za/journal
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https://doi.org/10.17159/0379-4350/2026/v80se1a07

temporal trends and relative comparisons are frequently more reliable than back-calculations of absolute consumption, particularly in developing WBE regions.[9] Responsible data transmission, avoiding community stigmatisation, and alignment with public health goals rather than punitive enforcement are examples of ethical considerations that are becoming more widely acknowledged. These challenges are particularly pertinent in socioeconomically varied urban areas.

In this study, weekly influent samples gathered over 16 consecutive weeks (February–May) at a significant wastewater treatment facility in Nairobi, Kenya, to systematically profile illicit and licit drug biomarkers using WBE. The targeted analytes, which are in line with global best practices for WBE monitoring, include amphetamine (AMP), methamphetamine/amphetamine marker (MAMP), benzoylecgonine (BE), cocaine (COC), morphine (MOR), codeine (COD), and THC-COOH. In order to create a solid baseline dataset for an understudied area, this study focusses descriptive statistics and short-term temporal variability rather than only consumption back-calculation.

There are three main contributions that make this work novel. First, it fills a significant geographical vacuum in the international literature by offering one of the first high-resolution WBE datasets for illicit drug biomarkers in Kenya. Second, it provides insight into temporal dynamics that are not available through traditional monitoring technologies by capturing week-to-week variability across several drug classes. Third, it contributes to the larger conversation on responsible WBE implementation in LMICs by critically examining analytical, infrastructural, and ethical concerns within the particular setting of a Sub-Saharan African entity.

This study's goals were to measure the weekly concentrations of specific stimulant, opioid, and cannabinoid biomarkers in Nairobi wastewater, characterise short-term variability and temporal patterns in drug incidence over a four-month monitoring period, and assess important sources of uncertainty and ethical issues related to the use of wastewater-based epidemiology (WBE) in Kenyan urban settings. This work shows the viability of WBE as a public health surveillance tool in Nairobi by establishing a quantitative baseline for community-level drug exposure. It also lays the groundwork for future longitudinal monitoring, inter-city comparisons, and evidence-based interventions in Kenya and similar urban environments.

EXPERIMENTAL SECTION

Study design

This study used wastewater-based epidemiology (WBE) to determine community-level exposure to specific illicit and regulated chemicals by quantifying human metabolic indicators in municipal wastewater. A non-invasive, observational monitoring design was used to detect short-term temporal fluctuation in drug metabolite concentrations. Influent wastewater samples were collected weekly during a 16-week period (February-May 2025), allowing for the analysis of temporal patterns while limiting day-to-day variability. The study design adhered to WBE best-practice frameworks for environmental drug surveillance.[15,16]

Study area

A large municipal wastewater treatment plant (WWTP) that serves the Nairobi metropolitan region in Kenya was the site of the sampling. Nairobi, the nation's main economic centre and a fast growing metropolis, is distinguished by its dense population, notable socioeconomic diversity, and vast residential, commercial, and institutional infrastructure. With little industrial input, the WWTP receives mixed influent from a sizable catchment that includes residential homes, public institutions, medical facilities, and businesses.

A well-mixed composite matrix that is indicative of aggregate community wastewater was obtained by sampling the influent wastewater at the WWTP inlet. This site was chosen because it incorporates wastewater from many demographic groups, reflecting the general substance-use trends of the population it serves. Throughout the study period, the plant runs continuously with a rather steady influent flow, enabling dependable longitudinal sampling and guaranteeing appropriateness for WBE use in an urban African setting.

Sample collection and strategy

Over the course of the 16-week monitoring period, samples of influent wastewater were taken once a week on the first day of each week. In order to improve comparability across sampling sessions and minimise variability related to daily variations in wastewater flow and human activity, sampling was carried out within a set early-morning window (07:00–09:00). Higher amounts of expelled metabolites are usually seen after nighttime physiological activities, which is why morning sampling was chosen.[17]

High-density polyethylene (HDPE) containers that had been previously cleaned were used to gather composite grab samples (1 L). Before being deployed, every container was completely cleaned with ultrapure water, cleaned with laboratory-grade detergent, and allowed to air dry in a hygienic laboratory setting. In order to eliminate stagnant material, influent flow at the WWTP intake was let to run freely for a few minutes prior to sample collection. Containers were submerged in the middle of the stream to collect samples without coming into contact with surface trash or channel walls.

Samples were put in insulated containers with ice packs as soon as they were collected in order to preserve the cold chain while being transported. Samples were kept at −20 °C upon arrival at the lab to prevent microbial activity and analyte degradation. Samples were homogenised by gently inverting them after being thawed at 4 °C for an entire night before extraction. For additional processing and instrumental analysis, a 100 mL aliquot was taken from each homogenised sample. For every sampling event, field metadata such as date, time, ambient temperature, observed flow conditions, and any unexpected influent features were recorded. Grab sampling is standard procedure in exploratory and baseline WBE research, especially when automated composite samplers are unavailable.[15,16,23] Although grab sampling does not fully capture diurnal variability, the use of a consistent sampling window and location across all weeks allows for reliable assessment of short-term temporal trends and relative concentration changes.

Reagents and standards

Methanol and acetonitrile were among the Agilent 6460 Triple Quadrupole LC–MS grade solvents utilised. A Milli-Q purification system was used to create ultrapure water (18.2 MΩ·cm). As a mobile phase modifier, formic acid (≥99%, LC–MS grade) was employed.

Analytes were identified and quantified using certified reference standards of amphetamine (AMP), methamphetamine/amphetamine marker (MAMP), benzoylecgonine (BE), cocaine (COC), morphine (MOR), codeine (COD), and 11-nor-9-carboxy-tetrahydrocannabinol (THC-COOH). To account for matrix effects, extraction efficiency, and experimental variability, isotopically labelled internal standards corresponding to each analyte (or substantially comparable analogues in the absence of exact isotopic matches) were utilised. Methanol was used to prepare stock standard solutions, which were then kept at -20 °C. Before analysis, fresh working standard solutions were made by serially diluting methanol–water (50:50, v/v).

Sample preparation and solid phase extraction

Wastewater samples were homogenised by gently inverting them after being thawed overnight at 4 °C. A predetermined volume of isotopically labelled internal standards was added to a 100 mL aliquot of each sample after it had been filtered to eliminate suspended particle debris.[18,19]

Oasis HLB cartridges (hydrophilic–lipophilic balanced sorbent) were used for solid-phase extraction (SPE), which was carried out in accordance with known wastewater-based epidemiology methods with minimal modifications for local laboratory circumstances. Five millilitres of methanol and five millilitres of ultrapure water were used to condition cartridges one after the other. Samples were loaded at a regulated flow rate (about 5 mL min^{-1}) under vacuum. Following loading, cartridges were vacuum-dried after being cleaned with 5 mL of ultrapure water to eliminate matrix interferences.

Five millilitres of acetonitrile were used to elute the analytes. The eluates were reconstituted in 1 mL of mobile phase (water:acetonitrile, 95:5 v/v, including 0.1% formic acid) after being dried out under a mild nitrogen stream at room temperature. For LC–MS/MS analysis, the reconstituted extracts were moved to autosampler vials.

LC-MS/MS analysis

LCMS/MS has been applied in similar studies.[20,21] Borrowing from their idea, An Agilent 6460 triple quadrupole liquid chromatography–tandem mass spectrometry (LC–MS/MS) system with an electrospray ionisation (ESI) source running in positive ion mode was used for the quantitative analysis.A reverse-phase C_{18} analytical column was used to accomplish chromatographic separation. The mobile phase was supplied under gradient elution conditions and included (A) water with 0.1% formic acid and (B) acetonitrile with 0.1% formic acid. Each sample had a total run time of about 12 minutes. The flow rate was 0.3 mL min^{-1}, and the injection volume was 10 µL. Certified reference materials were used to optimise multiple reaction monitoring (MRM) transitions for each analyte and associated internal standard. The drying gas temperature was 300 °C, the nebuliser pressure was 35 psi, the drying gas flow was 10 L min^{-1}, and the capillary voltage was 4,000 V. Software provided by the manufacturer was used for data collection and processing.

Target analytes

Due to their demonstrated usefulness as wastewater biomarkers of drug exposure at the community level and their extensive use in global wastewater-based epidemiological research, the target analytes assessed in this study were chosen. These included cocaine and its main human metabolite benzoylecgonine, stimulant biomarkers (amphetamine and methamphetamine/amphetamine marker), opioid biomarkers (morphine and codeine), and THC-COOH, the main human metabolite of cannabis.[22] Because of their primarily metabolic origin and relative stability in sewer systems, benzoylecgonine and THC-COOH were prioritised as robust indicators, whereas morphine and codeine were interpreted cautiously due to their potential contribution from both illicit use and legitimate medical consumption.

Quality assurance and quality control

To guarantee data dependability, quality assurance and control (QA/QC) processes were used to every analytical batch. Each batch contained procedural blanks, matrix-matched spiking samples, and quality control standards to evaluate instrument stability, extraction effectiveness, and possible contamination. QA/QC procedures were adapted from established protocols.[23]

Method validation

Recovery, limits of detection (LOD), and limits of quantitation (LOQ) for each target analyte were evaluated in order to verify the analytical method. Prior to extraction, wastewater samples were spiked at a concentration level of 50 ng L^{-1} in order to perform recovery studies. The measured concentrations were then compared with those derived from solvent-based standards. Signal-to-noise ratios of 3:1 and 10:1, respectively, were used to calculate limits of detection (LOD) and limits of quantification (LOQ).

Data analysis

Nanogrammes per litre (ng L^{-1}) were used to express the measured influent concentrations. For every analyte over the course of the 16-week monitoring period, descriptive statistics such as means, standard deviations, and coefficients of variation were computed.[24] Weekly concentration levels were linearly regressed against time (weeks) to evaluate short-term temporal patterns. The direction and amount of temporal variation over the study period were described using the obtained slopes. No back-calculation of per-capita drug consumption was carried out due to the lack of trustworthy influent flow and population data. Rather, in accordance with best-practice guidelines for early-stage wastewater-based epidemiological studies in low- and middle-income settings, the study concentrated on relative temporal patterns and comparative concentration profiles.

Accurate estimates of the population contributing to the sewage catchment and dependable influent flow data are necessary for the quantitative back-calculation of per-capita drug consumption from wastewater measurements. Due to operational and infrastructure limitations at the wastewater treatment facility, continuous influent flow measurements were not available throughout the whole monitoring period in this investigation. These limitations are prevalent in wastewater treatment facilities in low- and middle-income countries (LMICs), where flow meters may be absent, intermittently functional, or subject to calibration uncertainty, and where informal sewer connections and variable infiltration further complicate accurate flow characterization.[25,26]

Similar to this, everyday population mobility, unregistered or temporary contributors to the sewer network, and rapid urban expansion made it impossible to accurately estimate the population served by the WWTP. Due to commuting patterns, informal settlements, and partial sewer connectivity, the population size within wastewater catchments in urban African settings can vary significantly over time, adding significant uncertainty to population-normalized consumption estimates.[27]

Due to these limitations, rather than trying unknown per-capita consumption back-calculations, the current study purposefully concentrated on influent concentration data and relative temporal changes. Even without complete normalisation, recent methodological evaluations have shown that trend-based analyses of regularly collected concentration data can offer reliable and policy-relevant insights into temporal dynamics and comparative patterns of community-level drug exposure, especially in early-stage or exploratory WBE applications. The study guarantees that reported week-to-week differences represent actual temporal fluctuations rather than artefacts of methodological inconsistency by keeping a consistent sample location, time, and analytical methodology throughout all sampling sessions. For the Nairobi wastewater catchment during the research period, the results shown here should be taken as baseline concentration profiles and short-term temporal indicators. In order to enable quantitative consumption assessments as WBE capacity continues to grow in the region, these data offer a crucial basis for future WBE studies in Kenya that include longer monitoring periods, better flow measurement infrastructure, and improved population estimation techniques.

The research deliberately concentrated on influent concentration data and relative temporal patterns rather than absolute consumption back-calculation due to the exploratory and baseline-generating goals of this study. Acknowledged first-stage implementation strategy is concentration-based wastewater-based epidemiology, especially in situations where trustworthy flow and population data are either missing or extremely ambiguous. Consistent concentration profiling can produce reliable and policy-relevant insights into temporal dynamics without requiring full normalisation, as several early and foundational WBE investigations have shown. As a result, the methodological framework used here is enough to achieve the objectives of the study and is in line with frameworks for first-stage WBE implementation.

This study followed the institutional and national ethical criteria for environmental and public health research. WBE was considered non-invasive because no individual-level data or personal identifiers were gathered. Sampling was limited to aggregated influent at the WWTP intake, and no sub-catchment analysis was carried out. To reduce the possibility of indirect identification or stigmatisation, the findings were disclosed at the community level.

RESULTS AND DISCUSSION

Method validation and quality assurance

The analytical performance of the LC-MS/MS method was assessed to ensure accurate quantification of the target drug biomarkers in wastewater samples. The validated LC-MS/MS technology provided satisfactory analytical results for all analytes. Recovery rates reported from 78% to 108%, showing effective extraction with Oasis HLB solid-phase extraction cartridges. The matrix effects were within ±15%, indicating negligible signal suppression or augmentation during instrumental analysis.

Six-point calibration curves were created for each analyte over a concentration range of 0.01-100 ng L^{-1}. A strong linearity was achieved with correlation values greater than 0.99. Limits of detection (LOD) ranged from 0.003 to 0.09 ng L^{-1}, whereas limits of quantification (LOQ) varied from 0.01 to 0.30 ng L^{-1} based on the analyte. These sensitivity levels are comparable to earlier wastewater-based epidemiological investigations, indicating that the analytical approach is appropriate for detecting trace-level drug biomarkers in municipal wastewater. All wastewater extracts were examined in triplicate, and concentrations are shown as mean values with standard errors. Table 1 shows the technique validation parameters for the target analytes.

Concentration ranges and detection frequency

All seven target drug biomarkers — amphetamine (AMP), methamphetamine/amphetamine marker (MAMP), benzoylecgonine (BE), cocaine (COC), morphine (MOR), codeine (COD), and 11-nor-9-carboxy-tetrahydrocannabinol (THC-COOH) — were detected in every weekly influent wastewater sample collected during the 16-week monitoring period (February-May).The average influent concentrations ranged from 6.88 ng L^{-1} (COD) to 31.88 ng L^{-1} (AMP) (Table 3.1). Amphetamine had the greatest average concentration (31.88 ± 2.73 ng L^{-1}), followed by MAMP (21.77 ± 1.34 ng L^{-1}), THC-COOH (19.76 ± 1.51 ng L^{-1}), and BE (15.28 ± 1.26 ng L^{-1}). Cocaine was found at a mean value of 10.96 ± 0.96 ng/L. Morphine and codeine were found at lower mean values of 7.83 ± 0.57 ng L^{-1} and 6.88 ± 0.46 ng L^{-1}, respectively.

The consistent detection of all analytes during the monitoring period suggests that stimulants, opioids, and cannabinoids were present in the Nairobi wastewater catchment on a regular basis. Similar detection patterns have been observed in wastewater-based epidemiology studies undertaken in urban areas throughout Europe, Australia, and Asia, where stimulant chemicals and cannabis metabolites typically dominate concentration profiles[28,29].

Influent concentration stability and temporal variability

Weekly influent concentrations for all analytes showed little variation over the monitoring period (Figure 1). Sample standard deviations varied from 0.46 ng L^{-1} for codeine to 2.73 ng L^{-1} for amphetamine, with coefficients of variation typically less than 10%.Throughout the 16 weeks of sampling, no rapid concentration fluctuations or extreme outliers were identified. Week-to-week

These data point to rather consistent baseline levels of drug biomarker excretion within the research catchment, rather than episodic or event-driven discharge patterns. Similar stability has been observed in longitudinal wastewater monitoring studies undertaken in numerous urban areas, where weekly sampling frequently reveals stable baseline concentrations with relatively minor fluctuations due to

Table 1: Method validation parameters for target analytes.

Analyte	Recovery (%)	LOD (ng L^{-1})	LOQ (ng L^{-1})
AMP	93	0.010	0.030
MAMP	92	0.008	0.028
BE	102	0.006	0.022
COC	97	0.009	0.025
MOR	87	0.005	0.020
COD	80	0.004	0.018
THC-COOH	106	0.008	0.030

LOD: Limit of detection; LOQ: Limit of quantification.

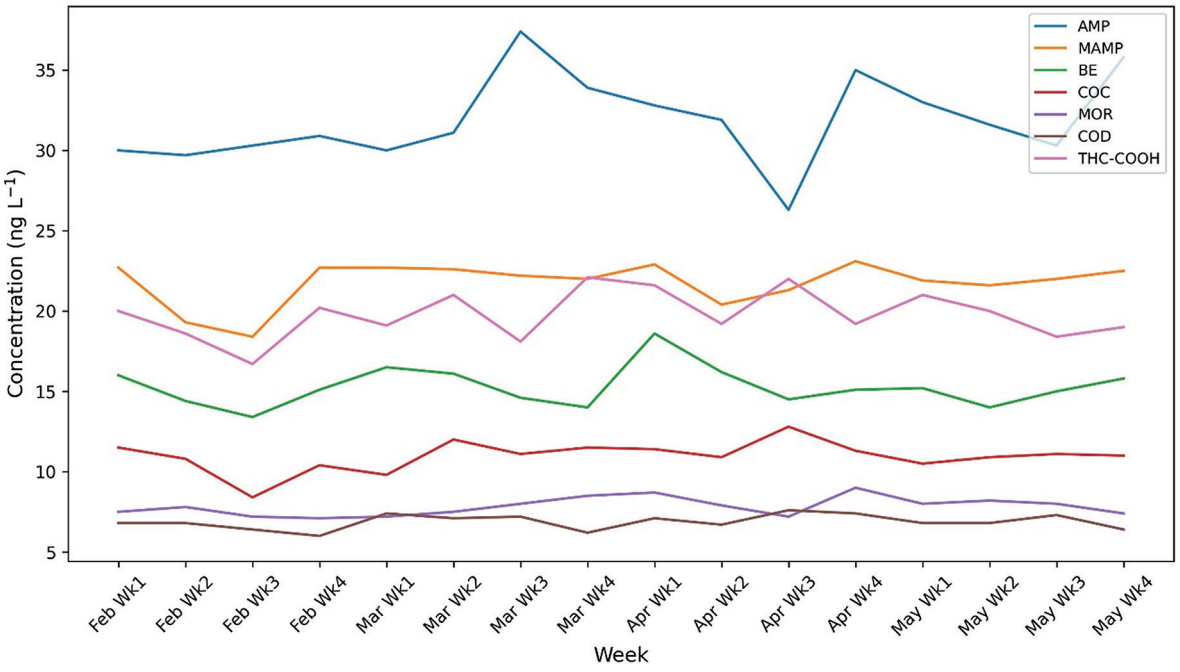


Figure 1: Weekly variation in concentrations of AMP, MAMP, BE,COC,MOR,COD and THC-COOH in influent wastewater over a 16-week monitoring period.

human behaviour and wastewater composition dynamics[35]. The weekly temporal variations of metabolite concentrations in the influent of the Nairobi wastewater treatment facility are shown in Figure 1

Temporal trends and comparison of drug biomarker profiles

Weekly influent concentration data were examined using linear regression to determine short-term temporal trends (Table 2). The predicted slopes varied from +0.006 ng L^{-1} $week^{-1}$ for benzoylecgonine to +0.179 ng L^{-1} $week^{-1}$ for amphetamine. When compared to the corresponding mean concentrations and standard deviations, these slopes were quite tiny, indicating only minor week-to-week volatility across the monitoring interval. Positive slopes were found for all analytes, indicating slight increasing trends; nevertheless, the degree of change remained small throughout the 16-week sampling period.

A comparative analysis of pharmacological biomarker classes revealed significant disparities in concentration profiles. Stimulant biomarkers (AMP and MAMP) were consistently higher mean concentrations than cocaine-related biomarkers (BE and COC). Opioid biomarkers (MOR and COD) persisted at significantly lower levels throughout the monitoring period.

THC-COOH, a cannabis metabolite, was found at amounts comparable to stimulant indicators and was consistently present at nanogram-per-liter levels in all samples. THC-COOH is a metabolite produced solely by human metabolism and is largely regarded as a credible biomarker for cannabis exposure in wastewater[31].

Interestingly, in every weekly sample, the amounts of benzoylecgonine were consistently higher than those of the parent molecule cocaine. This finding supports BE's dependability as a wastewater biomarker for cocaine exposure since it is consistent with known metabolic pathways and shows how stable BE is in sewer systems. Thirty Long-term wastewater monitoring studies carried out in urban areas throughout Europe have revealed similar temporal stability of benzoylecgonine [23, 25].

Among the drugs examined, amphetamine had the highest mean influent concentrations. Because amphetamine can come from both direct intake and the metabolic conversion of methamphetamine, the interpretation of amphetamine-type stimulants in wastewater is complicated. This analytical constraint has been brought to light by earlier wastewater-based epidemiology studies, which also stressed the significance of enantiomeric profiling for differentiating possible sources. Therefore, the lack of chiral analysis in this work is both a methodological drawback and a chance for future analytical improvement in Kenyan wastewater monitoring research.

Over the course of the monitoring period, morphine and codeine were found at lower amounts and showed no temporal fluctuation. Contributions from both non-medical exposure and therapeutic pharmaceutical usage confound the interpretation of opioid biomarkers in wastewater[32–34]. As a result, it is advisable to interpret opioid biomarker data with caution and to include complementary prescription or public health datasets.

The lack of continuous influent flow measurements and accurate population estimates for the wastewater catchment prevented quantitative back-calculation of per-capita drug consumption. Wastewater systems in low- and middle-income nations frequently have these restrictions. However, the current study reduced methodological variability and made it possible to reliably examine relative temporal patterns using concentration-based wastewater data by maintaining consistent sampling locations, collection times, and analytical techniques.

Overall, the findings show that concentration-based wastewater epidemiology can generate analytically sound baseline datasets for community-level drug exposure in urban Sub-Saharan African contexts. These findings provide an initial monitoring framework for Nairobi and promote the growth of wastewater-based drug surveillance in the region through longer monitoring periods, enhanced flow measuring infrastructure, and more sophisticated population normalisation methodologies[6].

Table 2 Mean, sample standard deviation (SD) and linear trend slope (ng·L^{-1} per week) for each analyte across 16 weeks (Feb–May).

Analyte	Mean (ng·L^{-1})	SD (ng·L^{-1})	Linear slope (ng·L^{-1}·$week^{-1}$)
AMP	31.875	2.725	+0.179
MAMP	21.769	1.336	+0.076
BE	15.281	1.255	+0.006
COC	10.963	0.961	+0.057
MOR	7.825	0.573	+0.046
COD	6.875	0.461	+0.021
THC-COOH	19.763	1.510	+0.051

SD: Standard deviation. Note: See Table S1 in the SI for data.

CONCLUSION

This study offers one of the first high-resolution wastewater-based epidemiology (WBE) evaluations of drug exposure at the community level in Kenya. Over the course of four months, influent wastewater from a significant Nairobi treatment plant consistently contained biomarkers for stimulants, cocaine, cannabinoids, and opioids. A strong baseline for future monitoring in this under-represented area is established by the consistent detection of all targeted analytes combined with mild week-to-week fluctuation, which suggests stable background exposure rather than intermittent discharge events.

The preponderance of amphetamine-class stimulants and the stable behaviour of THC-COOH and benzoylecgonine are consistent with global WBE data, indicating that internationally recognised biomarkers and analytical techniques can be applied in an urban Sub-Saharan African setting. However, the findings also point to important interpretive issues, such as source uncertainty for amphetamine-type stimulants and the impact of legal pharmaceutical use on opioid indicators, highlighting the necessity of more sophisticated analytical refinement and contextual data in subsequent research.

The descriptive concentration profiles and short-term temporal trends shown here show the technical viability and public-health significance of WBE in Nairobi, even though quantitative consumption estimates are not possible due to the lack of influent flow and population normalisation. WBE is a useful addition to conventional surveillance methods because it provides objective, anonymised indicators of drug exposure at the community level, especially in situations where self-reported or law enforcement data are few or skewed. Overall, this work emphasises the potential of WBE to inform integrated public-health, environmental, and policy responses and builds a core dataset for wastewater-based drug monitoring in Kenya. In order to enable quantitative consumption estimates and support evidence-based decision-making in rapidly urbanising low- and middle-income settings, future efforts should concentrate on expanded temporal coverage, spatial expansion across multiple catchments, integration of flow and population data, and adoption of advanced analytical techniques.

SUPPLEMENTARY INFORMATION

Supplementary information for this article is provided in the online supplement.

ACKNOWLEDGEMENTS

JKO would like to convey heartfelt gratitude to co-authors FOO and EAA of Rongo University for their great academic supervision, mentorship, and continuous support during the course of this study. JKO also thanks the management and staff at the Nairobi WWTP for their cooperation and help during the wastewater sample collecting period and the laboratory staff at Rongo University for their technical assistance with sample analysis and use of the LC-MS/MS.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

John K. Ochieng: conceptualisation, methodology, inquiry, data curation, formal analysis, visualisation, and original draft writing. Francis O. Olal: supervision, validation, methodology, writing, review and editing. Edward A. Anino and Dr. Maureen Adoyo: supervision, project administration, revision, writing, review and editing.

DECLARATION OF COMPETING OR FINANCIAL INTERESTS

The authors state that they have no known competing or financial interests that could have influenced the research presented in this study.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

The authors confirm that no generative artificial intelligence or AI-assisted technologies were used for the purpose of the research conducted or for the preparation of the manuscript.

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