Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Occurrence and variability of pharmaceuticals, pesticides, and polyphenols in Nyabugogo River, Rwanda

Brigitte Mukarunyana
Umeå University
Elias Nyandwi
University of Rwanda
Telesphore Kabera
University of Rwanda
Jerker Berglund Fick
jerker.fick@umu.se

Umeå University

Research Article

Keywords:

Posted Date: July 6th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9883112/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Environmental Monitoring and Assessment on October 15th, 2026. See the published version at https://doi.org/10.1007/s10661-026-16028-z.

Abstract

Pharmaceuticals, pesticides, and polyphenols are increasingly detected in aquatic environments, impacting water quality and aquatic life. This study screened these contaminants in Rwanda's Nyabugogo River, analysing 45 water samples from rural, peri-urban, and urban areas using solid-phase extraction and LC-MS/MS. Fifty-seven pharmaceuticals, five pesticides, and four polyphenols were quantified, with the highest average concentrations of albendazole (960 ng/L), metalaxyl (70 ng/L), and caffeic acid (49 ng/L). Pharmaceutical levels were significantly higher in urban areas, reflecting inadequate sanitation and wastewater management in Kigali, while pesticide and polyphenol concentrations varied across different types of land use, influenced by agricultural and urban discharges. Temporal sampling revealed significant within-day concentration fluctuations but consistent day-to-day levels, indicating persistent contamination sources. These findings provide essential baseline data for monitoring organic pollutants and informing strategies to mitigate contamination in urban river systems.

1. Introduction

The large-scale commercial production and use of human-made chemicals have led to the widespread release of harmful organic substances into river systems (Mishra et al., 2023; Wilkinson et al., 2022). Pharmaceuticals, pesticides, and polyphenols are among the most frequently detected contaminants in surface water, groundwater, and even drinking water, primarily due to their extensive use and inadequate disposal practices (Hejna et al., 2022; Mishra et al., 2023; Schwanen et al., 2023). Pharmaceuticals are medicinal substances used to diagnose, treat, prevent, or cure diseases in humans or animals. They include prescription drugs, over-the-counter medications, vaccines, and biologics. Their primary purpose is to improve health and manage medical conditions (Sittig, 2017). Pesticides are chemical or biological agents used to kill, repel, or control pests such as insects, weeds, fungi, rodents, or other organisms that threaten crops, human health, or the environment. Common categories include insecticides, herbicides, fungicides, and rodenticides (Elfikrie et al., 2020; Gruss et al., 2025). Polyphenols are a large class of organic compounds characterized by the presence of multiple phenol units, which consist of a benzene ring bonded to one or more hydroxyl groups. The main classes of polyphenols include flavonoids (such as catechins, isoflavones, quercetins, and cyanidins) and phenolic acids (such as chlorogenic, caffeic, and ferulic acids) (Di Lorenzo et al., 2021; Ndwabu et al., 2023). Polyphenols are primarily found in plants, fruits, chocolate, legumes, and beverages like tea, coffee, and wine, and encompass more than 8,000 different compounds (Di Lorenzo et al., 2021).

Pharmaceuticals enter the environment primarily through human and animal excretion, hospital and industrial discharges, and improper disposal of unused or expired medications (Anand et al., 2022; Larsson, 2014). A large proportion of pharmaceuticals consumed are eliminated either unchanged or as metabolites, which may retain similar or different characteristics compared to the original substances (Justyna & Zimmermann, 2022), and subsequently enter aquatic ecosystems through direct wastewater discharges or via discharges from municipal wastewater treatment plants (Anand et al., 2022; Justyna & Zimmermann, 2022). However, even treated effluent has been shown to contain elevated levels of

pharmaceuticals since most conventional treatment techniques have limited removal efficiency (Samal et al., 2022). Pesticides reach surface water mainly through agricultural runoff, spray drift, and leaching. Additionally, soil erosion in agricultural areas can transport pesticide-contaminated sediment into water bodies (Okoye et al., 2022; Zhou, Li, & Achal, 2025). Polyphenols originate from plants, but their presence in surface water can also result from anthropogenic activities, including agricultural runoff and discharges from industries such as pulp and paper, coffee processing, and olive washing stations (Lou et al., 2025; Wu et al., 2022). Additional sources include domestic wastewater and landfill leachate (Ndwabu et al., 2023). Concentrations of pharmaceuticals, pesticides, and polyphenols in surface water generally fall within the ng/L to µg/L range. These concentrations are associated with diffuse sources, including municipal wastewater effluents, agricultural runoff, and urban runoff (Mishra et al., 2023; Ndwabu et al., 2023; Wilkinson et al., 2022). Concentrations exceeding 100 µg/L indicate localized contamination, often found near direct discharge points such as industrial outfalls or heavily contaminated channels.

The ecological implications of pharmaceuticals, pesticides, and polyphenols have become an important focus of contemporary ecotoxicology. Pharmaceuticals, for example, can alter endocrine function, behaviour, metabolism, and reproduction in aquatic organisms, even at concentrations far below therapeutic doses (Anand et al., 2022; Larsson, 2014; Wilkinson et al., 2022). Pesticides, by design, are biologically active and can impair aquatic primary producers such as algae, phytoplankton, and aquatic plants (Abu Qamar et al., 2024). Insecticides can disrupt neurological function, leading to mortality or altered behaviour in invertebrates and fish, while herbicides can inhibit photosynthesis and reduce primary productivity, thereby influencing aquatic food webs. Fungicides may disrupt microbial communities that are essential for nutrient cycling (Abu Qamar et al., 2024; Gruss et al., 2025). Polyphenols can inhibit microbial growth, alter algal and plant physiology, and induce oxidative stress in aquatic organisms (Mumtaz et al., 2024; Ndwabu et al., 2023).

Several pharmaceuticals, pesticides, and polyphenols are persistent in aquatic ecosystems. Many pharmaceuticals are designed to resist metabolic and chemical degradation, thereby maintaining therapeutic activity in the human body (Gajula et al., 2021). These same properties chemical stability, low biodegradability, and resistance to hydrolysis and photolysis enable compounds such as antibiotics, antiretrovirals, and non-steroidal anti-inflammatories to persist in water bodies for prolonged periods (Anand et al., 2022; Gajula et al., 2021; Larsson, 2014). Likewise, numerous pesticides are formulated to resist environmental breakdown, providing long-lasting agricultural protection (Abu Qamar et al., 2024; Pathak et al., 2022). By contrast, polyphenols are generally more biodegradable; however, their persistence increases at high concentrations, when dissolved oxygen is limited, or when they bind to organic matter or sediments (Melo et al., 2005). Focusing on persistent compounds does not provide the full picture, as almost all of these are also pseudo-persistent, i.e., they are constantly present in certain aquatic environments due to constant release (Schwanen et al., 2023). Another complicating factor is the wide range of released pollutants, which can cause synergistic toxicity when combined, resulting in greater-than-expected harm and posing major risks to aquatic biodiversity (Mishra et al., 2023; Picó et al., 2020). This results from overlapping biological targets, cumulative stress, and complex interactions

among pharmaceuticals, pesticides, polyphenols, and other organic pollutants (Gruss et al., 2025). Together, these interacting pollutants suppress primary producers, destabilize food-web relationships, reduce species richness, and impair ecosystem recovery capacity, making contaminant mixtures a major driver of biodiversity decline in aquatic environments (Alameddine et al., 2021; Mishra et al., 2023).

There is an urgent need to investigate organic pollutants in African rivers, as information on the presence and distribution of these contaminants is still limited (Munzhelele et al., 2024; Okoye et al., 2022). These concerns are heightened by the increased use of pharmaceuticals in recent decades, improved agricultural practices, and the growth of the industrial sector (Okoye et al., 2022).

The Nyabugogo River is an important tributary of the Nyabarongo River, joining it shortly before the confluence with the Akanyaru River to form the Akagera River, which drains 85% of Rwanda's water into the Nile Basin via Lake Victoria (Julien et al., 2023; Omara et al., 2020). Previous studies indicate that the ecological health of the Nyabugogo River is declining rapidly due to dynamic land-use changes from rural to peri-urban and urban areas, the release of untreated sewage, plastic debris, industrial waste, and sediment accumulation from erosion (Omara et al., 2020). Several studies have been conducted in the Nyabugogo River to identify the presence of heavy metals, increased nutrient loads, chemical oxygen demand (COD), and biological oxygen demand (BOD) (Musabyimana & Bazimenyera, 2023; Nhapi et al., 2011). To our knowledge, no studies have identified and quantified organic pollutants in the river. This study aims to analyse pharmaceuticals, pesticides, and polyphenols in the Nyabugogo River, its tributaries, and channels discharging into the river, using an analytical method that covers a broad spectrum of these compounds.

2. Materials and methods

2.1. Description of sampling area

The Nyabugogo River stretches 46 km (Nzabonantuma et al., 2015) from the outlet of Lake Muhazi to its confluence with the Nyabarongo River (from 1°47'06"S and 30°07'57"E to 1°57'17"S and 30°00'24"E). The Nyabugogo catchment area (1,661 km²) covers rural, peri-urban, and urban areas, representing 6.31% of Rwanda's total surface area (26,338 km²) (Ministry of Environment, 2018). The number of people living within the catchment has been estimated at 1,400,000, with 47% in urban and peri-urban areas and 53% in rural areas (NISR, 2023). Upstream rural areas in Rwanda's Northern and Eastern Provinces have population densities of 340–630 inhabitants per km² and are predominantly agricultural, with maize, bean, vegetable, sugarcane, and rice cultivation, complemented by small-scale quarrying and cassiterite mining, as well as infrastructure including local markets and health centres (NISR, 2023; Republic of Rwanda, 2020). Peri-urban areas (1,100–1,700 inhabitants per km²) feature mixed land use, combining agriculture (rice, maize, and vegetables), small-scale quarrying, and limited industrial activities, including the Kabuye sugarcane factory, as well as markets and health facilities (NISR, 2023). Urban areas in Kigali have high population densities (7,600–17,000 inhabitants per km²), and are characterized by

concentrated industrial activities, extensive social infrastructure, and localized urban agriculture in the Nyabugogo wetland near the Nyabarongo River confluence (NISR, 2023).

2.2. Sampling sites and sampling

Sampling sites were selected based on the delineation of the Nyabugogo River in GIS. A total of 45 water samples were collected: 26 from the Nyabugogo River, from N1 (upstream, at its origin) to N26 (downstream, where it meets the Nyabarongo River), ten from tributaries (T1 to T10), and nine from channels or drains (C1 to C9). In tributaries and channels, water samples were taken ten metres before their confluences with the river, and corresponding river samples were taken approximately one hundred metres downstream.

Sampling sites N1–N6 and T1–T6 are in rural areas, N7–N14, T7, and C1–C2 are situated in the peri-urban area, and N15–N26, T8–T10, and C3–C9 are urban sites. From N14 to N26, the river traverses the Nyabugogo wetland. Sampling site locations and coordinates are provided in Fig. 1 and Table S1 (Supplementary Information), respectively.

Sampling occurred over three consecutive weeks, from 6 to 24 January 2025, each day from 8 a.m. until 5 p.m. One 450 ml sample was collected at each site. Additionally, samples were collected from site N21, located in the urban area of the Nyabugogo River in the Nyabugogo Centre, to monitor variations in concentrations of targeted organic pollutants. Sampling was conducted at N21 over five consecutive days at 8 a.m., 1 p.m., and 5 p.m. Water samples were collected at depths of 15 to 60 cm to avoid the surface layer at each site. The sampling process involved rinsing a 500 ml polyethylene bottle three times with water from the site, then submerging it and filling it with approximately 450 ml. At each sample collection site, the geographical coordinates were registered using the Google Earth application. The samples were quickly placed in cool boxes at around 4°C and transported within five hours to the chemistry laboratory at the University of Rwanda. They were stored at -18°C until analysis at Umeå University's environmental chemistry laboratory in Sweden.

2.2. Chemicals

All chemical standards, including the 24 internal standards used in this study, were classified as analytical grade (95–99.8%). Stock solutions for each analyte were prepared using methanol or acetonitrile and stored at -18°C. This study included 158 compounds: 145 pharmaceuticals, 9 pesticides, and 4 polyphenolic compounds, selected based on regional use. LC/MS grade methanol and acetonitrile (LiChrosolv hypergrade) were obtained from Merck (Darmstadt, Germany). To produce purified water, a Milli-Q Advantage system with an ultraviolet radiation source (Millipore, Billerica, USA) was used. Formic acid (Sigma-Aldrich, Steinheim, Germany) at 0.1% was used to prepare the mobile chromatographic phases.

2.3. Solid-phase extraction and LC-MS/MS analysis

Pretreatment was performed using solid-phase extraction (SPE). Before carrying out the SPE, 5 ng of internal standards containing labelled compounds were added to each sample (450 ml). The Oasis HLB

cartridges were conditioned using 5 ml of methanol and 5 ml of Milli-Q water. Samples were then loaded into the cartridges at a relatively low flow rate (0.1 ml/s) to allow analytes to bind to the stationary phase. Finally, analytes were eluted using 5 ml of methanol. The solution from the extraction of each sample was then evaporated to approximately 25 µl and reconstituted with methanol to 1 ml in LC-MS vials. Samples were analysed using ultra-high-performance liquid chromatography coupled with tandem mass spectrometry (UHPLC-MS/MS). A Dionex UltiMate 3000 UHPLC system, which comprises two liquid chromatography pumps (an Ultimate LPG 3400SD quaternary pump and an HPG 3400RS binary UHPLC pump), an analytical column (Thermo Scientific Hypersil GOLD Aq 100 × 2.1 mm, 3 µm), and a precolumn (Hypersil GOLD, 10 × 2.1 mm, 3 µm), all connected to a TSQ Quantiva triple quadrupole mass spectrometer (Thermo Scientific), was used to analyse samples. A heated-electrospray ionization (HESI) source was utilized in positive or negative ionization modes. Chromeleon Xpress (Thermo Scientific) was utilized to manage the UHPLC system. The chromatographic separation was conducted using a gradient of Milli-Q water and methanol (LiChrosolv, Merck, Darmstadt, Germany). The mobile phase featured a gradient containing 0.1% formic acid in Milli-Q water and 0.1% formic acid in methanol. The resolution for both quadrupole instruments was adjusted to 0.7 full width at half maximum height. The voltage for the spray was adjusted to 3,500 V with sheath gas at 40 arbitrary units, sweep gas at zero arbitrary units, ion transfer tube temperature at 350°C, and vaporizer temperature at 338°C. Two MS/MS transitions were tracked for each analyte: one for quantification and another for qualification. Peak identification was performed by comparing sample components with those of internal standards using Xcalibur™ 4.3 software (Thermo Fisher Scientific). To evaluate linearity and carry out quantification, an eight-point calibration curve ranging from 10 to 1,000 ng/L was utilized. The transitions, precursors, and collision energies of pesticides and polyphenols analysed in this study are presented in Table S2 of the supplementary materials.

2.4. Statistical analysis

For the observed pharmaceuticals, pesticides, and polyphenols, the following characteristics were measured: average (Av) and standard deviation (SD). For site N21, where data were collected for five consecutive days and three times a day, morning (8 a.m.), noon (1 p.m.), and evening (5 p.m.) – averages and SD were computed for each pharmaceutical, pesticide, and polyphenol at each time of collection. A comparative analysis, t-test, and ANOVA were conducted to test the significance of differences in the average concentrations of detected compounds between rural, peri-urban, and urban areas, and in the times and days of collection. For this analysis, a 5% level of significance was used.

3. Results and discussion

3.1. Analysis of water samples

The average concentrations (n = 45) ranged from < LOQ to 960 ng/L for pharmaceuticals, 1.9 to 70 ng/L for pesticides, and 3.6 to 49 ng/L for polyphenols. The maximum concentrations detected were 4,200

ng/L for pharmaceuticals (albendazole) at site C9, 130 ng/L for pesticides (metalaxyl) at site C9, and 190 ng/L for polyphenols (ferulic acid) at site C2.

Of the 145 targeted compounds, 57 pharmaceuticals were detected and quantified, representing five major groups and 21 therapeutic classes under the Anatomical Therapeutic Chemical (ATC) classification system (Table S3). Detected compounds comprised 12 antibacterials, eight antiretrovirals, and four antimycobacterials; nine cardiovascular agents (including calcium channel blockers, angiotensin-related agents, and beta blockers); and eight nervous system drugs (psycholeptics, psychoanaleptics, and antiepileptics). Additional detections included five respiratory drugs (mainly antihistamines), four musculoskeletal anti-inflammatories, four alimentary tract and metabolism agents (stomatologicals, antacids, and antidiarrheals), two dermatological agents, and one antihelminthic. These results indicate a complex mixture of pharmaceuticals exerting diverse contamination pressures on the Nyabugogo River system. In the river samples (n = 26), average concentrations ranged from < LOQ ng/L to 740 ng/L. The five pharmaceuticals with the highest concentrations were albendazole, paracetamol, triclosan, tetracycline, and nevirapine, with average concentrations of 740 ng/L, 620 ng/L, 120 ng/L, 98 ng/L, and 90 ng/L, respectively. Their maximum concentrations were 2,200 ng/L, 2,100 ng/L, 210 ng/L, 180 ng/L, and 250 ng/L, respectively. Albendazole, found in samples, is widely utilized to treat parasitic worm infections in both humans and animals (Ido et al., 2025). Rwanda, similarly to other sub-Saharan African countries, implements large-scale albendazole administration through school- and community-based mass deworming programmes, resulting in widespread and recurrent population exposure to albendazole (WHO, 2018). The average concentration of albendazole in this study (960 ng/L) was lower than the estimated surface water concentration in the East African region (20,000 ± 150 ng/L), calculated using a model based on consumption (Belew et al., 2021).

Five of the nine targeted pesticides and all four targeted polyphenols were detected (Table S4 in the supplementary information). The average concentration of metalaxyl found in this study (70 ng/L) was within the range of 60 to 4,800 ng/L reported for samples from Lake Muhazi, Lake Mugesera, and the Sebeya River in Rwanda (Houbraken et al., 2017). Metalaxyl has been detected in surface waters worldwide, with average concentrations ranging from 18 ng/L to 1,300 ng/L (Struger et al., 2016; Zheng et al., 2016), consistent with observations in this study. Caffeic acid was the most abundant polyphenol, with an average concentration of 49 ng/L and a maximum concentration of 160 ng/L. Reported concentrations of polyphenols, including chlorogenic and ferulic acids, range from 60 ng/L to 24,000 ng/L (Chen et al., 2021; Ramos et al., 2021). Levels of polyphenols in aquatic environments depend on factors such as waste management, land use, seasonal runoff, and vegetation inputs (Ramos et al., 2021; Ziegler et al., 2025).

2.2. Distribution of organic compounds in the Nyabugogo River

Concentrations of pharmaceuticals in the Nyabugogo River showed a distinct rural–urban gradient, with consistently low levels in rural and peri-urban areas and markedly high levels in urban areas (Fig. 2).

In addition, statistics indicated that the difference in average concentrations in the river between rural and peri-urban areas was not significant ($p = 0.08$), whereas the difference between rural and urban areas was significant ($p = 0.017$). The highest concentrations were recorded at sites N18–N21, which are reported to be the most polluted points in the Nyabugogo wetland (Sekomo et al., 2014). At the urban sites, the Nyabugogo River receives untreated domestic, institutional (healthcare and educational), and commercial effluents via channels C5–C8, as well as treated and untreated inputs from the Mpazi tributary (T9) and industrial discharges from Kigali. Additional pollution sources include untreated wastewater and sewage from the Nyabugogo food market (via C9), as reported in studies of the Nyabugogo wetland (Ministry of Environment, 2018; Musabyimana & Bazimenyera, 2023; Omara et al., 2020). No channels were identified between N21 and N26, and pharmaceutical concentrations declined along this reach, likely due to dilution by the Yanze tributary (T10) between N22 and N23 and in-stream degradation processes.

The concentrations of pesticides and polyphenols measured in the Nyabugogo River across rural, peri-urban, and urban sites did not differ significantly (t-test, $p = 0.99$), see Fig. 3.

Although total concentrations generally decreased downstream, substantial overlap among land-use categories was observed, indicating that the river functions as a hydrologically integrated system rather than discrete pollution zones (Gavrilaș et al., 2025). This homogenization is caused by continuous inputs from multiple wastewater tributaries and channels discharging into the river (Anand et al., 2022; Gavrilaș et al., 2025). The fact that these discharges are scattered can increase variability within these three areas and obscure any significant differences expected between rural and peri-urban agricultural sources and urban runoff (Gavrilaș et al., 2025; Ziegler et al., 2025). Moreover, flow dynamics and degradation processes such as microbial breakdown and photolysis further mix and normalize concentrations across the river continuum (Picó et al., 2020; Schwanen et al., 2023).

Pesticide occurrence in rural and peri-urban areas is primarily attributable to agricultural activities and runoff from cultivated fields. In urban areas, despite limited agricultural activity, elevated pesticide concentrations at sites N18–N20 may also result from wastewater generated during the washing of fruits and vegetables at the major food market at the Nyabugogo Centre. Additionally, the Mpazi tributary (T9) may also contribute by transporting wastewater from restaurants and abattoirs at the centre.

The presence of polyphenols in the Nyabugogo River is likely attributable to the degradation of fruit and vegetable waste entering the aquatic system (Ndwabu et al., 2023). In addition, effluents from industries, e.g. the Kabuye sugar factory, are discharged directly into the river and may substantially contribute to the elevated concentrations of caffeic and ferulic acids observed at sampling site N10 in the peri-urban zone, since sugarcane stems and leaves are known to contain significant levels of phenolic acids, particularly caffeic and ferulic acids (Lou et al., 2025). Further potential sources of polyphenols include coffee-roasting facilities, discarded spent coffee grounds, used tea leaves, and residues from other plant-derived beverages (Wu et al., 2022) originating from hotels and restaurants situated along the Nyabugogo River corridor.

3.2. Concentration variability at the N21 sampling site in the Nyabugogo River

The investigation of variations in concentrations of selected compounds in water samples collected at site N21 showed that the average concentrations of detected pharmaceuticals over the five days ranged from < LOQ ng/L to 1,400 ng/L, as indicated in Table S5 of the supplementary materials. Figure 4 showed that concentrations of pharmaceuticals at 8 a.m. and 5 p.m. were higher than at midday (1 p.m.), and the p-values from the ANOVA in Table S6 of the supplementary materials indicated that differences in concentrations for each analyte at these times of day were statistically significant (all P values were lower than 0.05).

Variations in pharmaceutical concentrations observed at N21 in the Nyabugogo River (approximately 200 metres from the Nyabugogo Centre) reflect both the daily patterns of domestic water use and the structural characteristics of Kigali's sanitation and faecal sludge management systems. The elevated concentrations detected at 8 a.m. may be linked to morning sanitation activities and an increased pollutant load. This observation corresponds with the fact that approximately 95% of households in Kigali rely on onsite sanitation systems, with pit latrines accounting for roughly 85% of these facilities, which can overflow or leak into adjacent channels (Akumuntu et al., 2017; Murebwayire et al., 2025; Rutayisire & Kuria, 2024). In addition, Kigali does not yet have a formal centralized sewer network; instead, it operates with 15 semi-centralized sewage treatment systems that only serve a small fraction of the urban population, leaving most wastewater and faecal sludge unmanaged or partially treated before entering the environment (Burt et al., 2019; Murebwayire et al., 2025; Rutayisire & Kuria, 2024).

In addition to these structural limitations, human behaviour related to faecal sludge disposal can also contribute, since there is limited access to affordable and reliable faecal sludge management services (Burt et al., 2019; Tsinda et al., 2021). Illegal faecal sludge dumping, driven by the high cost and limited capacity of formal emptying services in Kigali, has been reported (Akumuntu et al., 2017; Rutayisire & Kuria, 2024; Tsinda et al., 2021) and is typically carried out early in the morning or in the evening to minimize the risk of being caught and punished (Murebwayire et al., 2025; Tsinda et al., 2013). Moreover, informal channels, commonly found in upstream informal settlements, may accumulate wastewater overnight and then release it in a concentrated flush in the morning.

Results from the N21 site also showed that the average levels of pesticides and polyphenols ranged from 1.3 ng/L to 40 ng/L for pesticides, and from 1.9 ng/L to 37 ng/L for polyphenols, as shown in Table S7 of the supplementary information. Also, as shown in Fig. 5a, concentrations at 8 a.m. and 5 p.m. were higher than those at midday (around 1 p.m.).

This could also be due to domestic wastewater, discharges from food markets, and restaurant cleaning, which often takes place in the morning and evening. The food market (Mutangana market) located at the Nyabugogo Centre is one of the main markets in Kigali, selling fruits and vegetables. When fruits and vegetables are washed at processing plants or in agricultural settings, the pesticides on their surfaces

are washed into the water used (Sayed et al., 2021). Moreover, non-edible fractions of fruits and vegetables, including peels, skins, and leaves, are known to retain measurable pesticide residues (Sayed et al., 2021). During processing or disposal of these plant materials, the resulting wastewater can therefore serve as a pathway for the release of pesticide contaminants into the surrounding environment (Nuruzzaman et al., 2025).

Caffeic acid and chlorogenic acid showed a different trend, with higher concentrations observed at midday (Fig. 5b). These elevated concentrations may be linked to wastewater discharges occurring during industrial working hours (8 a.m.–5 p.m.). Effluent discharged from industries located in the Kigali Special Economic Zone (KSEZ) will reach the N21 sampling point in the Nyabugogo River after one hour. KSEZ hosts over 100 industries, including coffee bean roasting facilities. Coffee beans contain high levels of chlorogenic acids, especially 5-caffeoylquinic acid (Pyrzynska, 2025; Rodrigues et al., 2023; Wu et al., 2022), which break down when roasted to form caffeic and quinic acids, along with smaller amounts of ferulic acid resulting from the decomposition of minor feruloyl quinic acid derivatives and phenolics linked to lignin (da Silva et al., 2025; Rodrigues et al., 2023; Wu et al., 2022). Therefore, wastewater from coffee-roasting facilities is expected to contain low levels of ferulic acid and be dominated by chlorogenic and caffeic acids (Pyrzynska, 2025; Wu et al., 2022). This may explain the study's observations, where chlorogenic acid and caffeic acid show pronounced midday and evening peaks, while ferulic acid levels remain comparatively lower (Wu et al., 2022).

P-values from ANOVA indicated that the concentration variations between days for pharmaceuticals, pesticides, and polyphenols were not statistically significant, suggesting that sources of contamination were constant.

These findings demonstrate how both infrastructural challenges and socially mediated disposal practices influence the temporal variability of pharmaceutical pollution in the Nyabugogo River. They also underscore the need for strengthened faecal sludge management regulation, enhanced wastewater treatment capabilities, and enforcement strategies to mitigate pollutant loadings and protect water quality in rapidly urbanizing locations such as Kigali.

4. Conclusion

The contamination of Rwandan rivers with pharmaceuticals, pesticides, and polyphenols is a critical issue that demands attention from all stakeholders. This study detected 66 chemicals in the Nyabugogo River, and the chemicals with the highest average concentrations were albendazole (960 ng/L) for pharmaceuticals, metalaxyl (70 ng/L) for pesticides, and caffeic acid (49 ng/L) for polyphenols. The highest concentrations of pharmaceuticals were observed in samples collected from urban areas, indicating the inadequacy of sanitation systems in Kigali. Pesticide and polyphenol concentrations did not differ significantly between rural, peri-urban, and urban areas, suggesting that agricultural activities in rural and peri-urban areas contribute significantly to contamination of the Nyabugogo River far downstream. The analysis of concentration changes at site N21 near the Nyabugogo Centre revealed

that differences in concentrations of all analysed pharmaceuticals and pesticides within the day were statistically significant. However, their day-to-day variations were not statistically significant, indicating that contamination sources are likely permanent. Further studies are urgently needed to monitor organic contaminants in the Nyabugogo River and to assess the risks to aquatic life and human health.

Declarations

Author Contribution

B.M. Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Validation, Resources, Project administration, Writing - Original Draft, Visualization, Reviewing and EditingE.N. Conceptualization, Investigation, Methodology, Software, VisualizationT.K. Conceptualization, Funding acquisition, Project administration, resources, Supervision, Reviewing and EditingJ.F. Conceptualization, Methodology, Validation, Formal analysis, Resources, Data curation, Funding acquisition, Supervision, Project administration, Visualization, Reviewing and Editing

Acknowledgement

The authors wish to thank the Swedish International Development Agency for funding this study through the UR–Sweden cooperation programme. Sincere gratitude is extended to Prof. Wellars Banzi of the Department of Mathematics for assistance with the statistical analysis of the data. Many thanks also to Mr Mbanzi Iradukunda Valere for his help with the production of the sampling sites map. The authors also thank the laboratory technicians at the Department of Chemistry at the School of Science, University of Rwanda, for providing instruments and materials for storing and pre-treating water samples.

References

1. Abu Qamar, S. F., El-Saadony, M. T., Alkafaas, S. S., Elsalahaty, M. I., Elkafas, S. S., Mathew, B. T., Aljasmi, A. N., Alhammadi, H. S., Salem, H. M., Abd El-Mageed, T. A., Zaghloul, R. A., Mosa, W. F. A., Ahmed, A. E., Elrys, A. S., Saad, A. M., Alsaeed, F. A., & El-Tarabily, K. A. (2024). Ecological impacts and management strategies of pesticide pollution on aquatic life and human beings. *Marine Pollution Bulletin*, *206*, 116613. https://doi.org/https://doi.org/10.1016/j.marpolbul.2024.116613
2. Akumuntu, J. B., Wehn, U., Mulenga, M., & Brdjanovic, D. (2017). Enabling the sustainable Faecal Sludge Management service delivery chain—A case study of dense settlements in Kigali, Rwanda. *International journal of hygiene and environmental health*, *220*(6), 960–973.
3. Alameddine, M., Siraki, A., Tonoyan, L., & El-Din, M. G. (2021). Treatment of a mixture of pharmaceuticals, herbicides and perfluorinated compounds by powdered activated carbon and ozone: synergy, catalysis and insights into non-free OH contingent mechanisms. *Science of The Total Environment*, *777*, 146138.

4. Anand, U., Adelodun, B., Cabreros, C., Kumar, P., Suresh, S., Dey, A., Ballesteros, F., & Bontempi, E. (2022). Occurrence, transformation, bioaccumulation, risk and analysis of pharmaceutical and personal care products from wastewater: a review. *Environmental Chemistry Letters*, *20*(6), 3883–3904. https://doi.org/10.1007/s10311-022-01498-7
5. Belew, S., Suleman, S., Wynendaele, E., Duchateau, L., & De Spiegeleer, B. (2021). Environmental risk assessment of the anthelmintic albendazole in Eastern Africa, based on a systematic review. *Environ Pollut*, *269*, 116106. https://doi.org/10.1016/j.envpol.2020.116106
6. Burt, Zachary, Sklar, R., & Murray, A. (2019). Costs and willingness to pay for pit latrine emptying services in Kigali, Rwanda. *International Journal of Environmental Research and Public Health*, *16*(23), 4738.
7. Chen, Y., Zhang, J., Dong, Y., Duan, T., Zhou, Y., & Li, W. (2021). Phenolic compounds in water, suspended particulate matter and sediment from Weihe River in Northwest China. *Water Sci Technol*, *83*(8), 2012–2024. https://doi.org/10.2166/wst.2021.119
8. da Silva, W. B., Rocha, L. M., Soares, M. S., Good God, P. I. V., da Silva, S. A., Moreira, D. B., & Silva, G. H. (2025). Validation of Methodology for Quantifying Caffeic and Ferulic Acids in Raw and Roasted Coffee Extracts by High-Performance Liquid Chromatography. *J*, *8*(1), 8.
9. Di Lorenzo, C., Colombo, F., Biella, S., Stockley, C., & Restani, P. (2021). Polyphenols and human health: The role of bioavailability. *Nutrients*, *13*(1), 273.
10. Elfikrie, N., Ho, Y. B., Zaidon, S. Z., Juahir, H., & Tan, E. S. S. (2020). Occurrence of pesticides in surface water, pesticides removal efficiency in drinking water treatment plant and potential health risk to consumers in Tengi River Basin, Malaysia. *Science of The Total Environment*, *712*, 136540. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.136540
11. Gajula, S. N. R., R., S. N., Nadimpalli, N., & Sonti, R. (2021). Drug metabolic stability in early drug discovery to develop potential lead compounds. *Drug Metab Rev*, *53*(3), 459–477. https://doi.org/10.1080/03602532.2021.1970178
12. Gavrilaș, S., Burescu, F.-L., Chereji, B.-D., & Munteanu, F.-D. (2025). The impact of anthropogenic activities on the catchment's water quality parameters. *Water*, *17*(12), 1791.
13. Gruss, I., Bączek, P., Ćwieląg-Piasecka, I., Jędrzejewski, S., Magiera-Dulewicz, J., & Twardowska, K. (2025). Assessing the ecotoxicological effects of pesticides on non-target plant species. *Environmental Monitoring and Assessment*, *197*(9), 1047.
14. Hejna, M., Kapuścińska, D., & Aksmann, A. (2022). Pharmaceuticals in the Aquatic Environment: A Review on Eco-Toxicology and the Remediation Potential of Algae. *Int J Environ Res Public Health*, *19*(13). https://doi.org/10.3390/ijerph19137717
15. Houbraken, M., Habimana, V., Senaeve, D., López-Dávila, E., & Spanoghe, P. (2017). Multi-residue determination and ecological risk assessment of pesticides in the lakes of Rwanda. *Science of The Total Environment*, *576*, 888–894.
16. Ido, A., Inoue, Y., Okujima, C., Okamoto, M., Miura, T., Kawashima, A., & Takahashi, S. (2025). Distribution and persistence of the anthelmintic drug albendazole in yellowtail aquaculture.

Aquaculture Reports, *44*, 103038. https://doi.org/https://doi.org/10.1016/j.aqrep.2025.103038

17. Julien, N., Innocent, N., Innocent, N., & Alice, M. M. (2023). Assessment on the impacts of urbanization on Wetlands. Case Study City of Kigali. *Global Scientific Journals*, *11*(11), 1325–1340.
18. Justyna, R., & Zimmermann, A. (2022). Household Pharmaceutical Waste Disposal as a Global Problem—A Review. *International Journal of Environmental Research and Public Health*, *19*(23), 15798. https://www.mdpi.com/1660-4601/19/23/15798
19. Larsson, D. (2014). Pollution from drug manufacturing: review and perspectives. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1656).
20. Lou, H., Xie, L., Wang, X., Li, X., He, L., & Li, F. (2025). Metabolomic Analysis Revealed the Differences in Metabolites Between Three Different Sugarcane Stems and Leaves. *Metabolites*, *15*(5), 327. https://www.mdpi.com/2218-1989/15/5/327
21. Melo, J. S., Kholi, S., Patwardhan, A. W., & D'Souza, S. F. (2005). Effect of oxygen transfer limitations in phenol biodegradation. *Process biochemistry*, *40*(2), 625–628. https://doi.org/https://doi.org/10.1016/j.procbio.2004.01.049
22. Ministry of Environment. (2018). *Nyabugogo Catchment Management Plan (2018–2024)*.
23. Mishra, R. K., Mentha, S. S., Misra, Y., & Dwivedi, N. (2023). Emerging pollutants of severe environmental concern in water and wastewater: A comprehensive review on current developments and future research. *Water-Energy Nexus*, *6*, 74–95. https://doi.org/https://doi.org/10.1016/j.wen.2023.08.002
24. Mumtaz, F., Li, B., Al Shehhi, M. R., Feng, X., & Wang, K. (2024). Treatment of phenolic-wastewater by hybrid technologies: A review. *Journal of Water Process Engineering*, *57*, 104695. https://doi.org/https://doi.org/10.1016/j.jwpe.2023.104695
25. Munzhelele, E. P., Mudzielwana, R., Ayinde, W. B., & Gitari, W. M. (2024). Pharmaceutical Contaminants in Wastewater and Receiving Water Bodies of South Africa: A Review of Sources, Pathways, Occurrence, Effects, and Geographical Distribution. *Water*, *16*(6), 796. https://www.mdpi.com/2073-4441/16/6/796
26. Murebwayire, M. L., Nilsson, E., Nhapi, I., & Wali, U. G. (2025). A Systematic Review of Households' Fecal Sludge Management Situation to Identify Gaps and Improve Services: A Case of Kigali City, Rwanda. *Sustainability*, *17*(17), 7588.
27. Musabyimana, J. P., & Bazimenyera, J. d. D. (2023). Assessment of the Impacts of Converting Natural Wetlands to Agricultural Farms. Case of Nyabugogo, Kigali City, Rwanda. *Agricultural Sciences*, *14*(3), 422–431.
28. Ndwabu, Sinayo, Malungana, M., & Mahlambi, P. (2023). Phenolic compounds—Occurrence in water, sediment and sludge, and ecological risk evaluation. *CLEAN–Soil, Air, Water*, *51*(10), 2200404.
29. Nhapi, I., Uwonkunda, B., Nsengimana, H., Banadda, N., & Kimwaga, R. (2011). Assessment of Water Pollution Levels in the Nyabugogo Catchment, Rwanda. https://doi.org/10.2174/1874829501104010040

30. NISR. (2023). *Fifth Rwanda Population and Housing Census, 2022* (National Institute of Statistics of Rwanda, Issue.
31. Nuruzzaman, Md, Bahar, M. M., & Naidu, R. (2025). Diffuse soil pollution from agriculture: Impacts and remediation. *Science of The Total Environment*, *962*, 178398. https://doi.org/https://doi.org/10.1016/j.scitotenv.2025.178398
32. Nzabonantuma, L, Munyaneza, O., & Uwurukundo, E. (2015). Morphodynamic Study of A River to Attenuate Flood Waves, Case Study of Nyabugogo River in Rwanda. *Nile Water Science & Engineering Journal*, *8*, 78–90.
33. Okoye, C. O., Okeke, E. S., Okoye, K. C., Echude, D., Andong, F. A., Chukwudozie, K. I., Okoye, H. U., & Ezeonyejiaku, C. D. (2022). Occurrence and fate of pharmaceuticals, personal care products (PPCPs) and pesticides in African water systems: A need for timely intervention. *Heliyon*, *8*(3), e09143. https://doi.org/https://doi.org/10.1016/j.heliyon.2022.e09143
34. Omara, T., Nteziyaremye, P., Akaganyira, S., Opio, D. W., Karanja, L. N., Nyangena, D. M., Kiptui, B. J., Ogwang, R., Epiaka, S. M., & Jepchirchir, A. (2020). Physicochemical quality of water and health risks associated with consumption of African lung fish (Protopterus annectens) from Nyabarongo and Nyabugogo rivers, Rwanda. *BMC Research Notes*, *13*(1), 66.
35. Pathak, V. M., Verma, V. K., Rawat, B. S., Kaur, B., Babu, N., Sharma, A., Dewali, S., Yadav, M., Kumari, R., & Singh, S. (2022). Current status of pesticide effects on environment, human health and it's eco-friendly management as bioremediation: A comprehensive review. *Frontiers in microbiology*, *13*, 962619.
36. Picó, Y., Alvarez-Ruiz, R., Alfarhan, A. H., El-Sheikh, M. A., Alshahrani, H. O., & Barceló, D. (2020). Pharmaceuticals, pesticides, personal care products and microplastics contamination assessment of Al-Hassa irrigation network (Saudi Arabia) and its shallow lakes. *Science of The Total Environment*, *701*, 135021. https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.135021
37. Pyrzynska, K. (2025). Spent Coffee Grounds as a Source of Chlorogenic Acid. *Molecules*, *30*(3), 613. https://www.mdpi.com/1420-3049/30/3/613
38. Ramos, R. L., Lebron, Y. A. R., Moreira, V. R., de Souza Santos, L. V., & Amaral, M. C. S. (2021). Phenolic compounds in surface water: methodology and occurrence in Doce River, Brazil. *Environ Monit Assess*, *193*(10), 687. https://doi.org/10.1007/s10661-021-09420-4
39. Republic of Rwanda. (2020). *National land use & development master plan 2020–2050*.
40. Rodrigues, Raquel, Oliveira, M. B. P. P., & Alves, R. C. (2023). Chlorogenic acids and caffeine from coffee by-products: A review on skincare applications. *Cosmetics*, *10*(1), 12.
41. Rutayisire, B., & Kuria, N. (2024). *Baseline Assessment of Faecal Sludge Management and Pit Latrine Emptying in Kigali, Rwanda*.
42. Samal, Kundan, Mahapatra, S., & Hibzur Ali, M. (2022). Pharmaceutical wastewater as Emerging Contaminants (EC): Treatment technologies, impact on environment and human health. *Energy Nexus*, *6*, 100076. https://doi.org/https://doi.org/10.1016/j.nexus.2022.100076

43. Sayed, A., Chys, M., De Rop, J., Goeteyn, L., Spanoghe, P., & Sampers, I. (2021). Pesticide residues in (treated) wastewater and products of Belgian vegetable- and potato processing companies. *Chemosphere*, *280*, 130619. https://doi.org/https://doi.org/10.1016/j.chemosphere.2021.130619
44. Schwanen, C. A., Kronsbein, P. M., Balik, B., & Schwarzbauer, J. (2023). Dynamic Transport and Distribution of Organic Pollutants in Water and Sediments of the Rur River. *Water, Air, & Soil Pollution*, *235*(1), 9. https://doi.org/10.1007/s11270-023-06786-8
45. Sekomo, Uwamaliya Valentine, Omar Munyaneza, & Nkundimana, E. (2014). *Assessment of surface and groundwater quality in the Nyabugogo wetland–Impacts of domestic, industrial wastewaters and climate change* (University of Rwanda, College of Science and Technology, Issue.
46. Sittig, D. F. (2017). 1 - Category Definitions. In D. F. Sittig (Ed.), *Clinical Informatics Literacy* (pp. 1-170). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-803206-0.00001-8
47. Struger, J., Grabuski, J., Cagampan, S., Sverko, E., & Marvin, C. (2016). Occurrence and distribution of carbamate pesticides and metalaxyl in southern Ontario surface waters 2007–2010. *Bulletin of environmental contamination and toxicology*, *96*(4), 423–431.
48. Tsinda, Aime, Abbott, P., & Chenoweth, J. (2021). What makes Eastern African households living in urban informal settlements dissatisfied with their toilets? *Available at SSRN 3981338*.
49. Tsinda, A., Abbott, P., Pedley, S., Charles, K., Adogo, J., Okurut, K., & Chenoweth, J. (2013). Challenges to Achieving Sustainable Sanitation in Informal Settlements of Kigali, Rwanda. *International Journal of Environmental Research and Public Health*, *10*(12), 6939–6954. https://www.mdpi.com/1660-4601/10/12/6939
50. WHO. (2018). Schistosomiasis and soil-transmitted helminthiases: number of people treated in 2016. *Wkly Epidemiol Rec*, *92*(49), 749–760.
51. Wilkinson, J. L., Boxall, A. B. A., Kolpin, D. W., Leung, K. M. Y., Lai, R. W. S., Galbán-Malagón, C., Adell, A. D., Mondon, J., Metian, M., Marchant, R. A., Bouzas-Monroy, A., Cuni-Sanchez, A., Coors, A., Carriquiriborde, P., Rojo, M., Gordon, C., Cara, M., Moermond, M., Luarte, T.,.. . Teta, C. (2022). Pharmaceutical pollution of the world's rivers. *Proceedings of the National Academy of Sciences*, *119*(8), e2113947119. https://doi.org/doi:10.1073/pnas.2113947119
52. Wu, Hanjing, Lu, P., Liu, Z., Sharifi-Rad, J., & Suleria, H. A. (2022). Impact of roasting on the phenolic and volatile compounds in coffee beans. *Food science & nutrition*, *10*(7), 2408–2425.
53. Zheng, S., Chen, B., Qiu, X., Chen, M., Ma, Z., & Yu, X. (2016). Distribution and risk assessment of 82 pesticides in Jiulong River and estuary in South China. *Chemosphere*, *144*, 1177–1192.
54. Zhou, W., Li, M., & Achal, V. (2025). A comprehensive review on environmental and human health impacts of chemical pesticide usage. *Emerging Contaminants*, *11*(1), 100410. https://doi.org/https://doi.org/10.1016/j.emcon.2024.100410
55. Ziegler, A. D., Lee, T. H., Srinuansom, K., Boonta, T., Promya, J., & Webster, R. D. (2025). Canals, Contaminants, and Connections: Exploring the Urban Exposome in a Tropical River System. *Urban Science*, *9*(8), 302.

Figures

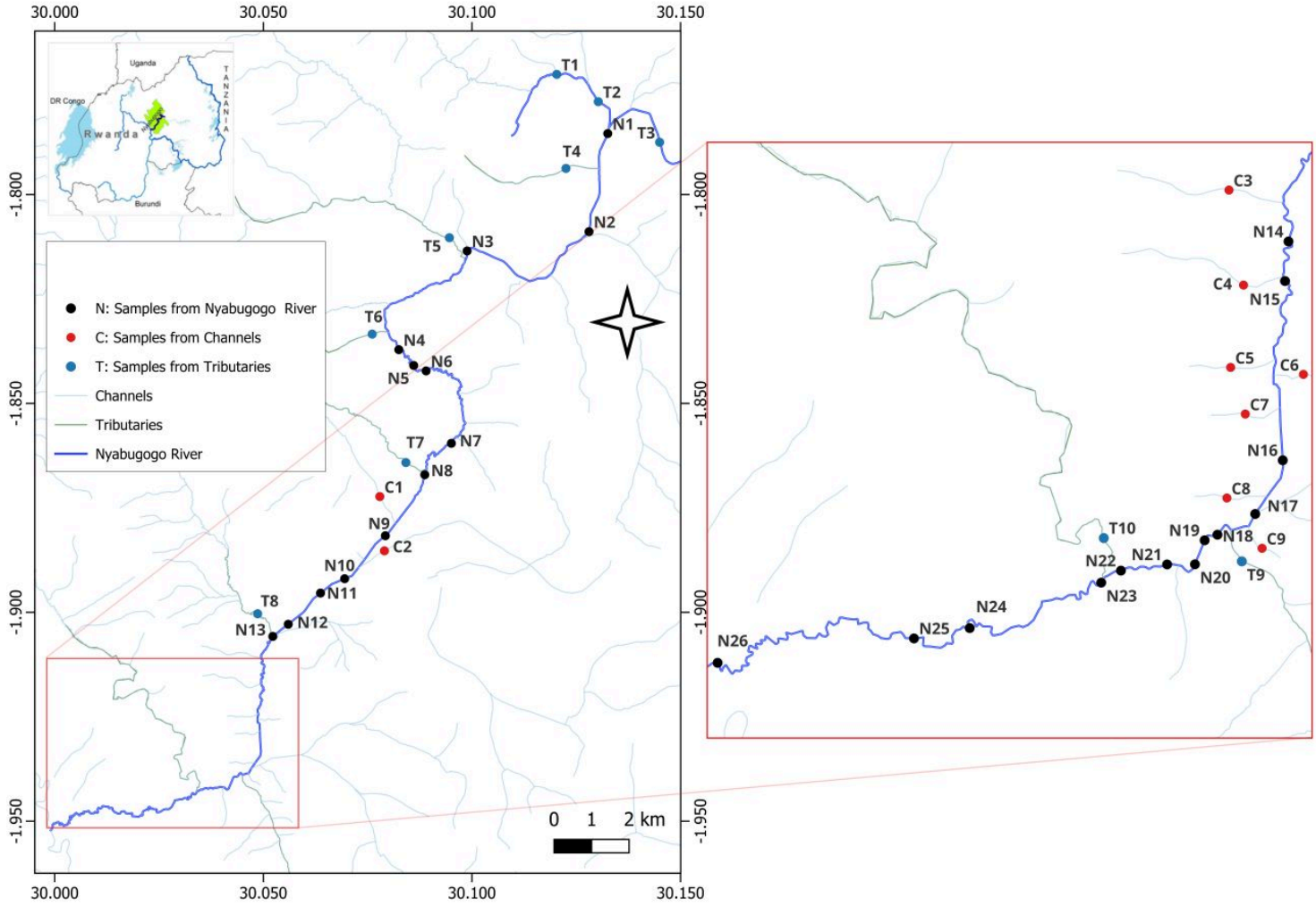


Figure 1

Legend not included with this version

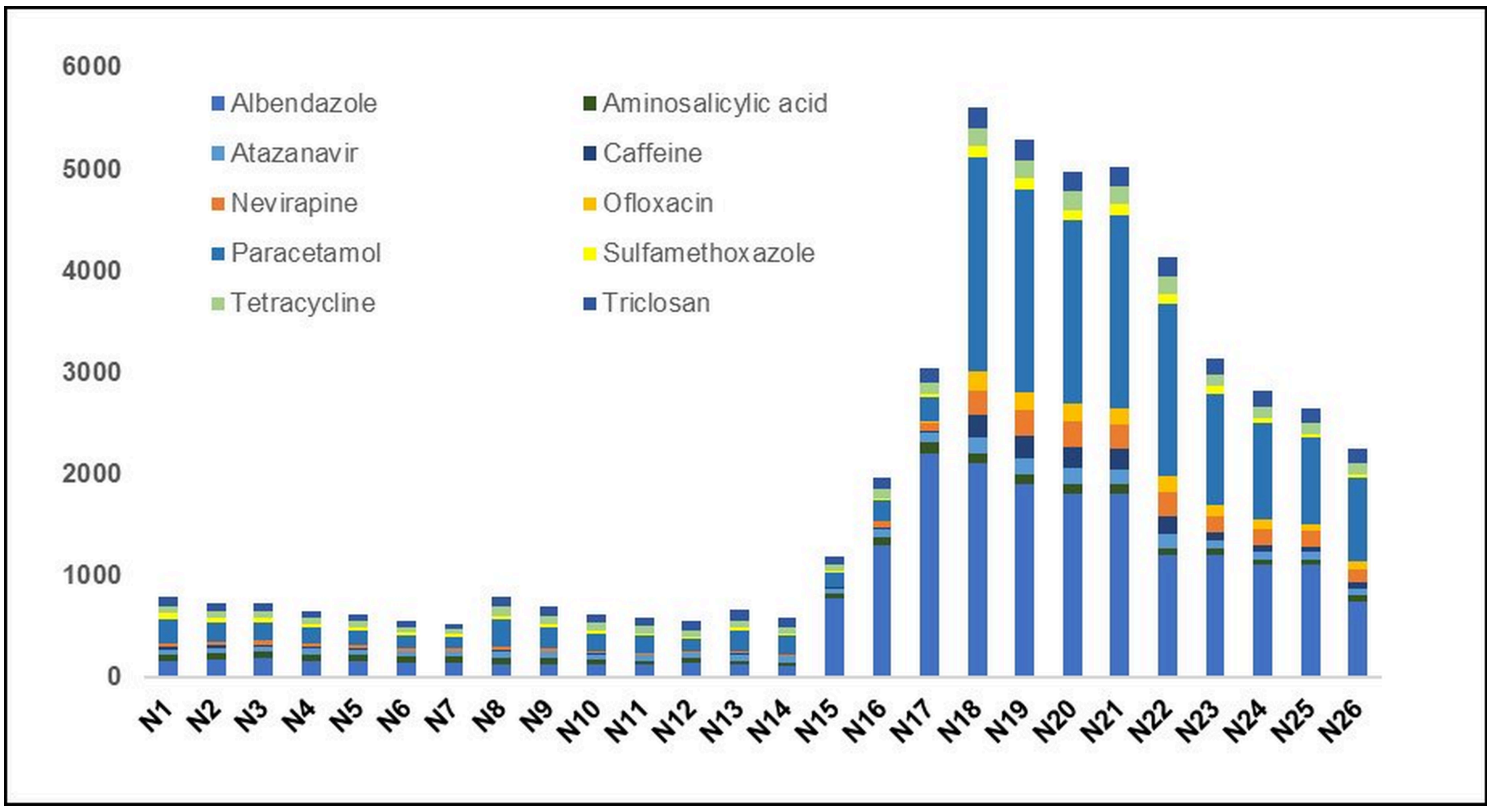


Figure 2

Legend not included with this version

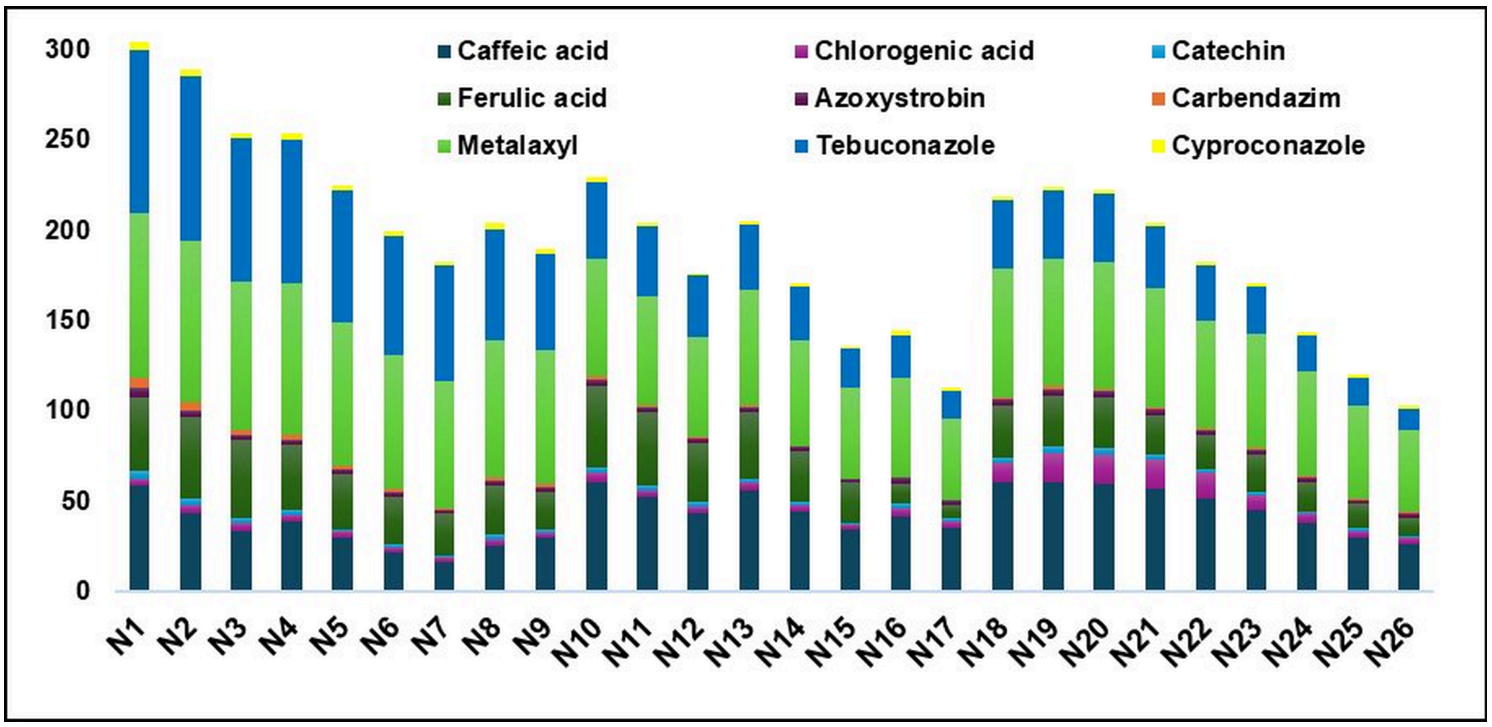


Figure 3

Legend not included with this version

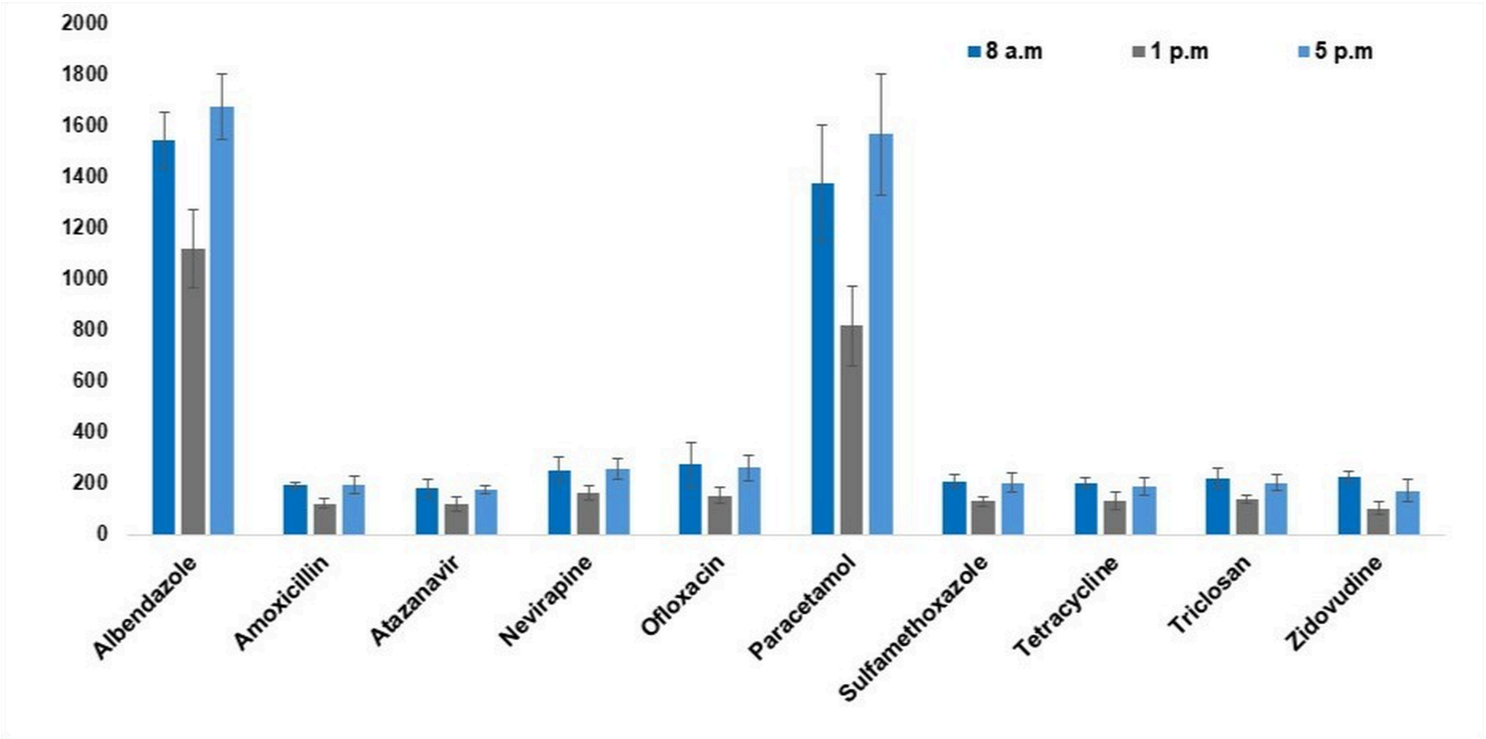


Figure 4

Legend not included with this version

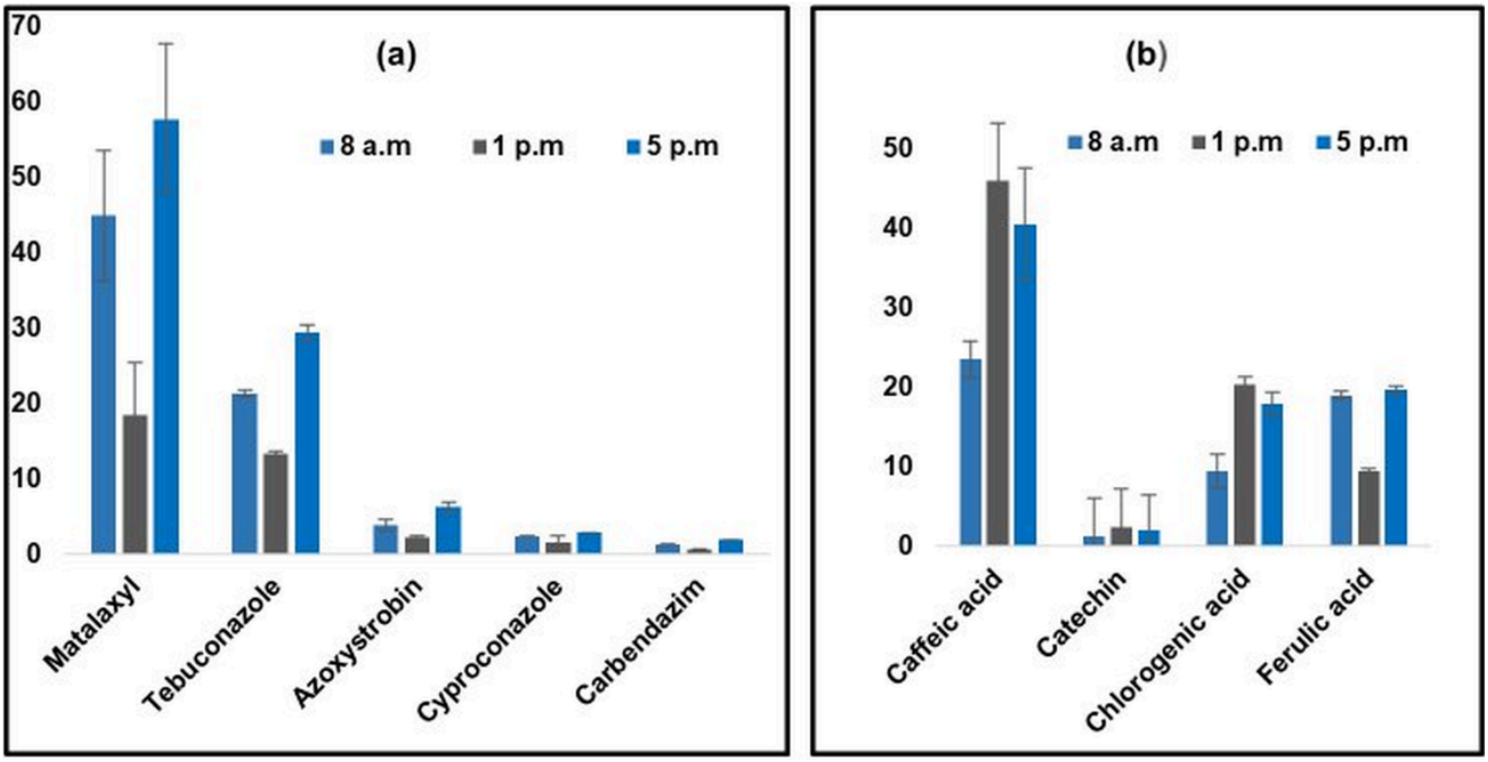


Figure 5

Legend not included with this version

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- TableS1.xlsx
- TableS2.xlsx
- TableS3.xlsx
- TableS4.xlsx
- TableS5.xlsx
- TableS6.xlsx