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Bacterial hazards in urban stream irrigation in peri-urban interface of Nairobi-Machakos counties, Kenya

Arcadius Martinien Agassin Ahogle[a,b], Nicholas K. Korir[c], Pascal Houngnandan[b,d], Lina Abu-Ghunmi[e] and Sammy Letema[a]

[a]Department of Spatial and Environmental Planning, Kenyatta University, Nairobi, Kenya; [b]Laboratory of Soil Microbiology and Microbial Ecology, Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin; [c]Department of Agricultural Science and Technology, Kenyatta University, Nairobi, Kenya; [d]School of Plant and Seed Production and Management, National University of Agriculture, Ketou, Benin; [e]Water Energy and Environmental Centre, The University of Jordan, Amman, Jordan

ABSTRACT

Bacterial contamination in fruits and vegetables cultivated in urban and peri-urban areas constitutes a serious public health risk. This paper investigates bacterial contamination in irrigation water of the Nairobi-Machakos counties interface, Kenya. Sixty-six irrigation water samples were tested for total coliforms, *Escherichia coli*, *Shigella* spp. *Pseudomonas aeruginosa*, *Enterococcus faecalis*, *Vibrio cholerae*, *Salmonella typhi*, BOD, COD, and pH. Results shows a high load of bacterial pathogens in all samples except for *Salmonella typhi*, which tested negative. Based on Kenya's standards and WHO guidelines, the irrigation water samples are unfit for fruit and vegetable irrigation. Urgent and effective measures are required, including regular monitoring, sensitisation, and enforcement of phytosanitary and regulatory measures.

KEYWORDS

Peri-urban agriculture; health risk; food safety

Introduction

Fresh fruits and vegetables are essential for human health [1]. A diet rich in fruits and vegetables is associated with lower risk of cardiovascular diseases, blood pressure-related diseases, some cancers, and diabetes [2]. Consequently, there is an increased demand for fresh fruit and vegetable especially in metropolitan populations. In the peri-urban areas of most developing countries, fresh fruit and vegetable production remains a significant source of revenue and employment, with substantial contribution to communities' livelihoods [3]. In Kenya, the cumulative export value of horticultural products from 2019 to 2021 was approximately US$635 million [4] and a year-round production of fresh fruits and vegetables depends on irrigation even during rainy seasons, owing to erratic climatic patterns [5]. Since fresh water is scarce in Kenya, most farmers in urban and peri-urban areas rely on urban hydrological flows (streams, rivers, drainage canals, urban sewage, and effluents) for farm irrigation [6,7]. The poor sewer line coverage in Nairobi and Machakos counties (51% and 14%, respectively) leads to the diversion of

CONTACT Arcadius Martinien Agassin Ahogle ahoglearcadius@gmail.com Department of Spatial and Environmental Planning, Kenyatta University, P.O. Box 43844-00100, Nairobi, Kenya

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domestic sewage and industrial effluent from a large portion of the region into urban streams and rivers [8]. Consequently, urban streams and rivers are fed with urban wastewater, raw and partially treated sewage [9,10].

Poor irrigation water quality exposes fruits and vegetables to various contaminants, such as heavy metals, persistent organic pollutants, and bacterial pathogens, which can have deleterious effect on human health [11,12]. Bacterial pathogen contamination in fresh fruits and vegetables has been associated with recurrent foodborne disease outbreaks by *Shigella* spp., *Escherichia coli*, *Salmonella typhi*, *Pseudomonas aeruginosa*, *Enterococcus faecalis* and *Vibrio cholerae*, etc [13,14]. The joint FAO/WHO expert meeting on microbial hazards pointed out that irrigation water remains the primary entry point of bacterial pathogens in fresh fruits and vegetables [15]. The adverse effects of bacterial contaminants on health range from personal distress, nausea, vomiting, abdominal pain, diarrhoea and fever to severe outbreaks that can cause widespread deaths [16]. For instance, a *cholera* outbreak in western Kenya (near Lake Victoria) from January to April 2008 resulted in 790 cases and 53 fatalities [17]. Between January 2009 and May 2010, another *cholera* outbreak in the country affected 56 districts, with 11,769 cases and 274 deaths [18]. Moreover, the emergence of resistant bacterial strains against various antibacterial medical treatments over the last decade has created more complications in the treatment of bacterial contamination related diseases [19].

Despite the extent of health risk related to bacterial pathogen contamination in fresh fruits and vegetables, there is limited information on the bacteriological quality of irrigation water in peri-urban agro-systems in Kenya. The contamination of fresh fruits and vegetables by bacterial pathogens is still neglected in most developing countries, including Kenya [3], with barely 1.7% of the literature reporting on contamination in urban and peri-urban agriculture [20]. Most literature on bacteriological pathogens in developing countries is limited *E. coli* and *Salmonella* spp. [21]. Less is known about bacterial contamination in urban stream irrigation in Nairobi peri-urban interface, which is the principal source of fruits and vegetables supplied to the metropolitan markets [22]. Previous studies [23–25] evaluating water-borne bacterial pathogens in surface waters in Nairobi and Athi Rivers, did not capture bacterial contamination at small-scale vegetable farmland level irrigation across the peri-urban landscape. Therefore, this paper aims to meet this need in the Nairobi-Machakos interface.

Materials and methods

Study area

The paper is based on a study carried out on peri-urban farmlands along Nairobi-Machakos counties interface in Kenya, lying between 1°14‘32“and 1°29’21” S latitude and between 36°57‘59“and 37°07’30” E longitude (Figure 1). Kenya is largely arid and semi-arid (80%) with a per capita water supply of 583.9 m^3 in 2019, which is below the minimum 1000 m^3 per capita [26]. The country is classified as water-scarce, with about 43% of the population still using unimproved water sources such as ponds and rivers for their domestic water needs [27]. The climate is a subtropical highland type with a bimodal rainfall pattern from mid-March to mid-May and from October to November with an average annual rainfall of 700–900 mm. Annual average temperature

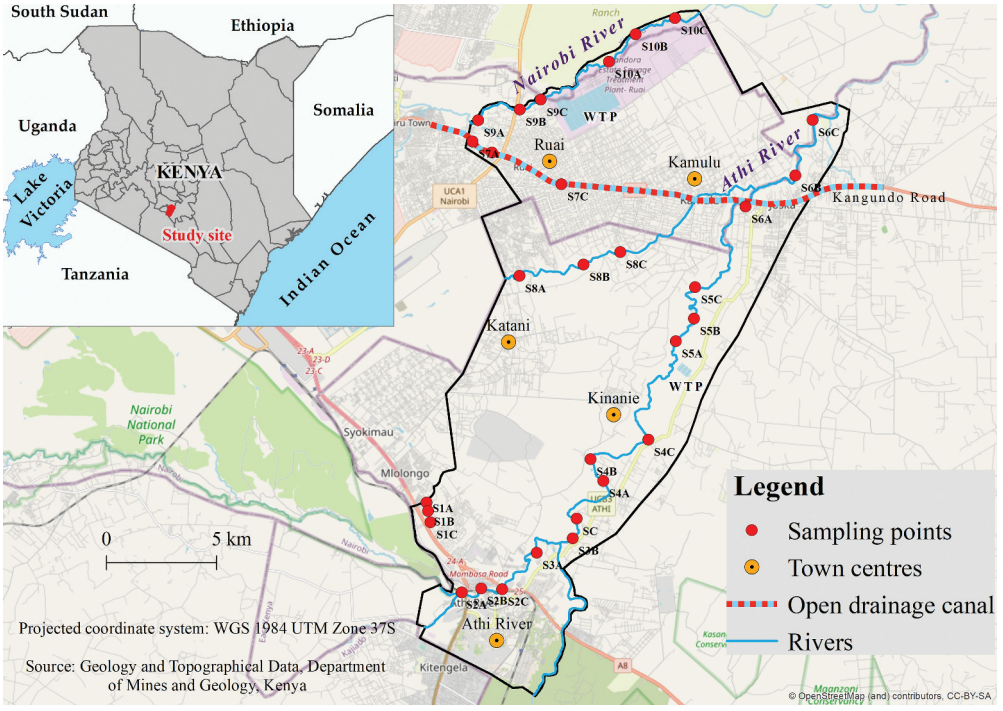

Figure 1. Map of the area of interest in Nairobi-Machakos counties interface.

ranges from 18°C to 28°C. Athi River is one of the biggest industrial hubs of the country [28]. The area was purposefully chosen first owing to its extensive streams network, including Nairobi River and Athi River, and their tributaries that favour year-round cultivation of fresh fruits and vegetables, which supply the metropolitan markets [29]. Secondly, the area is located on the fast-growing peri-urban interface of Nairobi city, polluted by poor sanitation and waste management [30]. Thirdly, the streams receive significant amounts of raw and partially treated domestic and industrial wastewater between 50-500 m^3/s, making the surface water polluted [31]. Cultivation of fresh fruits and vegetables takes place on vacant plots along railway reserves, road reserves, urban streams (streambanks, and riverbanks), or along drainage canals that are used for farm irrigation.

Irrigation water sampling

An exploration of the peri-urban interface of Nairobi-Machakos counties was carried out to map fresh fruit and vegetable farmlands. The farmlands were stratified into ten sampling zones, S1-S10, based on farmland locations, neighbouring land uses, and potential contamination sources (Figure 1 and Table 1) [12]. A detailed description of the sampling sites, including their geographical coordinates is provided in the Supplementary Materials (Table S1). Random sampling method was used in each sampling zone to collect irrigation water samples three times during the dry season of September and the wet season of November 2021. Irrigation water samples were collected

Table 1. Sampling site characteristics.

Sampling sites	Stations description	Irrigation water sources
S1	Residential-industrial mixed area, Pridelands	Raw domestic sewage
S2	Athi River Town industrial area	Mixture of domestic sewage and river water (Athi River)
S3	High-density residential area, Athi River town	Mixture of domestic sewage and river water (Athi River)
S4	Before the EPZ wastewater treatment plant, Kinanie	Mixture of domestic sewage and river water (Athi River)
S5	After the EPZ wastewater treatment plant Kinanie	Mixture of domestic sewage, river water (Athi River) and WTP effluent 61,943 m3/day
S6	Muthwani-Kamulu, Nairobi-Machakos borders	Mixture of domestic sewage, river (Athi River) and WTP effluent flowing from
S7	Kangundo Road, Nairobi	Open drainage canal flow, mixture of domestic sewage
S8	Stream, Katani-Utawala bridge	Mixture of domestic sewage and urban stream water
S9	Before the wastewater treatment plant discharge point, Ruai	Mixture of domestic sewage, river water (Nairobi River)
S10	Downstream after the wastewater treatment plant discharge point, Ruai	Mixture of domestic sewage, river water (Nairobi River) and WTP effluent 80,000 m^3/day

WTP: wastewater treatment plant; EPZ: export processing zone.

in the morning between 7 and 10 a.m. The temperatures during the sampling period ranged from 18–23°C in dry season and 16–20°C in wet season. At each sampling station, composite samples were obtained from eight to ten collection points. The samples were collected at 5–10 cm depth from the surface using 1 l clean-sterilised and corrosion-resistant plastic bottles. The samples were kept in cool thermostatic boxes at 4°C from the sampling stations to the laboratory for processing and bacterial pathogen analyses. Additionally, three tap water samples and three borehole water samples were added to each season's samples to serve as control, resulting in 66 water samples in total. The samples were tested for bacterial parameters including BOD, COD, total coliform, *Escherichia coli*, *Shigella* spp., *Pseudomonas aeruginosa*, *Enterococcus faecalis*, *Vibrio cholerae, Salmonella typhi* and pH.

Bacteriological analysis

Bacteriological testing was performed based on the East African Standards (EAS *12*: 2017) and the International Organisation for Standardisation ISO 11,133:2014/Amd 1: 2020. BOD, COD and pH were determined following the standards methods for water quality analysis described in ISO 5815–1:2003, ISO 15,705:2002 and ISO 10,523:2008, respectively. The log dilution method was applied to reduce the bacterial population to a level that would be easier to count when plated to an agar plate. For each bacterial pathogen analysis, 1 ml of homogenised water sample was aseptically pipetted, transferred into 9 ml sterile distilled water, and thoroughly homogenised by vigorous agitation using a vortex. This dilution process was replicated until the desired dilution was attained. Specific selective enrichment culture media (15 ml) were used to isolate each bacterial pathogen using 1 ml of the diluted sample.

Violet Red Bile Agar, Eosin Methylene Blue Agar (EMB), MacConkey Agar, Cetrimide Agar, Slanetz and Bartley medium (SBM), *Rappaport-Vassiliadis* medium with soya (RVS broth) and Thiosulfate-Citrate-Bile Salts-Sucrose (TCBS) Agar were used as culture media in isolating total coliforms, *E. coli*, *Shigella* spp., *P. aeruginosa*, *S. faecalis*, *S. typhi*, and *V. cholerae*, respectively. For

Table 2. Specific media, internal microscopic and biochemical tests performed on isolates.

Bacterial pathogens	Isolation media	Microscopic and biochemical tests
Total coliform	Violet Red Bile Agar	-
Shigella spp.	MacConkey agar, Xylose Lysine Deoxycholate Agar (XLD) and SS agar	Gram staining, Shape, spore, motility, oxidase, catalase, urease, citrate
Pseudomonas aeruginosa	Cetrimide agar	Gram staining, shape, motility, capsule, spore, flagella, oxidase, catalase, citrate, urease, arginine dehydrolase, pigment, oxidative/fermentative, methyl red, indole, gas, and nitrate reduction
Escherichia coli	Eosin Methylene Blue Agar	Gram staining, shape, spore, flagella, motility, oxidase, catalase, urease, oxidative/fermentative, indole, gas, nitrate reduction, citrate
Enterococcus faecalis	Slanetz and Bartley medium (SBM)	Gram Staining, shape, motility, spore, oxidase, catalase, indole, citrate, urease, nitrate reduction, PYR, 6.5% NaCl, oxidative/fermentative, pigment, maltose fermentation.
Salmonella Typhi	Rappaport-Vassiliadis medium with soya (RVS broth)	-
Vibrio cholerae	Thiosulfate-Citrate-Bile Salts-Sucrose (TCBS) Agar	Gram staining, motility, shape, capsule, spore, flagella, oxidase, indole, catalase, citrate, urease, arginine dehydrolase, Hemolysis, methyl red, indole, gas and nitrate reduction

**PYR: Pyrrolidonyl aminopeptidase test.

Shigella spp., Xylose Lysine Deoxycholate Agar (XLD) and Salmonella Shigella (SS) Agar were used alongside MacConkey agar. The presumptive isolates were subjected to various internal microscopic and biochemical tests to confirm the isolated bacteria (Table 2). After incubation within the specific period for each bacterial pathogen, the typical colony forming units (CFU) were counted and the numbers of confirmed colonies were first reported as the number of colonies per 1 ml and multiplied by 100 as described in Equation (1), where DF is the appropriate dilution factor:

$$\text{Confirmed count}(\text{CFU}/100\ \text{ml}) = \frac{\text{Number of colonies} \times \text{DF}}{\text{Volume of sample}(\text{ml})} \times 100 \qquad (1)$$

Data analysis

The measured and calculated parameters for the different sampling stations were compared to the permissible thresholds of water quality for unrestricted irrigation according to national and international standards using descriptive statistics [32,33]. For inferential statistical analyses, the normality test of Shapiro-Wilk performed on the dataset (Table 3) showed that the data were not following a normal distribution, therefore non-parametric statistical methods were applied. Kruskal-Wallis test was used to assess the variability of bacteriological parameters between the sampling stations, and Mann-Whitney test was used to assess seasonal variability. Pearson correlation matrix was used to assess eventual correlation between bacteriological variables [34]. The confidence interval was 95% and significance threshold was 5%. All statistical analyses were performed in R statistical software version 4.1.

Table 3. Normality test on the bacteriological variables.

	Dry season		Wet season	
Parameters	Rayan Joiner statistic	*p*-value	Rayan Joiner statistic	*p*-value
Total coliform (cfu/100 ml)	0.914	<.01	0.945	<.01
E. coli (cfu/100 ml)	0.801	<.01	0.312	<.01
Shigella spp. (cfu/100 ml)	0.819	<.01	0.345	<.01
P. aeruginosa (cfu/100 ml)	0.942	<.01	0.947	0.04
E. faecalis (cfu/100 ml)	0.894	<.01	0.975	<.01
V. cholerae (cfu/100 ml)	-	<.01	0.746	<.01
Salmonella spp. (cfu/100 ml)	-	-	-	-
BOD (mg/l)	0.815	<.01	0.801	<.01
COD (mg/l)	0.891	<.01	0.950	<.01
pH	0.938	<.01	0.888	<.01

BOD: Biological Oxygen Need, COD: Chemical Oxygen Need.

Result

Bacterial properties of irrigation water

The bacterial properties of irrigation water were evaluated in dry (Table 4) and wet (Table 5) seasons and compared to the permissible threshold set by the World Health Organisation (WHO) for safe use of wastewater in agriculture and the one set by Kenya's National Environment Management Authority (NEMA). *Salmonella typhi* was not detected in all the samples, but *V. cholerae* tested positive in samples from station (S2) in wet season with an average count of 1.6×10^5 CFU/100 ml. The bacterial pathogens *E. coli*, *Shigella* spp., *P. aeruginosa* and *E. faecalis* tested positive in the samples from most of the sampling stations. The bacteriological quality of the irrigation water differed significantly between the tested pathogenic bacteria ($p < 0.001$) and the sampling stations ($p < 0.001$). The prevalence of total coliform in irrigation water was 100% in all the stations, with CFU means ranging from 7.2×10^4 to 2.4×10^6 CFU/100 ml in dry season and 9.3×10^4 to 1.8×10^6 CFU/100 ml in wet season. The lowest CFU mean was recorded at the station S4 with 7.2×10^4 CFU/100 ml in dry season and station S5 with 9.3×10^4 CFU/100 ml in wet season.

E. coli was the most abundant bacterial pathogen detected in all the sampling stations for the two seasons, with CFUs means ranging from 3.3×10^4 to 1.6×10^6 CFU/100 ml in dry season and 4.1×10^4 and 1.5×10^7 CFU/100 ml in wet season. The *E. coli* CFUs in irrigation water in all the stations were above the permissible threshold of 10^3 CFU/100 ml set by the WHO for safe use of wastewater in agriculture [33] and the threshold of zero/100 ml set by the NEMA [32].

Shigella spp. were detected in all the samples in dry season, with average CFU count ranging from 3.2×10^4 to 1.5×10^7 CFU/100 ml. *Shigella* spp. were detected in 60% of the samples in wet season, with the highest counts recorded at the sampling station S1 (1.5×10^7 CFU/100 ml), but tested negative for the stations S2, S5, S8 and S10. The average CFU of *Shigella* spp. in all dry season samples and 60% of wet season samples exceeded the maximum permissible limit of zero per 100 ml recommended by the WHO [33] and the United States Environmental Protection Agency (USEPA) [35] for unrestricted irrigation.

Pseudomonas aeruginosa tested positive in 50% of the samples in dry season and 60% in wet season, with average CFU counts ranging from 3.1×10^3 to 1.6×10^6 and

Table 4. Dry season bacterial contamination in irrigation water in Nairobi city catchment.

Stations		Bacterial pathogen load (10^4 CFU/100 ml)							Water quality indicators			
		Total coliform	*E. coli*	*Shigella* spp.	*P. aeruginosa*	*E. faecalis*	*V. cholerae*	*Salmonella typhi*	BOD (mg/l)	COD (mg/l)	BOD/COD	pH
S1	Median	13	7.1	15	ND	8.1	ND	ND	37.9	733	0.05	8.17
	Range	13–14	7.0–7.6	15–16	-	8.1–8.2	-	-	35.1–39.7	733–742	0.04–0.05	7.15–9.01
S2	Median	140	56	7.9	4.1	0.5	ND	ND	42.5	369	0.12	7.96
	Range	140–150	55–59	7.7–8.1	4.1–4.2	0.5–0.6	-	-	40.1–44.0	365–374	0.11–0.12	7.96–7.97
S3	Median	16	13	6.4	160	6.4	ND	ND	44.9	1846	0.02	8.86
	Range	15–16	12–13	6.4–6.5	150–160	6.3–6.5	-	-	44.8–45.0	1844–1850	0.01–0.02	8.75–8.97
S4	Median	7.2	3.3	8.2	ND	0.4	ND	ND	41.9	369	0.11	7.43
	Range	7.2–7.3	3.3–3.4	8.2–8.3	-	0.4–0.5	-	-	41.6–42.2	359–379	0.11–0.12	7.41–7.46
S5	Median	110	13	6.2	ND	1.3	ND	ND	37.9	3698	0.01	9.12
	Range	110–120	12–14	6.1–6.5	-	1.2–1.3	-	-	36.4–39.4	3529–3872	0.01–0.01	9.09–9.17
S6	Median	8.6	5.8	1.3	ND	0.3	ND	ND	38.3	1109	0.03	7.02
	Range	8.6–8.7	5.8–5.9	1.3–1.4	-	0.3–0.4	-	-	36.8–40.4	1098–1121	0.03–0.04	7.01–7.04
S7	Median	190	160	1600	3.2	14	ND	ND	41.7	3681	0.01	6.89
	Range	190–200	160–1700	1300–1700	3.2–3.3	13–14	-	-	41.0–43.0	3661–3703	0.01–0.01	6.89–6.9
S8	Median	17	12	7.1	0.3	31	ND	ND	47.5	1846	0.03	7.62
	Range	17–18	11–12	7.1–7.2	0.29–032	29–32	-	-	45.2–49.4	1842–1852	0.02–0.03	7.52–7.7
S9	Median	240	18	130	ND	13	ND	ND	47.4	365-	0.13	7.15
	Range	240–250	18–19	120–130	-	12–13	-	-	46.3–48.2	362–368	0.13–0.13	7.10–7.19
S10	Median	130	10	130	5.2	9.2	ND	ND	40.9	370	0.11	7.00
	Range	120–130	9.7–11	120–130	5.2–5.3	9.1–9.2	-	-	38.2–44.3	363–377	0.10–0.12	7.0–7.01
T	Median	ND	ND	ND	ND	ND	ND	ND	-	-	-	7.37
	Range	-	-	-	-	-	-	-	-	-	-	7.36–7.37
B	Median	ND	ND	ND	ND	ND	ND	ND	-	-	-	8.06
	Range	-	-	-	-	-	-	-	-	-	-	8.04–8.08
P-value		<.001	<.001		<.001	<.001	<.001	<.001	<.001	<.001		<.001
Permissible ranges		1[A] 0.1[B]	0.1[A] 0[B,C]	Nil	Nil	Nil	Nil	Nil	10[B] 10–20[D]	150[B]		6.5–8.5[A]

[A]WHO [33]; [B]USEPA [35]; [C]NEMA [32]; [D]Paranychianakis et al. [36].

Table 5. Wet season bacterial contamination in irrigation water in Nairobi city catchment.

		Bacterial pathogen load (10^4 CFU/100 ml)							Water quality indicators			
Stations		Total coliform	*E coli*	*Shigella spp.*	*P. aeruginosa*	*E. faecalis*	*V. cholerae*	*Salmonella typhi*	BOD	COD	BOD/COD	pH
S1	Median	1500	1100	1500	5.8	11	ND	ND	40.3	1346	0.03	6.83
	Range	1400–16000	120–1200	110–16000	5.7–5.9	10–12	-	-	39.1–41.3	1319–1372	0.02–0.03	6.78–6.89
S2	Median	230	75	ND	7.7	13	16	ND	45.3	1108	0.04	6.76
	Range	220–240	62–92	-	6.8–8.8	12–18	14–6.4	-	45.0–46.0	1091–1125	0.03–0.04	6.68–6.93
S3	Median	120	100	83	ND	ND	ND	ND	43,2	1489	0.03	6.73
	Range	110–120	100–110	83–92	-	-	-	-	40.2–45.2	1421–1557	0.02–0.03	6.63–6.83
S4	Median	130	120	3.2	ND	ND	ND	ND	45.3	1847	0.02	6.93
	Range	130–140	120–130	3.1–3.4	-	-	-	-	44.1–46.2	1833–1862	0.02–0.03	6.76–7.08
S5	Median	9.3	4.1	ND	ND	ND	ND	ND	35.2	885	0.04	7.9
	Range	8.6–10	4.1–4.2	-	-	-	-	-	34.1–36.3	858–909	0.04–0.04	7.86–7.96
S6	Median	110	11	100	4.0	ND	ND	ND	38.0	1810	0.02	6.98
	Range	110–120	110–120	90–120	3.8–4.2	-	-	-	37.8–38.2	1807–1816	0.01–0.02	6.96–7.02
S7	Median	170	120	110	5.6	18	ND	ND	42.6	3851	0.01	6.58
	Range	170–180	120–130	110–120	5.5–5.8	17–18	-	-	39.9–45.2	3700–3098	0.01–0.01	6.5–6.66
S8	Median	120	43	ND	ND	ND	ND	ND	46.1	2284	0.02	6.97
	Range	110–120	42–45	-	-	-	-	-	44.2–48.0	2173–2392	0.01–0.02	6.96–7.0
S9	Median	180	140	5.5	2.2	15	ND	ND	43.4	712	0.06	6.59
	Range	170–190	140–15000	5.3–5.7	2.2–2.3	15–16	-	-	41.2–46.4	697–739	0.05–0.06	6.56–6.64
S10	Median	130	150	ND	4.9	1.4	ND	ND	40.9	739	0.06	6.9
	Range	130–1400	100–1200	-	4.8–4.9	14–15	-	-	39.0–43.4	734–747	0.05–0.06	6.90–6.92
T	Median	320	ND	ND	ND	ND	ND	ND	-	ND	ND	8.15
	Range	290–370	-	-	-	-	-	-	-	-	-	8.13–8.17
B	Median	ND	ND	ND	ND	ND	ND	ND	-	-	-	8.06
	Range	-	-	-	-	-	-	-	-	-	-	8.05–8.08
P-value		<.001	<.001		<.001	<.001	<.001	ND	<.001	<.001		<.001
Permissible ranges		1[A] 0.1[B]	0.1[A] Nil[B,C]	Nil[A, B]	Nil[A, B]	Nil[A,B]	Nil[A, B]	Nil[A, B]	10[B] 10–20[D]	1000[A] 150[B]		6.5–8.5[A]

[A]WHO [33]; [B]USEPA [35]; [C]NEMA [32]; [D]Paranychianakis et al. [36].

from 2.2×10^4 to 5.8×10^4, respectively; thus exceeding the permissible threshold of zero/100 ml by the WHO [33] and the USEPA [35]. The pathogen was not detected at the sampling stations S4, S5, S6 and S9 in dry season and S3, S4, S5 and S8 in wet season.

Enterococcus faecalis was detected in all samples in dry season, with average CFUs ranging from 3.3×10^3 to 9.2×10^4 CFU/100 ml and detected in 50% of the samples in wet season, with average CFUs varying from 1.1×10^5 to 1.8×10^5 CFU/100 ml; thus exceeding the permissible threshold of zero/100 ml by the WHO [33] and the USEPA [35]. However, *E. faecalis* tested negative at the stations S3, S4, S5, S6 and S8 in wet season.

The Biological Oxygen Need (BOD) of irrigation water samples ranged from 37.9 mg/l to 47.4 mg/l in dry season and from 35.2 mg/l to 45.3 mg/l in wet season. The highest values of BOD (>40 mg/l) were recorded in the stations S2, S3, S4, S7, S8, S9 and S10 in dry season and the stations S1, S2, S3, S4, S7, S8, S9 and S10 in wet season. There is no established threshold value for BOD and COD in Kenya's standards for irrigation water quality (NEMA) and the WHO guidelines for safe use of wastewater in agriculture. The BOD values recorded in all the stations were above the maximum permissible threshold of 10 mg/l of the USEPA [35] and the European Union (EU) guidelines of 10–20 mg/l [36].

The value of Chemical Oxygen Need (COD) recorded in dry season ranged from 365 mg/l to 3698 mg/l and from 712 to 3851 mg/l in wet season. The highest values were reported at the stations S5 (3698 mg/l) and S7 (3681 mg/l) in dry season and S7 (3681 mg/l) in wet season. The COD values were above the standards of 150 mg/l set by the USEPA [35] for unrestricted irrigation water.

The pH values ranged from 6.88 to 9.11 in dry and 6.58 to 8.14 in wet season, with the highest recorded at the station S5 in both seasons (9.11 and 7.9). All the samples except S5 during dry season indicated neutral pH, hence were within the admissible limit for suitable irrigation water quality for agriculture (6.5–8.5). The pH values were slightly lower in wet season than in dry season.

Seasonal variation of bacterial properties of irrigation water

The bacteriological quality of the irrigation water exhibited significant variations (Figure 2) between the seasons at $p < 0.001$. The average CFU counts of total coliforms and *E. coli* were high in wet season in all stations except S5, S6 and S9 where the bacterial loads were lower in wet season than in dry season. The loads of *Shigella* spp. in irrigation water were higher in dry season than in wet season in most of the stations except S1, S3 and S6. Similarly, the CFU counts of *P. aeruginosa* in irrigation water were higher in wet season than in dry season, except in stations S3, S8 and S10. The CFU of *E. faecalis* in irrigation were higher in wet season than in dry season at the stations S1, S2, S7, S9 and S10, representing 50% of the samples, whereas *V. cholerae* was detected only during wet season.

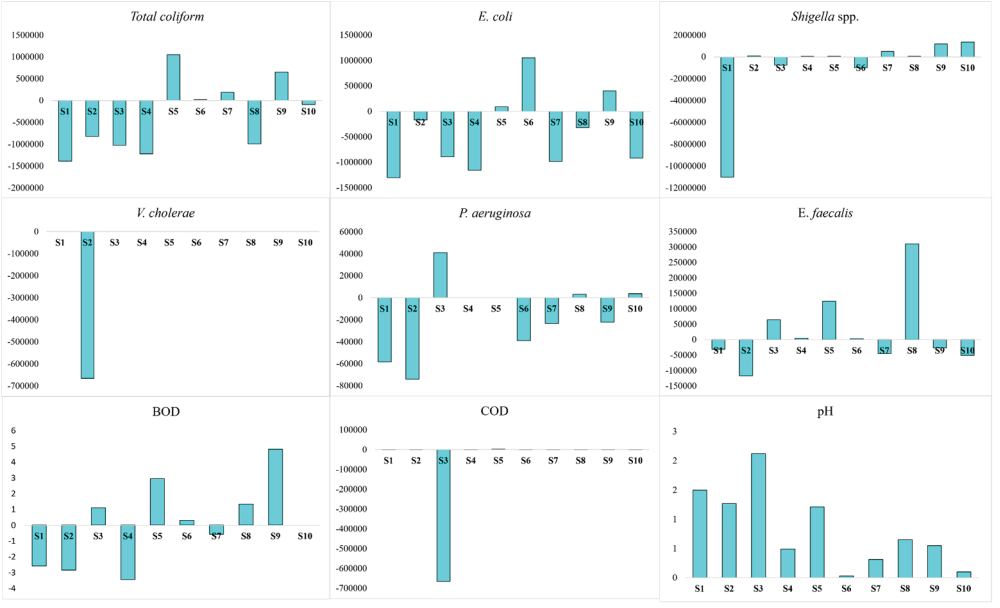

Figure 2. Seasonal variations of bacterial properties in irrigation water.

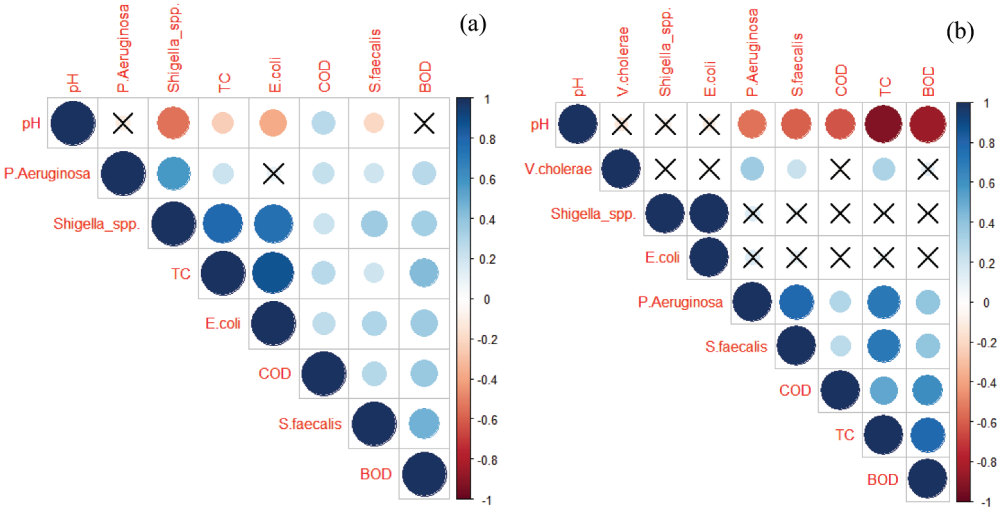

Figure 3. Pearson correlation matrix for bacterial parameters (a) dry season, (b) wet season. TC: Total coliforms; BOD: Biological Oxygen Need; COD: Chemical Oxygen Need.

Pearson correlation on bacterial characteristic of irrigation water

Figure 3 shows the results of Pearson correlation analysis performed on the bacterial properties of irrigation water in dry and seasons. The pH showed a strong negative correlation with the load of bacteriological pathogens in irrigation water samples. Higher pH values appeared deleterious for the pathogens isolated from irrigation water. In dry

season, strong positive correlations ($r > 0.80$) were observed between total coliform and *E. coli*, total coliform and *Shigella* spp., *E. coli* and *Shigella* spp., *E. coli* and BOD, and total coliform and BOD. In contrast, in wet season, strong positive correlations ($r > 0.80$) were observed between total coliform and *P. aeruginosa*, total coliform and *E. faecalis*, total coliform and BOD, total coliform and COD, *E. coli* and *shigella* spp., *P. aeruginosa* and *E. faecalis*, and BOD and COD.

Discussion

The paper assessed the bacteriological quality of urban stream water used for growing fruits and vegetables in the Nairobi-Machakos peri-urban interface. The results indicate that irrigation water was contaminated in all the sampling stations with significant loads of bacterial pathogens, including *E. coli* (up to 1.5×10^7 CFU/100 ml), *Shigella* spp. (1.6×10^7 CFU/100 ml), *P. aeruginosa* (up to 0.6×10^6 CFU/100 ml), *E. faecalis* (up to 1.8×10^5CFU/100 ml), and *V. cholerae* (up to 1.6×10^5 CFU/100 ml). This report is consistent with the findings of Musyoki et al. [24] in Nairobi River and Athi River (Kenya), who reported up to $1.0 \times 10^4 \pm 2.6 \times 10^3$/100 ml *E. coli*, $1.2 \times 10^1 \pm 1.2 \times 10^1$/100 ml *Shigella* spp., $3.6 \times 10^3 \pm 3.2 \times 10^3$/100 ml *E. faecalis*, $6.5 \times 10^2 \pm 1.1 \times 10^2$/100 *P. aeruginosa*, $1.6 \times 10^1 \pm 1.1 \times 10^1$/100 ml, *Salmonella typhi*, $5.6 \times 10^2 \pm 1.0 \times 10^2$/100 ml *V. cholerae*. The globally high average CFU counts of bacterial pathogens recorded in this study indicate the presence of a significant load of faecal material in the streams used as irrigation water sources for farm irrigation. This is attributed to discharge of raw sewage and effluent from informal settlements and wastewater treatment plants (WTPs) to the urban stream [23]. The urban streams in the Nairobi-Machakos peri-urban interface are more degraded than they were ten years ago.

The CFUs were significantly higher at the stations located after WTPs discharge point (S5 and S10) and those along roads in high density residential areas (S1 and S7). This is attributable to the incoming effluent and sewage, which generally does not comply with standards for discharge into the environment. The stations along Athi River (S2-S6) recorded low bacterial load counts compared to those located along Nairobi River (S9 and S10). This is consistent with Bagnis et al. [37], who showed that Nairobi River and its two tributaries that pass through the city's informal settlements have higher levels of bacterial contamination because of poor sanitation and disposal of waste into the river network [23,38–41]. In addition, settlements along Athi River are less congested than those along Nairobi River and the total amount of raw sewage and WTP effluent discharged daily into Nairobi River is greater than the burden imposed on Athi River i.e. 80000 + 11,000 m^3/day Vs 61,943 m^3/day of WTP effluent [42–44].

Pseudomonas aeruginosa and *E. faecalis* tested negative at some of the sampling stations, yet they were positive at some upstream sampling stations. This could be partially attributed to higher inflow of water, which eventually contributes to reduction or increase in bacterial pathogen loads in urban streams. This highlights the potential influence of upstream land uses on bacteriological quality of surface water. Socio-economic activities along streams can quickly alter the quantities of contaminants getting into the stream [45,46]. Unlike chemical contaminants, the spread of bacterial pathogens in surface water is complex and influenced by water inflows and upstream land uses

[47,48]. Bacterial pathogens may show exponential load count across water flows and their load count may significantly decrease after some distance [47].

This study showed that seasons influence the level of bacterial contamination in irrigation water. The bacterial pathogens *Shigella* spp., *P. aeruginosa* and *E. faecalis* were low or undetected in some of the stations during dry and wet seasons. This can be attributed to the fact that bacterial pathogens can originate from point and non-point source pollution. Although the inflow of fresh water during rain events can dilute streams and so reduce the level of bacterial contamination in the stream [23], inflow from contaminated stations can lead to higher contamination [21]. Furthermore, the amount of effluent discharged into the rivers is very high during wet season owing to the clogging power after heavy rains [31]. As the rivers tributaries join the mainstem, depending on their level of contamination, their contribution to bacteria load will vary accordingly. This is consistent with Wiegner et al. [49] and Ahmed, R. et al. [50], who illustrated the influence of rainstorm water inflow on high bacterial contamination of surface water in wet season.

BOD and COD values were high for all the stations and the ratios BOD/COD were low, suggesting that the irrigation water contains high nutrient load, high amount of active biological substance and biologically inactive organic matter. The values of BOD and COD observed in this study indicate poor water quality, implying that the treatment of such water will incur high costs [51]. The results showed that the samples with higher BOD and COD exhibited higher pathogen load contamination as well, which confirms that BOD and COD can be used as indicators for primary assessment of bacteriological quality of water in urban streams [52]. The strong positive correlation between bacterial pathogens indicates that they grow in similar conditions and thus a common source.

The strong positive correlation between BOD and COD was expected since BOD measures the amount of organic matter that can be biologically oxidised, while COD measures the amount of organic matter that can be chemically oxidised. The strong positive correlations between BOD and the pathogens suggest that high BOD is associated with a high load of bacterial pathogens in water. The negative correlation between pH and bacterial pathogens is consistent with previous studies [53,54] which showed that *E. coli*, *P. aeruginosa*, *Shigella* spp., *E. faecalis* and *V. cholera* have their optimum growth at neutral pH and reduce as the pH values move from the neutral ranges. The slightly higher pH observed in dry season compared to wet season could be a consequence of high nutrient content during dry season, which favours algae growth and photosynthesis, followed by CO_2 reduction and release of oxygen and hydroxide alkalinity.

The WHO guidelines for wastewater use in agriculture for unrestricted irrigation indicate that *E. coli* count in the water should be less than 1000 CFU/100 ml. For the USEPA [35] and the NEMA [32], it should be free of *E. coli*. By these criteria, irrigation water from the sampling stations in Nairobi-Machakos peri-urban interface is unfit for irrigation. The use of such water exposes farmers, consumers and downstream water users to serious health risks [33]. *E. coli* is the most commonly used indicator in evaluating bacterial contamination in water [55]. Therefore, detection of the bacterium implies faecal contamination of water, even though mere detection could be insufficient to understand the extent of bacterial risks. For instance, irrigation water could have below the permissible range for *E. coli* of zero or 1000 CFU/100 ml by the NEMA [32]

and the WHO [33], but other deadly bacterial pathogens like *Salmonella typhi, Shigella* spp. and *Vibrio cholerae* could be present. In a study carried out in Asia by Ahmed et al. [56], 12% of the water samples had ≤1 CFU of *E. coli*, yet the samples tested positive for other pathogenic bacteria such as *S. typhi* and *Enterococcus* spp.

Therefore, we argue that the assessment of bacterial contamination of irrigation water for unrestricted irrigation should be expanded to include pathogens that could trigger severe outbreaks such as *Salmonella typhi, P. aeruginosa, Shigella* spp. and *Vibrio cholerae*. Moreover, there are no explicit regulations for monitoring bacteriological quality of fruits and vegetables supplied to the local market in Kenya. Attention is here drawn to the assessment of irrigation water for bacterial pathogens in order to avert public health emergency, as previously reported, sometimes with several fatalities [17,18]. Such control and monitoring can prevent foodborne diseases and ensure safe and healthy food for metropolitan populations. One cannot overlook the fact that settlements are sited (along the Athi and Nairobi rivers) where settlements are a danger to themselves and to others. Kenya should have an effective housing policy which works together with an effective health policy.

Conclusion

In this paper, we evaluated the bacteriological quality of irrigation water in Nairobi-Machakos peri-urban farmlands. The results indicated that the bacterial characteristics of irrigation water in the peri-urban interface exceed the permissible threshold set by the WHO and the National Environment Management Authority (NEMA, Kenya) for unrestricted irrigation and, therefore, are unfit for fruit and vegetable farming. *Escherichia coli* was the most prevalent and abundant in the sampling stations, which indicates contamination with faecal materials resulting from poor sanitation and waste management.

Although *E. coli* testing is commonly used indicator in evaluating bacterial contamination in water, it is inadequate since compliance with national and international standards does not imply the absence of deadly bacterial pathogens like *Salmonella typhi*, *Shigella* spp. and *Vibrio cholerae*. Therefore, the monitoring of bacterial contamination in water meant for unrestricted irrigation should apply to other bacterial pathogens that trigger severe outbreaks such as *Salmonella typhi, Pseudomonas aeruginosa, Enterococcus faecalis, Shigella* spp. and *Vibrio cholerae*. Continuing uncertainty about water supply means that health risks must be confronted.

Disclosure statement

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ORCID

Arcadius Martinien Agassin Ahogle http://orcid.org/0000-0001-8332-7823
Lina Abu-Ghunmi http://orcid.org/0000-0003-3385-5489
Sammy Letema http://orcid.org/0000-0002-8766-0022

Data availability statement

The original contributions presented in the study are included in the paper/supplementary material. Further inquiries can be directed to the corresponding author.

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