Greywater Quantities and Qualities in Low-Income Kumasi, Ghana: Implications for Sustainable Water Management.

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Abstract

Household greywater, comprising laundry, kitchen, and bathroom wastewater, poses significant environmental and public health challenges in peri-urban communities with limited sanitation infrastructure. This study quantified and characterized greywater from 10 households in Kotei, a peri-urban community in Kumasi, Ghana, over 10 weeks in 2023. Using a cross-sectional design, daily greywater volumes were measured via a bucket-based approach, and physicochemical, microbial, and chemical properties were analyzed for laundry, kitchen, and bathroom streams. Results showed a mean daily greywater generation of 110.0 ± 64.2 litres per household, with bathing contributing 58% (63.4 ± 28.9 litres/day), laundry 23% (25.6 ± 20.1 litres/day), and kitchen 19% (20.8 ± 16.0 litres/day). Laundry greywater exhibited the highest organic loads (BOD_5: 5431.67 ± 3440.42 mg/L; COD: 12469.00 ± 7325.75 mg/L), electrical conductivity (3825.00 ± 2635.61 μS/cm), and total dissolved solids (1600.89 ± 417.37 mg/L), while kitchen greywater had the highest microbial contamination (total coliforms: 136.17 ± 66.94 cfu/ml; E. coli: 34.83 ± 24.70 cfu/ml). Phosphate levels exceeded EPA guidelines across all sources, and trace metals (e.g., Pb, Fe) and triclosan were detected, indicating potential environmental risks. Multivariate Analysis of Variance (MANOVA) confirmed significant differences in greywater characteristics across sources ($p < 0.001$). These findings highlight the need for source-specific greywater treatment strategies to mitigate environmental pollution and enable safe reuse in water-scarce regions. The study aligns with SDG 6 (Target 6.3) and WHO reuse guidelines, informing global WASH policies. The study

underscores the importance of tailored wastewater management policies in peri-urban LMICs to promote sustainable water use and protect public health.

Keywords: Domestic, Greywater, Qualities, Quantities, Sustainable Water Management

INTRODUCTION

Household greywater, defined as wastewater generated from domestic activities such as laundry, kitchen use, and bathing, constitutes a significant portion of urban and peri-urban wastewater in low- and middle-income countries (LMICs) [1]. Unlike blackwater, which contains faecal matter and urine, greywater is typically less contaminated but still poses environmental and public health risks due to its organic, nutrient, microbial, and chemical content [2,3]. Globally, greywater accounts for 50–80% of household wastewater, with daily per capita generation ranging from 50 to 150 litres in LMICs, driven by water-intensive activities like bathing and laundry [4–7]. These activities are often gendered, with women handling laundry and kitchen tasks predominantly influencing greywater volumes and composition [8]. In regions with limited sanitation infrastructure, such as sub-Saharan Africa, improper greywater disposal into open drains and water bodies exacerbates environmental degradation, contributing to eutrophication, soil contamination, and pathogen transmission [8,9]. Effective greywater management is thus critical to mitigating these risks and promoting sustainable water use, particularly in water-scarce regions [10].

The environmental health implications of greywater are well-documented. High organic loads, measured as biochemical oxygen demand (BOD) and chemical oxygen demand (COD), can deplete dissolved oxygen in receiving waters, disrupting aquatic ecosystems [11]. Elevated nutrient levels, particularly phosphates from detergents, contribute to eutrophication, while heavy metals and antimicrobial agents like triclosan pose risks of soil accumulation and microbial resistance when greywater is reused for irrigation [12,13]. Microbial contamination, including pathogens like Escherichia coli, further complicates greywater reuse, necessitating treatment to meet safety guidelines [3]. Despite these challenges, greywater reuse offers significant potential for water conservation, particularly in peri-urban communities with limited access to centralized water and sanitation systems [14–16]. However, the lack of source-specific data on greywater characteristics hinders the design of effective treatment and reuse strategies, especially in resource-constrained settings [17].

In Ghana, rapid urbanization and inadequate sanitation infrastructure amplify the challenges of greywater management. Studies estimate that 60–90% of urban households in Ghana rely on on-site sanitation systems, such as pit latrines and septic tanks [18–20], with greywater often discharged untreated into open drains [21] This practice not only pollutes local water bodies but also limits opportunities for greywater reuse in agriculture or domestic applications. While previous studies in Ghana have quantified greywater volumes [10,21], few have characterized its physicochemical, microbial, and chemical profiles across distinct sources (laundry, kitchen, bathroom) in peri-urban contexts. Source-specific characterization is critical, as greywater composition varies significantly depending on household activities, with laundry greywater often containing high detergent-derived pollutants, kitchen greywater rich in organic matter, and bathroom greywater carrying microbial loads from personal care products ([4,22]).

This study addresses these gaps by quantifying and characterizing household greywater from laundry, kitchen, and bathroom sources in Kotei, a peri-urban community in Kumasi, Ghana. The objectives are to: (1) quantify daily greywater generation patterns and source contributions, (2) characterize the physicochemical, microbial, and chemical properties of greywater from each source, and (3) assess the environmental and public health implications of greywater composition for reuse and disposal. The findings contribute to the global literature on greywater management by offering insights into localized greywater profiles, supporting the development of targeted treatment technologies, and informing policy for sustainable wastewater management in similar settings.

MATERIALS AND METHODS

Study Area

The study was conducted in Kotei, a peri-urban community within the Oforikrom Municipal Assembly (OFMA) in Kumasi, Ghana (6°39'0" N, 1°34'0" W; elevation 233 m). Located 2 km from Kwame Nkrumah University of Science and Technology (KNUST) and 10 km from central Kumasi, Kotei has a population of 15,637 and features a mix of densely packed old town (low-income) and middle-class new town areas [10]. Established in 2018 under LI 2291, OFMA is one of 43 districts in the Ashanti Region, characterized by limited sanitation infrastructure and reliance on communal water sources [23].

Study Design and Household Selection

This study was conducted in Kotei, a peri-urban community in Kumasi, Ghana, over a 10-week period from June to August 2023, to quantify and characterize household greywater from laundry, kitchen, and bathroom sources. A cross-sectional study design was employed to capture variability in greywater generation and composition. Ten households were purposively selected based on three criteria: (i) willingness to segregate greywater into laundry, kitchen, and bathroom streams to ensure source-specific data collection; (ii) use of non-waterborne sanitation (e.g., pit latrines or septic tanks) to isolate greywater from blackwater; and (iii) availability of tertiary drains or open spaces for greywater disposal. Engagement meetings were held with household heads and local opinion leaders in May 2023 to explain the study objectives, procedures, and potential benefits (for example, improved greywater management). Written informed consent was obtained using the Kwame Nkrumah University of Science and Technology (KNUST) Institutional Review Board-approved forms (IRB approval number: CHRPE/AP/517/22). Sampling times were adjusted based on community feedback to avoid disrupting household routines, ensuring ethical compliance approved by the IRB. Households were trained on greywater segregation and collection protocols to ensure consistency and compliance.

Greywater Quantification

Greywater volume was quantified daily over the 10-week study period using a bucket-based measurement approach, adapted from Oteng-Peprah et al. [7], due to its simplicity, cost-effectiveness, and suitability for low-resource settings. Each of the 10 households was provided with three 18-L high-density polyethylene buckets, labelled for laundry, kitchen, and bathroom greywater streams. Households were instructed to collect all greywater from each source in the respective buckets before disposal. Trained data collectors visited each household daily to record the number of full buckets emptied, using tally cards to ensure accuracy and minimize recall bias. Partially filled buckets were estimated to the nearest litre using graduated markings on the buckets. Daily volumes were aggregated to calculate weekly and total greywater generation per household and source, enabling the assessment of temporal patterns and source-specific contributions.

Greywater Sample Collection

Greywater samples were collected over a 4-week period (weeks 3–6 of the 10-week study) to characterize the physicochemical and microbial properties of greywater from laundry, kitchen, and bathroom sources. Four rounds of sampling were conducted, with one round per week. For each of the 10 households, one grab sample was collected per greywater stream (laundry, kitchen, bathroom) during each sampling round, resulting in 120 grab samples (10 households × 3 streams × 4 rounds). Laundry samples were collected directly from manual washing activities (e.g., wash basins), kitchen samples from dishwashing receptacles, and bathroom samples from post-bathing containers. To ensure representativeness, composite samples were prepared for each greywater stream by mixing equal volumes of grab samples collected from the 10 households within each sampling round. For each composite sample (3 streams × 4 rounds = 12 composite samples), a 500-mL subsample was transferred to sterilized high-density polyethylene (HDPE) bottles, pre-rinsed with deionized water to prevent contamination. All samples were immediately stored in an ice chest maintained at 4°C to minimize microbial activity and chemical degradation, following standard protocols for environmental sample preservation [24] Samples were transported to KNUST's Environmental Quality Laboratory and Central Laboratory within 4 hours of collection to ensure analytical integrity, as rapid transportation reduces the risk of parameter alteration (e.g., DO depletion or microbial proliferation).

Laboratory Analysis

Physicochemical parameters (pH, temperature, EC, TDS, DO, BOD_5, COD, oil and grease, NO_3^-, PO_4^{3-}, triclosan) were analyzed using standard methods [24]. On-site measurements (pH, temperature, EC, TDS, DO) used a Palintest Micro 800 Multi meter and Hach HQ30d probe. Laboratory analyses at KNUST's Environmental Quality Laboratory included BOD_5

(dilution method, Hach BOD pillows), COD (reactor digestion, Hach vials), oil and grease (gravimetric partition, APHA 5520-B), and nutrients (Hach reagents). Triclosan was quantified via high-performance liquid chromatography (HPLC) following extraction protocols adapted from Hernandez-Leal et al. [25]. Heavy metals (Cu, Mn, Pb, Cd, Fe, Cr, Ni, Mg, K, Ca, Na) were measured by Atomic Absorption Spectroscopy (AAS) at KNUST's Central Laboratory. Microbial analysis (total coliform, E. coli) used the spread plate method with Chromocult Coliform Agar [24].

Data Analysis

Greywater data were analyzed using MS Excel 365 and SPSS version 27 to quantify and compare volumes and characteristics across laundry, kitchen, and bathroom sources. Descriptive statistics, including means and standard deviations, were calculated for greywater quality parameters (pH, temperature, EC, TDS, DO, BOD_5, COD, oil and grease, NO_3^-, PO_4^{3-}, triclosan, heavy metals, total coliforms, E. coli) and presented in Table 1. Daily greywater generation volumes were visualized using bar graphs (Figs 1 and 2), while boxplots (Figs 3 and 4) illustrated volume distributions by day and source. Marginal means of physicochemical and microbial parameters were plotted for each greywater source (Fig. 5). Scatterplots (Fig. 6) compared observed and predicted values to assess model accuracy.

Inferential analyses were conducted to assess differences in greywater characteristics among sources. A Multivariate Analysis of Variance (MANOVA) was used to test for multivariate differences across the three greywater sources (supplementary information). Greywater source was used as the independent variable, and physicochemical and microbiological parameters were used as dependent variables. Prior to MANOVA, Box's Test of Equality of Covariance Matrices was performed to assess the assumption of homogeneity of covariance matrices across groups. The results of the Box's test indicated significant differences, rejecting the null hypothesis of equal covariances. However, given the uniform sample sizes across groups, MANOVA's robustness to violations of covariance equality was maintained [26]. Pillai's Trace was then employed as a robust test statistic to mitigate sensitivity to assumption violations [26]. Normality was assessed via skewness and kurtosis, ensuring values fell within the acceptable range of -2 to +2 [27]. Following significant multivariate results, univariate Analysis of Variance (ANOVA) and between-subject effects tests were conducted to identify specific group differences (Table 3). After establishing a significant disparity among the groups, we discerned the parameters responsible for the mean differences observed across the three categories of greywater sources. Tukey's post hoc tests were employed to identify specific group differences. Parameter estimates were calculated to quantify the contribution of each parameter to greywater characteristics, with 95% confidence intervals to assess statistical significance. To stabilize variance, mitigate the influence of outliers, and enhance data symmetry, a logarithmic transformation (lnx) was employed, where x represents the coefficient of the parameter. This approach was implemented to ensure adherence to the assumptions of normality and homoscedasticity. For the purpose of reporting, the results were exponentiated (e^x) to facilitate interpretation in their original scale values.

Diagnostic scatterplots of observed versus predicted values and standardized residuals were used to evaluate model fit, ensuring assumptions of normality and homoscedasticity were met.

RESULTS

Household greywater generation pattern

A 10-week study in Kotei quantified greywater generation from 10 households, focusing on three sources: kitchen, laundry, and bathing. The mean daily greywater volume per household was 110.0 ± 64.2 litres (range: 37–242 litres). Bathing was the largest contributor, accounting for 58% of the total volume (63.4 ± 28.9 litres/day), followed by laundry (23%, 25.6 ± 20.1 litres/day) and kitchen (19%, 20.8 ± 16.0 litres/day). These source-specific contributions are summarized in Fig. 1, which shows the proportional distribution of greywater by source across the study period.

Fig 1: Proportional Contribution of Greywater Sources

Daily greywater volumes varied moderately across the week, as shown in Fig. 2. The highest mean daily volume occurred on Monday (129.9 ± 57.5 litres/day), followed by Wednesday (123.4 ± 61.8 litres/day) and Saturday (116.1 ± 38.6 litres/day). Sunday had the lowest mean volume (96.6 ± 37.5 litres/day), followed by Tuesday (99.4 ± 45.7 litres/day) and Thursday (100.3 ± 30.7 litres/day). Wednesday exhibited the most significant variability (SD = 61.8 litres), while Thursday showed the least (SD = 30.7 litres).

Figure 3 illustrates weekly trends in mean daily greywater volumes over the 10-week period. Notable peaks occurred in Week 5 (Monday, maximum: 242 litres) and Week 7 (Wednesday, maximum: 215 litres), reflecting high-volume activities in specific households. Conversely, Week 6 recorded consistently low volumes (mean: 50.3 ± 10.2 litres/day). A single-factor ANOVA, conducted on mean daily volumes per household across the 7 days of the week, revealed no significant differences ($p = 0.565$), which suggests that daily greywater generation was relatively stable despite observed fluctuations.

Fig 2: Boxplot showing mean greywater generation by day of the week

Fig 3: Total mean daily greywater generation volumes by day of the week

Variations in greywater generation by source

Greywater volumes differed significantly across sources (Fig 4-5). Bathing generated the highest mean daily volume (63.4 ± 28.9 litres/day, range: 16–118 litres), followed by laundry (25.6 ± 20.1 litres/day, range: 4–100 litres) and kitchen (20.8 ± 16.0 litres/day, range: 4–90 litres). Fig 4 illustrates daily greywater generation by source over the 10-week period, showing consistent dominance of bathing across all days, with laundry and kitchen contributions peaking sporadically. Fig 5 shows a boxplot of daily volumes by source, highlighting the greater median and variability of bathing volumes, with outliers observed for laundry (e.g., 100 litres/day) and kitchen (e.g., 90 litres/day) in specific households. Paired t-tests confirmed that bathing volumes were significantly higher than laundry ($p < 0.001$) and kitchen volumes ($p < 0.001$), and laundry volumes exceeded kitchen volumes ($p = 0.042$).

Fig 4: Line plot illustrating daily greywater generation by source

Fig 5: Boxplot of greywater volumes by source

Characteristics of greywater sources

Greywater from all sources exhibited pH values within the EPA guideline range of 6–9 (Table 1). Laundry greywater was the most alkaline (8.65 ± 0.56), followed by bath (8.06 ± 0.97) and kitchen (7.08 ± 0.81), likely due to detergent and soap residues. Temperature was consistent across sources, ranging from 28.44 ± 1.02°C (kitchen) to 28.89 ± 1.31°C (laundry), reflecting ambient conditions. Dissolved oxygen (DO) levels were moderate, with laundry greywater showing the highest (7.35 ± 2.75 mg/L), followed by kitchen (6.39 ± 1.70 mg/L) and bath (6.27 ± 2.42 mg/L), indicating varying oxygen demands due to organic loads.

Laundry greywater exhibited the highest electrical conductivity (EC; 3825.00 ± 2635.61 μS/cm) and total dissolved solids (TDS; 1600.89 ± 417.37 mg/L), exceeding EPA thresholds (EC: 1,500 μS/cm; TDS: 1,000 mg/L; Table 1). Bath greywater also surpassed these limits (EC: 2160.40 ± 1854.18 μS/cm; TDS: 1599.18 ± 1392.32 mg/L), while kitchen greywater was compliant with TDS (788.01 ± 929.76 mg/L) and below the EC threshold (1475.09 ± 1737.27 μS/cm). The high variability in EC and TDS suggests diverse ionic and solute contributions from source-specific activities.

Biochemical oxygen demand (BOD5) and chemical oxygen demand (COD) were significantly elevated across all sources, exceeding EPA guidelines (BOD5: 50 mg/L; COD: 250 mg/L; Table 1). Laundry greywater recorded the highest levels (BOD5: 5431.67 ± 3440.42 mg/L; COD: 12469.00 ± 7325.75 mg/L), followed by bath (BOD5: 4986.67 ± 2019.09 mg/L; COD: 11452.33 ± 4157.26 mg/L) and kitchen (BOD5: 3786.67 ± 2797.32 mg/L; COD: 8740.33 ± 6007.88 mg/L). The high organic loads indicate considerable pollution from detergents, soaps, and food residues.

Phosphate (PO_4^{3-}) concentrations exceeded the EPA guideline of 2 mg/L across all sources, with laundry greywater showing the highest levels (54.78 ± 17.98 mg/L), followed by bath (40.17 ± 15.90 mg/L) and kitchen (38.28 ± 20.31 mg/L; Table 1). Nitrate (NO_3^--N) levels were well below the EPA threshold of 75 mg/L, ranging from 11.92 ± 5.56 mg/L (kitchen) to 16.85 ± 6.47 mg/L (laundry). Oil and grease concentrations were highest in bath greywater (15.68 ± 14.54 mg/L), followed by kitchen (6.66 ± 14.49 mg/L), while laundry exhibited negligible levels (0.13 ± 0.10 mg/L). The high variability in oil and grease suggests inconsistent contributions from soaps and cooking residues.

Trace metal concentrations vary across sources. Lead (Pb) concentrations exceeded the EPA guideline of 0.1 µg/L across all sources, with bath greywater showing the highest levels (1.66 ± 0.83 µg/L), followed by laundry (1.46 ± 0.40 µg/L) and kitchen (1.42 ± 0.58 µg/L; Table 1). Iron (Fe) also surpassed the EPA threshold of 10 µg/L, with laundry greywater exhibiting the highest concentration (50.37 ± 26.63 µg/L), followed by bath (18.64 ± 11.24 µg/L) and kitchen (12.35 ± 10.24 µg/L). Copper (Cu) remained below the EPA guideline of 2.5 µg/L across all sources. Other metals, including chromium (Cr), nickel (Ni), and aluminium (Al), showed higher concentrations in laundry and bath greywater, particularly with laundry Cr (2.05 ± 2.64 µg/L) and Ni (4.53 ± 4.21 µg/L) notably elevated. Triclosan was detected in all sources, with laundry greywater showing the highest levels (17.81 ± 24.91 µg/L), indicating contributions from antimicrobial agents in detergents and personal care products.

Microbial loads, measured as total coliforms and Escherichia coli, exceeded EPA guidelines (total coliforms: 2.6 cfu/ml; E. coli: 1 cfu/ml) across all sources. Kitchen greywater exhibited the highest contamination (total coliforms: 136.17±66.94 cfu/ml; E. coli: 34.83±24.70 cfu/ml), followed by bath (total coliforms: 111.17±58.06 cfu/ml; E. coli: 25.33±34.37 cfu/ml) and laundry (total coliforms: 84.33±32.07 cfu/ml; E. coli: 18.17±12.31 cfu/ml). These elevated levels indicate significant microbial risks, particularly for reuse applications without treatment.

Table1: Descriptive Statistics of Greywater Characteristics Across Sources

Parameter	**Unit**	**EPA Guideline**	**Laundry (Mean±SD)**	**Kitchen (Mean±SD)**	**Bath (Mean±SD)**
pH	N/A	6 – 9	8.65±0.56	7.08±0.81	8.06±0.97
Temperature	°C	n/a	28.89±1.31	28.44±1.02	28.71±1.93
EC	µS/cm	1,500	3825.00±2635.61	1475.09±1737.27	2160.40±1854.18
TDS	mg/L	1,000	1600.89±417.37	788.01±929.76	1599.18±1392.32
DO	mg/L	n/a	7.35±2.75	6.39±1.70	6.27±2.42
COD	mg/L	250	12469.00±7325.75	8740.33±6007.88	11452.33±4157.26
BOD5	mg/L	50	5431.67±3440.42	3786.67±2797.32	4986.67±2019.09
BOD/COD	–	n/a	–	–	–
Oil & Grease	mg/L	n/a	0.13±0.10	6.66±14.49	15.68±14.54
Phosphate ($PO4^{3-}$)	mg/L	2	54.78±17.98	38.28±20.31	40.17±15.90
Nitrate ($NO3^{-}$-N)	mg/L	75	16.85±6.47	11.92±5.56	15.43±5.34
Triclosan	µg/L	n/a	17.81±24.91	12.67±25.78	10.63±8.03
Mg	mg/L	n/a	6.57±2.59	4.97±1.71	5.69±2.02
K	mg/L	n/a	106.68±26.03	90.46±20.95	84.14±25.36
Ca	mg/L	n/a	13.24±6.15	7.28±3.45	6.44±3.40

Na	mg/L	n/a	10.06±1.03	6.78±1.96	8.91±1.54
Cu	µg/L	2.5	0.41±0.19	0.44±0.62	0.26±0.12
Mn	µg/L	n/a	0.65±0.28	0.33±0.13	0.49±0.18
Pb	µg/L	0.1	1.46±0.40	1.42±0.58	1.66±0.83
Cd	µg/L	<0.01	–	–	–
Fe	µg/L	10	50.37±26.63	12.35±10.24	18.64±11.24
Cr	µg/L	n/a	2.05±2.64	0.48±0.33	2.96±3.63
Ni	µg/L	n/a	4.53±4.21	1.23±0.40	1.80±1.46
Al	µg/L	n/a	11.90±8.54	3.95±4.13	5.68±4.23
Total Coliform	cfu/ml	2.6	84.33±32.07	136.17±66.94	111.17±58.06
E. coli	cfu/ml	1	18.17±12.31	34.83±24.70	25.33±34.37

Statistical Analysis of Source-Specific Greywater Characteristics

Multivariate analysis of variance (MANOVA) confirmed significant differences in greywater characteristics across laundry, kitchen, and bath sources (Pillai's Trace = 1.73, $F(63, 363) = 7.81$, $p < 0.001$) (see supplementary information). Univariate ANOVA further identified significant differences for all 22 parameters ($p < 0.001$), with laundry greywater explaining 96.1% of the variance ($F(21, 121) = 142.63$, $p < 0.001$), bath greywater 91.8% ($F(21, 121) = 64.25$, $p < 0.001$), and kitchen greywater 83.2% ($F(21, 121) = 28.47$, $p < 0.001$). These results indicate distinct pollution profiles driven by source-specific activities.

Parameter estimates from ANOVA (Table 2) represent standardized effect sizes, reflecting the relative contribution of each parameter to source-specific pollution. For laundry greywater, COD (9.24±0.24), BOD5 (8.37±0.24), EC (8.10±0.19), and TDS (7.34±0.19) showed the largest positive effects, indicating high organic and ionic loads. Microbial contamination (total coliforms: 4.34±0.24; E. coli: 2.79±0.33) and nutrients (phosphate: 3.92±0.24; nitrate: 2.75±0.24) were also significant. Oil and grease had a negative effect (-2.48±0.29), suggesting a lower relative contribution. Lead (0.56±0.29) and chromium (0.66±0.41) had CIs including zero, indicating marginal significance.

For kitchen greywater, COD (2.23±0.13), BOD5 (2.13±0.13), EC (1.99±0.10), and TDS (1.94±0.10) showed moderate positive effects, reflecting organic and ionic pollution from food residues. Microbial loads (total coliforms: 1.50±0.13; E. coli: 1.16±0.18) and phosphate (1.28±0.13) were significant, while nickel (-0.39±0.18) had a negative effect. Lead (-0.10±0.16) and chromium (0.43±0.22) were not significant.

For bath greywater, COD (8.81±0.32), BOD5 (7.91±0.32), EC (6.94±0.26), and TDS (6.32±0.26) exhibited strong positive effects, driven by soaps and personal care products. Microbial contamination (total coliforms: 4.60±0.32; E. coli: 4.07±0.46) and phosphate (3.50±0.32) were significant. Oil and grease (-0.42±0.40), lead (0.60±0.40), chromium (-0.69±0.56), and nickel (0.18±0.46) were not significant. Tukey's post hoc tests (in supplementary information) confirmed that laundry and bath greywater had significantly higher COD, BOD5, EC, TDS, and phosphate levels than kitchen greywater ($p < 0.05$), while kitchen greywater had higher microbial loads ($p < 0.05$).

Table 2: Effect sizes for laundry, kitchen, and bath greywater parameters

Laundry	Kitchen	Bath

Parameter	Mean	Std. Error	95% CI	Mean	Std. Error	95% CI	Mean	Std. Error	95% CI
pH	2.16	0.192	[1.77 – 2.53]	0.73	0.104	[0.53 – 0.94]	1.95	0.263	[1.43 – 2.47]
Temperature	3.36	0.192	[2.98 – 3.74]	1.21	0.104	[1.02 – 1.42]	3.35	0.263	[2.83 – 3.87]
EC	8.1	0.192	[7.72 – 8.47]	1.99	0.104	[1.79 – 2.20]	6.94	0.263	[6.42 – 7.46]
TDS	7.34	0.192	[6.96 – 7.72]	1.94	0.104	[1.73 – 2.15]	6.32	0.263	[5.80 – 6.83]
DO	2.1	0.203	[1.67 – 2.50]	0.64	0.11	[0.42 – 0.85]	1.88	0.279	[1.33 – 2.43]
COD	9.24	0.235	[8.77 – 9.71]	2.23	0.127	[1.98 – 2.48]	8.81	0.322	[8.17 – 9.45]
BOD5	8.37	0.235	[7.91 – 8.84]	2.13	0.127	[1.88 – 2.38]	7.91	0.322	[7.28 – 8.55]
BOD/COD	–	–	–	–	–	–	–	–	–
Oil & Grease	-2.48	0.287	[-3.05 – -1.91]	0.8	0.156	[0.50 – 1.11]	-0.42	0.395	[-1.20 – 0.36]
Phosphate ($PO4^{3-}$)	3.92	0.235	[3.46 – 4.39]	1.28	0.127	[1.03 – 1.54]	3.5	0.322	[2.86 – 4.14]

Nitrate (NO_3^--N)	2.75	0.235	[2.28 – 3.21]	0.97	0.127	[0.71 – 1.22]	2.39	0.322	[1.75 – 3.02]
Triclosan	2.13	0.235	[1.66 – 2.59]	0.79	0.127	[0.54 – 1.05]	1.45	0.322	[0.81 – 2.08]
Mg	1.79	0.203	[1.38 – 2.19]	0.42	0.11	[0.21 – 0.64]	1.55	0.279	[1.00 – 2.10]
K	4.64	0.203	[4.23 – 5.04]	1.47	0.11	[1.25 – 1.69]	4.48	0.279	[3.93 – 5.03]
Ca	2.44	0.203	[2.04 – 2.84]	0.49	0.11	[0.27 – 0.71]	1.86	0.279	[1.31 – 2.41]
Na	2.3	0.203	[1.90 – 2.70]	0.77	0.11	[0.55 – 0.99]	1.88	0.279	[1.33 – 2.43]
Cu	–	–	–	–	–	–	–	–	–
Mn	–	–	–	–	–	–	–	–	–
Pb	0.56	0.287	[-0.01 – 1.12]	-0.1	0.156	[-0.41 – 0.21]	0.6	0.395	[-0.18 – 1.38]
Cd	–	–	–	–	–	–	–	–	–
Fe	3.75	0.203	[3.34 – 4.15]	0.8	0.11	[0.58 – 1.01]	2.24	0.279	[1.69 – 2.79]
Cr	0.66	0.406	[-0.15 – 1.46]	0.43	0.22	[-0.01 – 0.86]	-0.69	0.558	[-1.79 – 0.42]
Ni	0.82	0.332	[0.17 – 1.48]	-0.39	0.18	[-0.74 – -0.03]	0.18	0.456	[-0.73 – 1.08]

Al	2.37	0.217	[1.94 – 2.80]	0.47	0.118	[0.24 – 0.71]	1.04	0.298	[0.44 – 1.63]
Total Coliform	4.34	0.235	[3.88 – 4.81]	1.5	0.127	[1.25 – 1.76]	4.6	0.322	[3.96 – 5.23]
E. coli	2.79	0.332	[2.13 – 3.45]	1.16	0.18	[0.81 – 1.51]	4.07	0.456	[3.17 – 4.97]

Model Fit and Source-Specific Pollution Profiles

Diagnostic scatterplots of observed versus predicted values (Fig 6) demonstrated strong model fit for all greywater sources, with linear trends indicating high predictive accuracy (R^2 > 0.90 for all sources). Kitchen greywater showed the tightest clustering (R^2 = 0.95), followed by laundry (R^2 = 0.92) and bath (R^2 = 0.90). Residual plots confirmed homoscedasticity and normality, with no systematic patterns. Bath greywater residuals exhibited slightly greater spread, reflecting higher variability in pollutant concentrations.

Profile plots of standardized marginal means (Fig 7) illustrated source-specific pollution patterns. Laundry greywater exhibited the highest marginal means for COD, BOD5, EC, TDS, and phosphate, indicating substantial organic and ionic loads. Bath greywater showed comparable trends, with elevated COD, BOD5, and oil and grease. Kitchen greywater had lower marginal means for most parameters, but the highest microbial loads. Nitrate marginal means were positive across all sources, consistent with Table 1, with laundry showing the highest values.

Fig 6: Scatterplots of Observed versus Predicted Values for Greywater Parameters

Fig 7: Profile Plots of Standardized Marginal Means for Greywater Parameters

DISCUSSION

Greywater Generation Patterns

This study quantified household greywater generation in Kotei, Ghana, revealing a mean daily volume of 110.0 ± 64.2 litres per household, with bathing (58%, 63.4 ± 28.9 litres/day), laundry (23%, 25.6 ± 20.1 litres/day), and kitchen activities (19%, 20.8 ± 16.0 litres/day) as the primary sources. These findings align with global estimates of household greywater production, which typically range from 50 to 150 litres per capita per day (LPCD) in low- and middle-income countries (LMICs) [1,4,7]. Morel and Diener [1] reported average greywater generation of 90–120 litres per household per day in low-income urban areas of sub-Saharan Africa. Similarly, Katukiza et al. [4] found a mean of 105 litres per household per day in Kampala, Uganda. However, the daily household generation rate in this study is lower than prior study conducted in Kumasi by Dwumfour-Asare [21]. This variation is possibly due to water access constraints or differences in water use practices. Again, our results diverge from studies in high-income countries, where greywater volumes are often higher due to appliance use. For example, Friedler and Hadari (2006)[28] reported 150–200 litres per household per day in Israel. The dominance of bathing as the largest greywater source (58%) is consistent with studies in sub-Saharan Africa and South Asia, where bathing often accounts for 50–60% of household greywater [15,16,29]. A study in Jordan reported bathing contributing 54% of greywater, with laundry and kitchen sources at 24% and 22%, respectively [29], closely mirroring this study's proportions. In contrast to our findings, Friedler and Hadari (2006) [28] reported a 40% contribution from laundry to household greywater contribution due to the widespread use of washing machines. Our study's laundry contribution reflects manual washing practice, which consumes less water but exhibits high variability due to household size, washing frequency, and water access on greywater production. The relatively low kitchen contribution (19%) as found in this study also contrasts with findings from high-income countries, where kitchen greywater can constitute 30–40% due to widespread use of dishwashers and food preparation practices [5]. These discrepancies underscore the influence of socioeconomic factors and household technologies on greywater composition.

The observed temporal variations, with higher greywater volumes on Monday (129.9 ± 57.5 litres/day) and Wednesday (123.4 ± 61.8 litres/day) compared to Sunday (96.6 ± 37.5 litres/day), suggest behavioural patterns tied to weekly routines. Although the ANOVA indicated no significant differences across days ($p = 0.565$), the descriptive trend of elevated volumes early in the week aligns with studies reporting increased water use on weekdays [30]. In Oman, Prathapar et al. [30] noted a 20–30% increase in greywater generation on workweek days due to increased household chores [30]. Al Arni et al. (2022) [31]similarly reported higher greywater production at the start of weekdays in Jordan due to bulk laundry and cleaning, a pattern mirrored in our data. The high variability on Wednesday (SD = 61.8 litres) in this study may reflect sporadic high-volume activities, a pattern also observed in South African households Carden et al. [32] and other similar contexts [16,33]. Week 6's consistently low volumes could stem from external factors, such as water supply disruptions, which Katukiza et al., (2015) [4] identified as a key driver of reduced greywater generation. Similar anomalies have been reported in water-scarce regions, where greywater generation can drop significantly during supply restrictions [1].

Greywater quality and environmental implications

The characterization of greywater from laundry, kitchen, and bath sources in this study reveals significant variability in physicochemical, nutrient, trace metal, and microbial profiles, with implications for wastewater management and environmental health. The pH of greywater in this area is consistent with prior studies. For instance, Eriksson et al. (2002) [2] reported pH values of 7.0–8.5 for laundry and bath greywater, attributing alkalinity to detergents and soaps. The near-neutral pH of kitchen greywater aligns with findings by Boyjoo et al. (2013) [5] and Mohammad et al. (2018)[35], who noted pH values of 6.5–7.5 due to food residues and cleaning agents. The high variability in pH suggests household-specific differences in product use, warranting further investigation into consumer behaviour. Temperature consistency across sources (28.44–28.89°C) reflects ambient conditions, as noted by Friedler (2004) [11], and poses no immediate reuse constraints.

The study also recorded high electrical conductivity (EC) and total dissolved solids (TDS) in laundry and bath greywater that exceed EPA thresholds. The findings corroborate studies by Gross et al. (2005), Katukiza et al. (2015), and Travis et al. (2010) [4,22,36]. These findings align with [17], who reported EC values of 2000–4000 μS/cm for laundry greywater due to ionic surfactants in detergents. The lower EC and TDS in kitchen greywater are consistent with [4,37], who noted values of 800–1500 μS/cm in Ugandan households, attributed to food residues rather than ionic compounds. Laundry greywater has high metal and soiling content, hence increasing the EC, while kitchen greywater contains food particles that could increase the EC concentrations [5]. The high variability in EC and TDS suggests household-specific practices, a phenomenon also observed by Jefferson et al. (2004).

Organic pollution, measured as biochemical oxygen demand (BOD5) and chemical oxygen demand (COD), exceeds those reported in previous studies. Friedler [11] found COD levels of 400–1000 mg/L for bath greywater and 1000–2000 mg/L for laundry greywater in Israel, while Mohammad et al [34] reported BOD5 values of 200–600 mg/L for kitchen greywater in Malaysia. Kitchen greywater contains biodegradable dissolved food particles, which contribute to the BOD, while the high COD is due to the presence of detergents from laundry powders and dishwashing liquids [5]. The elevated organic loads in this study may reflect regional differences in detergent formulations, water usage, or sampling methods. The high BOD5/COD ratios suggest significant biodegradability, supporting the potential for biological treatment systems, as indicated by Li et al [38]

Greywater is reported to have high nutrient content due to residual food particles and phosphates from laundry detergents. Phosphate ($PO4^{3-}$) concentrations found in the greywater sources are consistent with those of Eriksson et al. [2], who reported high phosphate levels from detergents and cleaning agents. These levels are, however, higher than those reported by Gross et al [22], who found phosphate concentrations of 10–30 mg/L in laundry greywater in Israel. The high phosphate levels in kitchen greywater diverge from Al-Gheethi et al., (2019), who reported 5–15 mg/L in Malaysian kitchen greywater. Elevated phosphate levels pose risks of eutrophication in receiving waters [40], necessitating phosphorus removal technologies, such as adsorption or constructed wetlands, as recommended by Vymazal [9,41]. Nitrate ($NO3^{-}$-N) levels align with Gross et al [22] findings, who noted low nitrogen contributions in greywater compared to blackwater. Edwin et al [42] also reported a similar range of 10–20 mg/L in bath greywater. The moderate nitrate levels suggest limited nitrogenous organic inputs, contrasting with the high phosphate loads. The moderate variability in nutrient levels also suggests consistent detergent use across households, a pattern also observed by Katukiza et al [4].

It is well known that laundry detergents are a source of heavy metals such as Cd, Cu, Pb, Cr, and Zn [43]. Heavy metal concentrations pose environmental and public health risks. The reported concentration of Pb in this study's findings is consistent with [44], who reported Pb levels of 1–2 µg/L in Australian greywater. However, the Fe concentrations in this study are higher than those reported by Santos [45] (5–20 µg/L), possibly due to soil residues in laundry or regional differences in water chemistry. Higher Fe levels in laundry greywater may also reflect fabric-related contaminants, a claim supported by Jefferson et al. [17]. The presence of chromium (Cr), nickel (Ni), and aluminium (Al) in laundry and bath greywater aligns with Palmquist and Hanæus [46], who linked metal contamination to personal care products and detergents. These metals pose environmental risks if greywater is reused for irrigation, as they may accumulate in soils [12]. Copper (Cu) and manganese (Mn) concentrations were also consistent with low contributions from household sources [22].

Triclosan, detected in all sources, is a concern due to its antimicrobial properties and potential to disrupt microbial ecosystems. These levels are comparable to those reported by Donner et al [47] (5–20 µg/L in bath greywater) but are higher than those in Eriksson et al. (2003) (1–10 µg/L). Bakare and Adeyinka and Bedoux et al [48,49] linked antimicrobial agents in greywater to personal care products. The absence of GH EPA guidelines for triclosan highlights a regulatory gap and underscores the need for further research on its environmental fate and impacts, particularly in greywater reuse scenarios. According to Dhillon et al. [13] and Bakare and Adeyinka [49], its persistence poses ecological risks. The elevated microbial loads in kitchen greywater suggest inadequate handling of contaminated food and poor hygiene practices in the kitchen [8,50]. The low microbial load in laundry greywater may reflect detergent antimicrobial effects, a phenomenon observed by Friedler [11]. These findings underscore the need for disinfection prior to greywater reuse, as untreated reuse risks pathogen exposure [3,11,51]

Limitations and Future Research Directions

While this study provides valuable insights into greywater characteristics in Kotei, Ghana, several limitations warrant consideration. The sample size and geographic scope may limit generalizability to other regions with different water use practices or infrastructural constraints. The study's focus on one season (June–August 2023) may not capture wet versus dry season variations that affect greywater volumes and microbial loads.

Future research should include multi-site studies across urban and rural Ghana to capture diverse greywater profiles. Longitudinal studies over 12 months could investigate seasonal trends, consumer behaviour driving variability in greywater composition, and the long-term impacts of greywater reuse on soil and groundwater quality. Pilot studies testing low-cost treatment technologies, such as constructed wetlands or biochar filtration, could inform scalable solutions for LMICs. Furthermore, the environmental fate of triclosan and other emerging contaminants like microplastics requires urgent attention to develop regulatory frameworks and mitigation strategies.

CONCLUSION

This study provides a comprehensive analysis of household greywater generation and characteristics in Kotei, a peri-urban community in Kumasi, Ghana, revealing critical insights into its environmental and public health implications. The mean daily greywater production of

110.0 ± 64.2 litres per household, dominated by bathing (58%), aligns with global estimates for low- and middle-income countries but highlights the influence of local water use practices, such as manual laundry distinguishing it from higher volumes in high-income settings and prior Ghanaian studies. The significant variability in greywater composition across laundry, kitchen, and bathroom sources underscores the necessity of source-specific management strategies, with laundry showing high organic and ionic loads and kitchen elevated microbial contamination. The presence of phosphates, heavy metals (e.g., Pb, Fe), and triclosan across all sources indicates substantial environmental risks, including eutrophication and soil contamination, particularly if greywater is reused without treatment. These findings emphasize the urgent need for affordable, context-appropriate treatment technologies, such as constructed wetlands or biochar filtration, integrated into the Ghana WASH Sector Development Programme (GWASHSDP). A proposed Ghana EPA guideline for triclosan (10 µg/L) addresses regulatory gaps, aligning with SDG 6 (Target 6.3) and WHO reuse guidelines (E. coli < 1 cfu/ml), positioning Kotei as a model for LMIC greywater management.

Future research should include multi-site studies across urban and rural Ghana and longitudinal studies to capture seasonal variations. Investigation of emerging contaminants like microplastics and pharmaceuticals will build on this study's baseline, advancing sustainable WASH solutions.

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Availability of data

All relevant data are included in the paper or its supporting information.

Conflict of Interest

The authors declare no conflict of interest.

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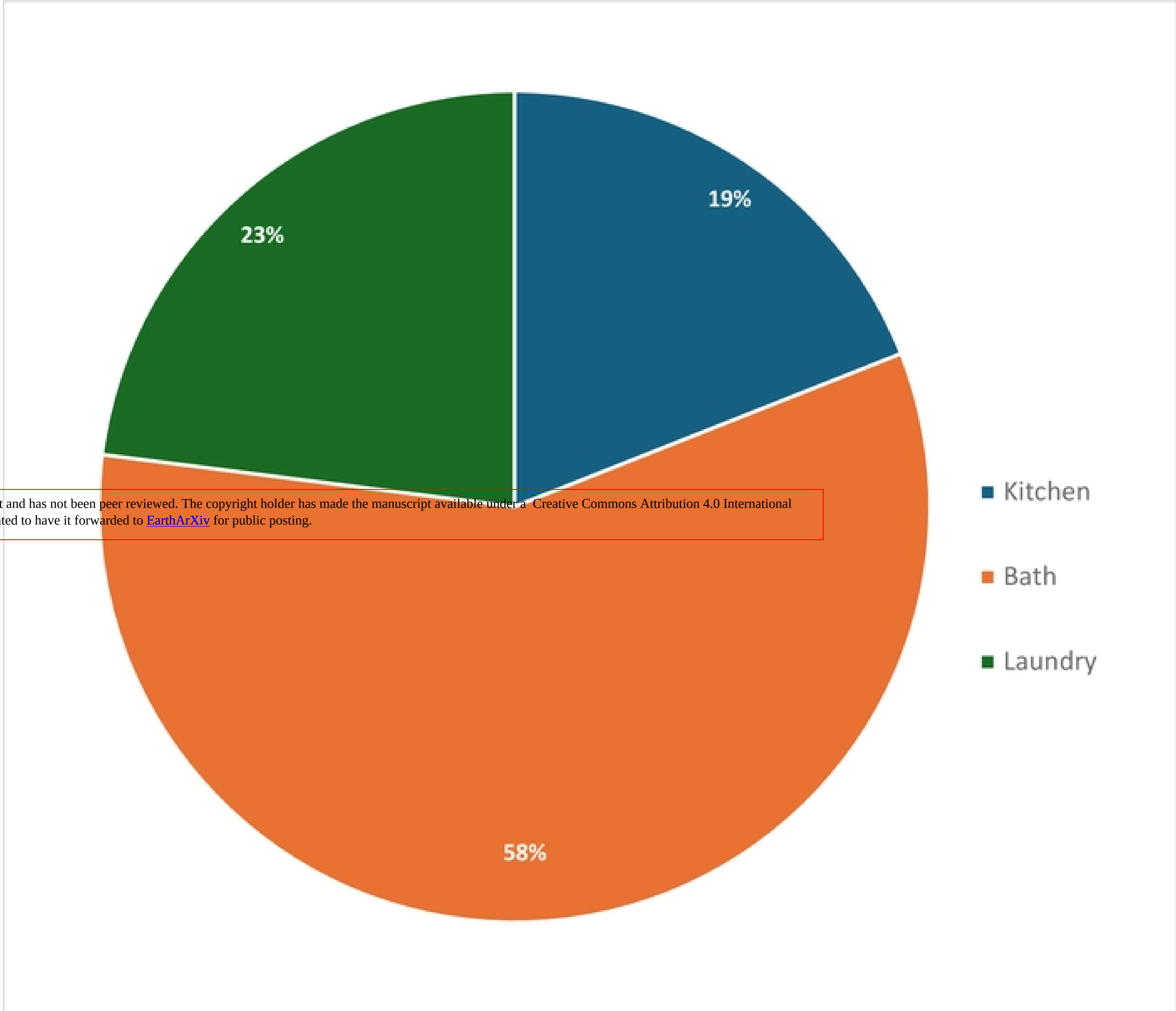
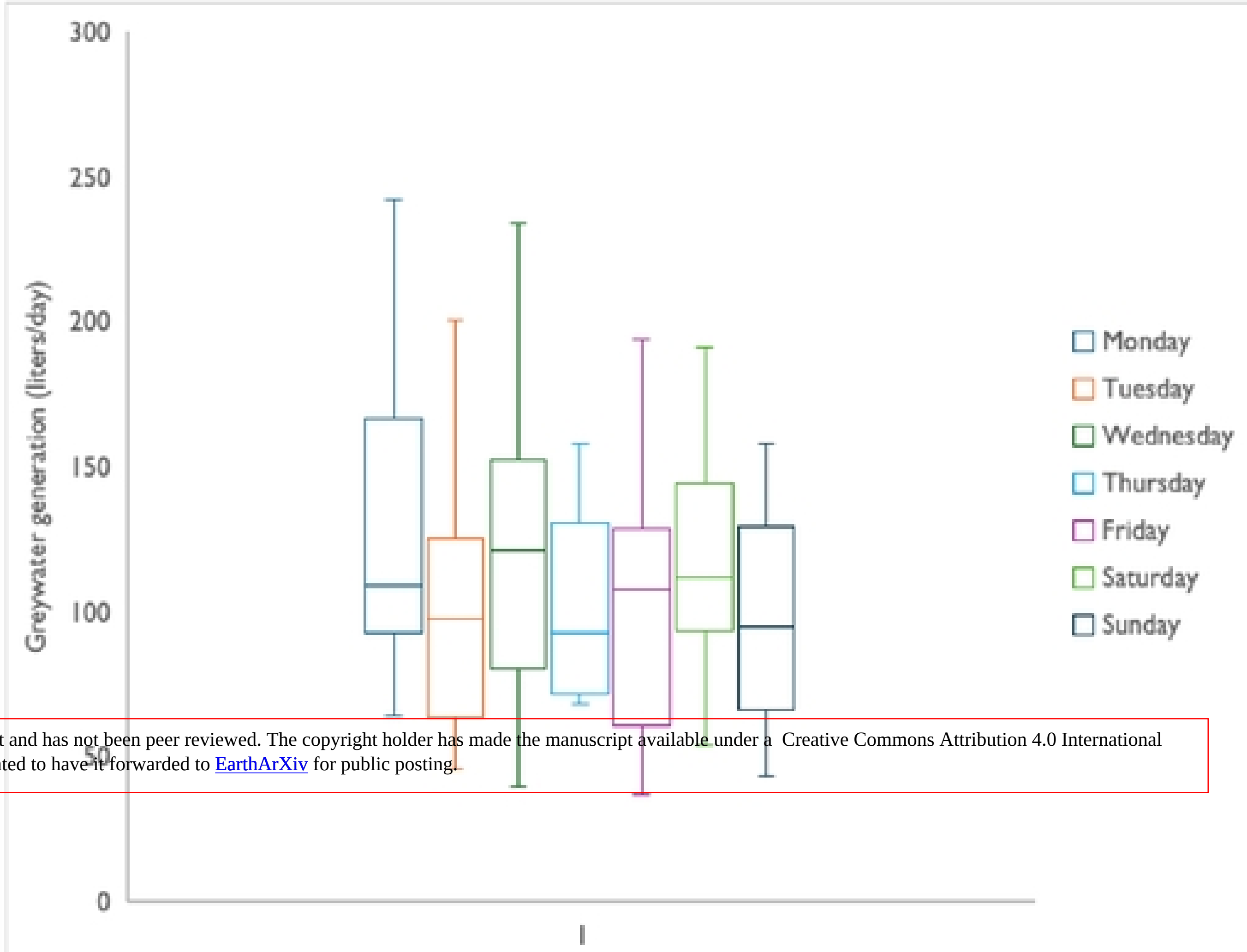


Fig 1

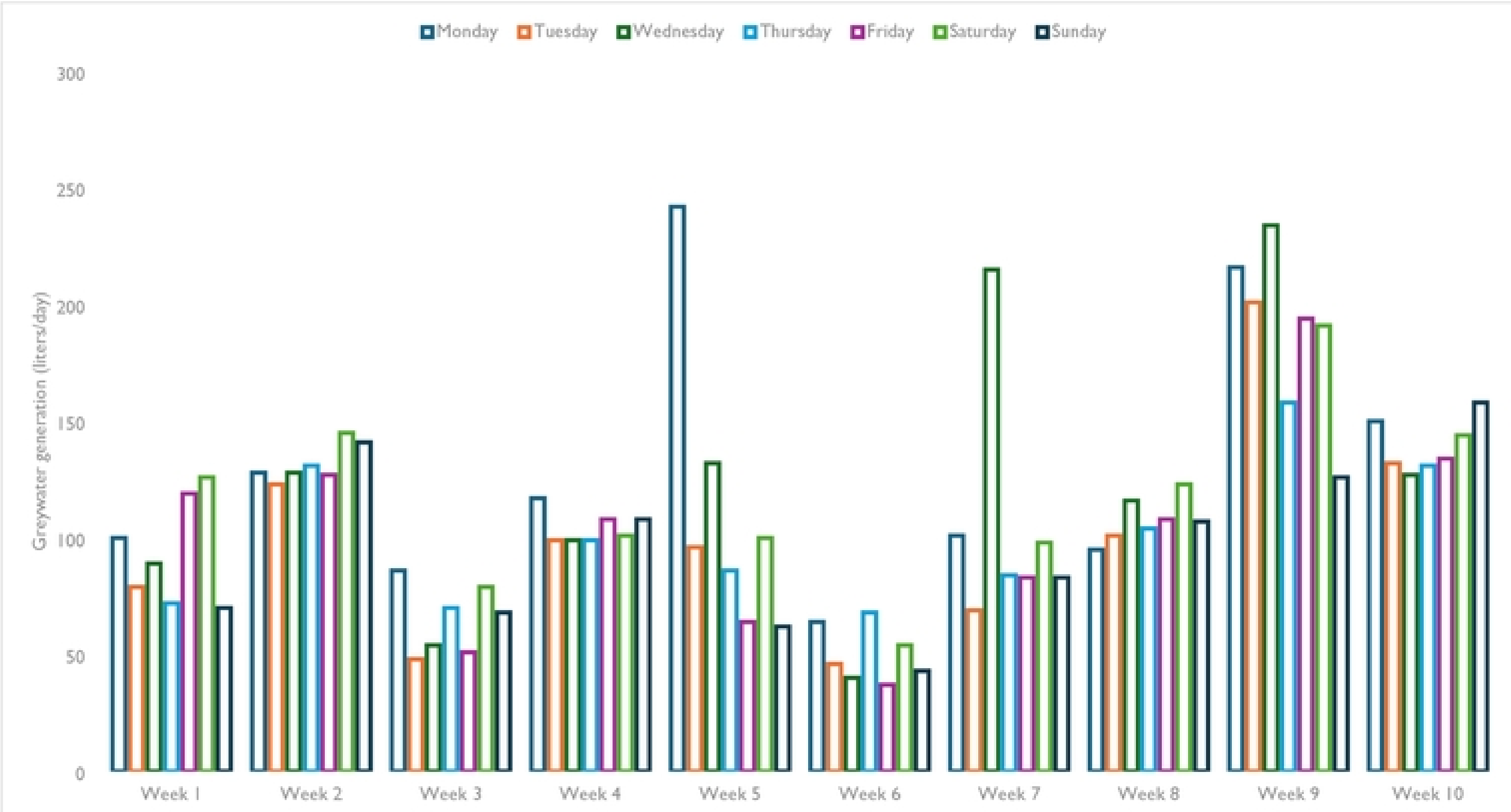
Figure



300
250
200
150
100
50
0
Greywater generation (liters/day)
1
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday

Fig 2

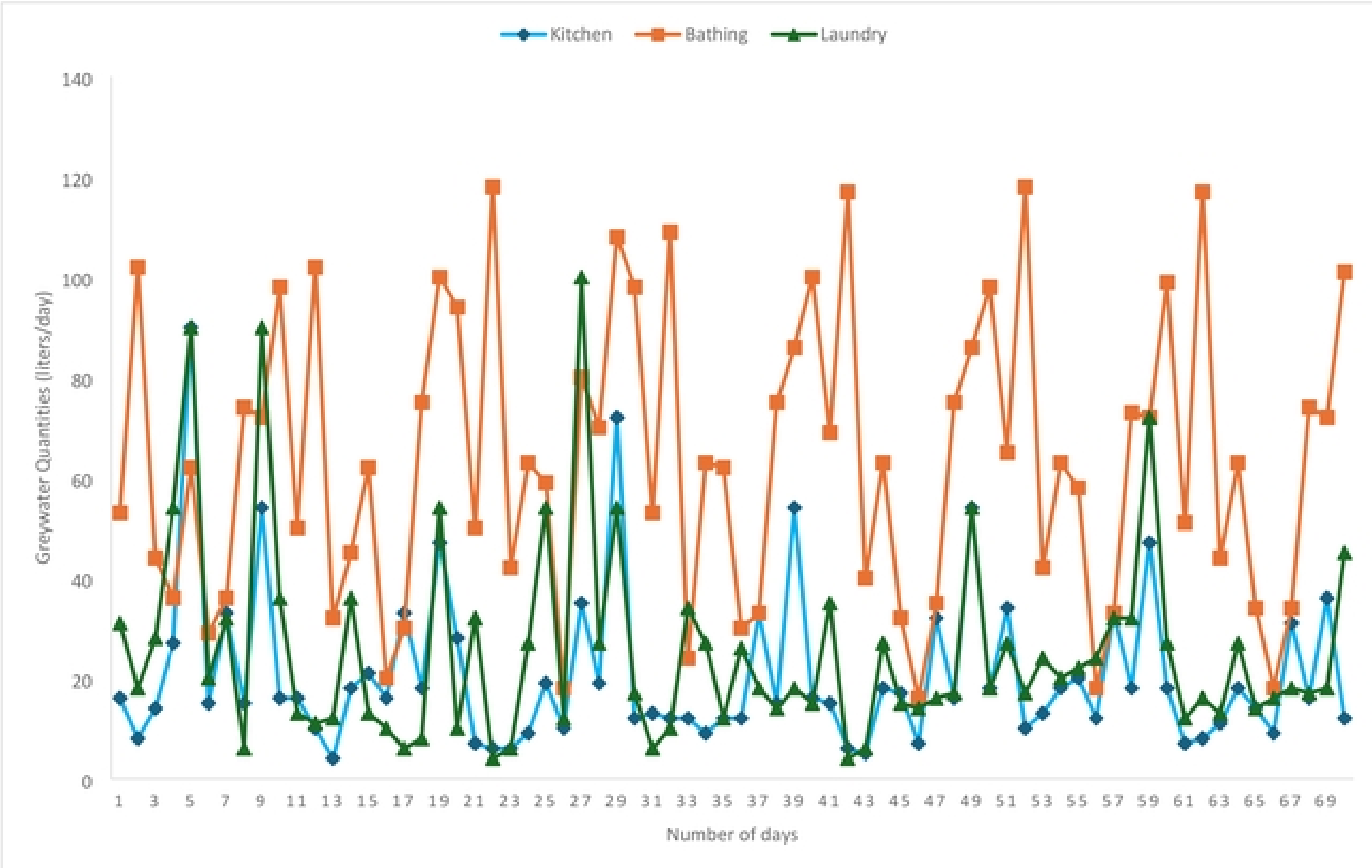
Figure



Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday
Greywater generation (liters/day)
300
250
200
150
100
50
0
Week 1
Week 2
Week 3
Week 4
Week 5
Week 6
Week 7
Week 8
Week 9
Week 10

Fig 3

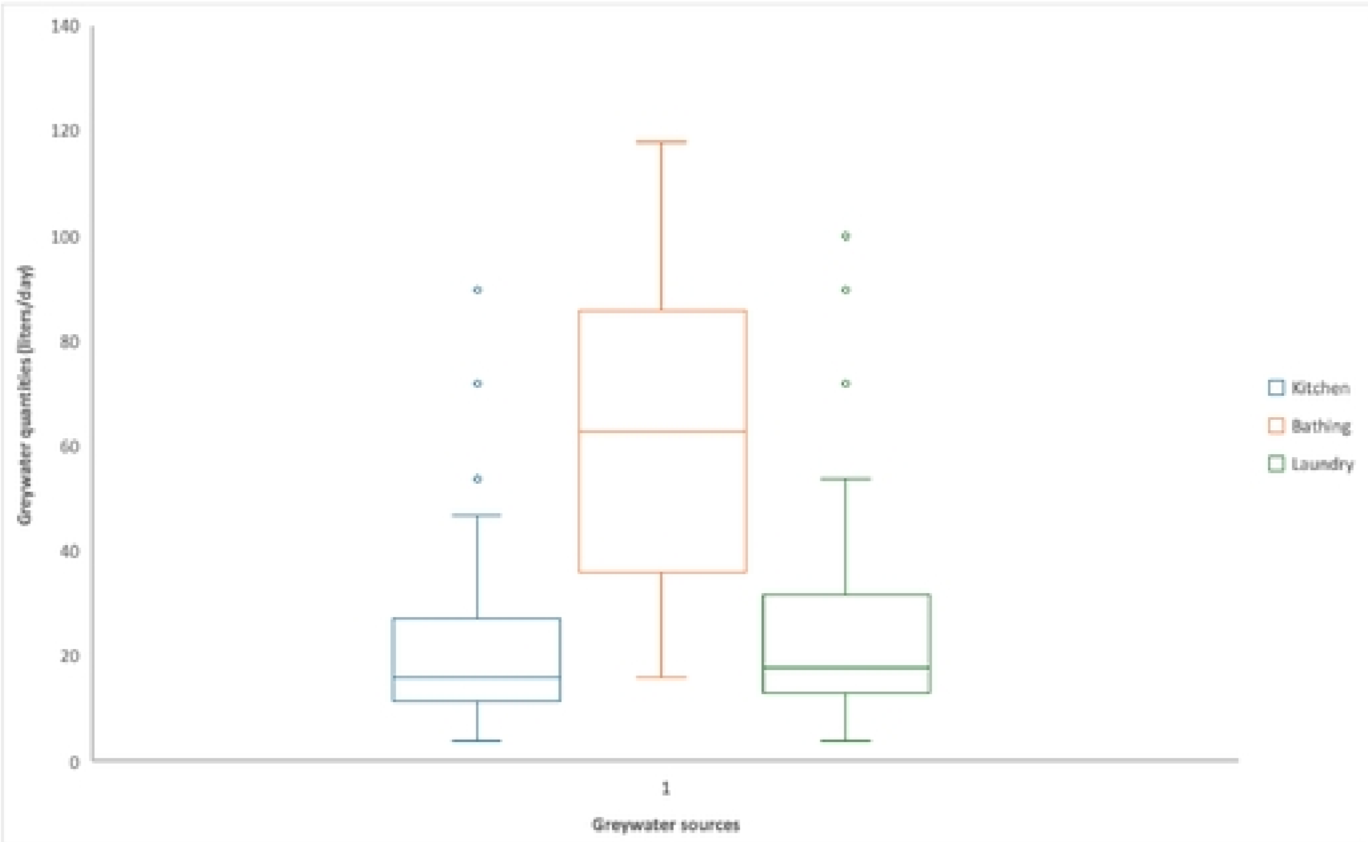
Figure



Kitchen
Bathing
Laundry
140
120
100
80
60
40
20
0
Greywater Quantities (liters/day)
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
41
43
45
47
49
51
53
55
57
59
61
63
65
67
69
Number of days

Fig 4

Figure



140
120
100
80
60
40
20
0
Greywater quantities (liters/day)
1
Greywater sources
Kitchen
Bathing
Laundry

Fig 5

Figure

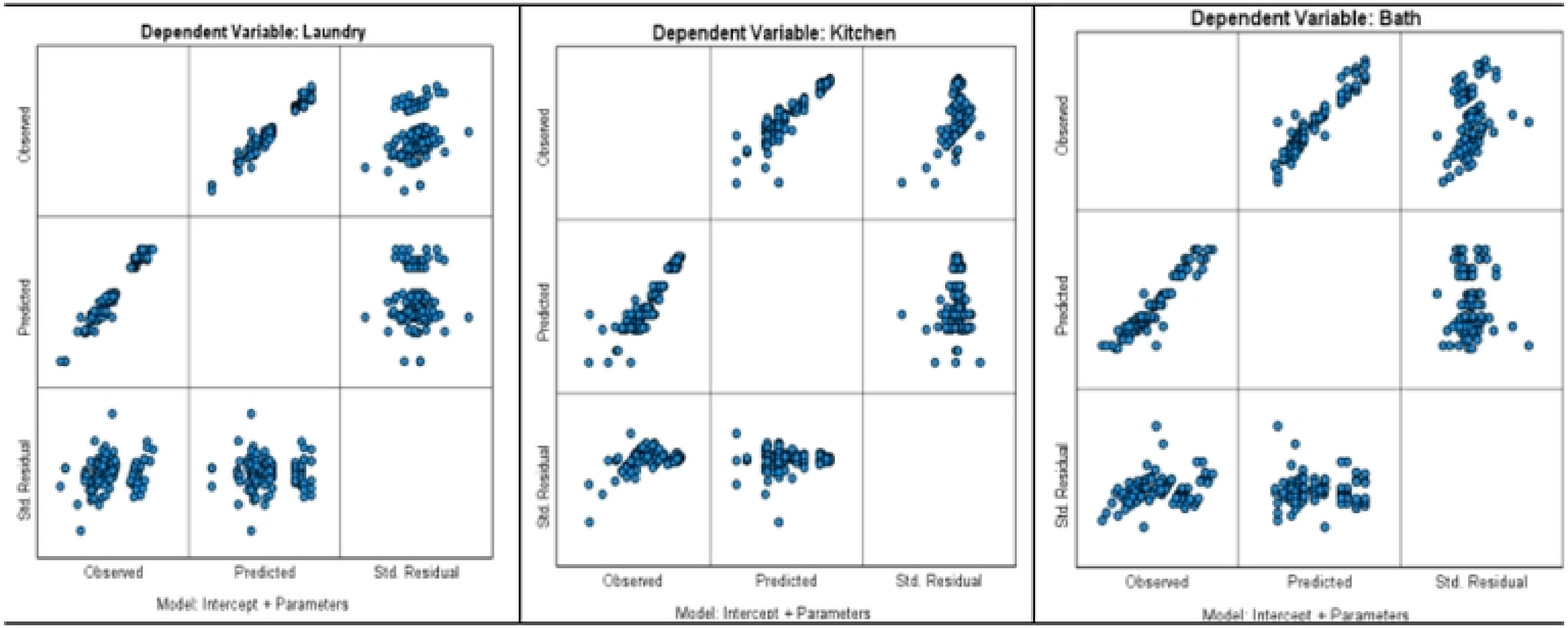

Dependent Variable: Laundry
Observed
Predicted
Std. Residual
Observed
Predicted
Std. Residual
Model: Intercept + Parameters
Dependent Variable: Kitchen
Observed
Predicted
Std. Residual
Observed
Predicted
Std. Residual
Model: Intercept + Parameters
Dependent Variable: Bath
Observed
Predicted
Std. Residual
Observed
Predicted
Std. Residual
Model: Intercept + Parameters

Fig 6

Figure

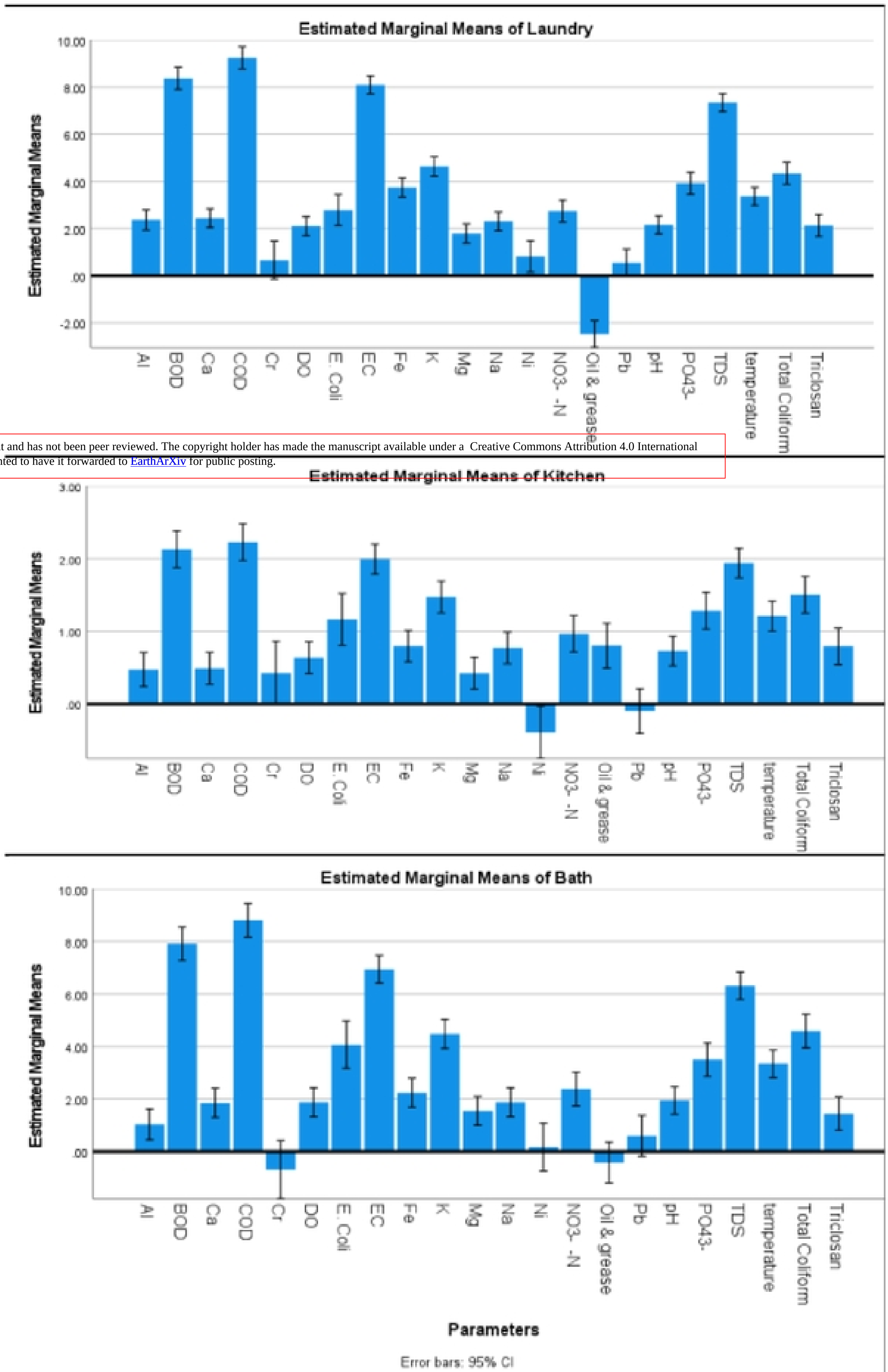

Estimated Marginal Means of Laundry
Estimated Marginal Means
10.00
8.00
6.00
4.00
2.00
.00
-2.00
Al
BOD
Ca
COD
Cr
DO
E. Coli
EC
Fe
K
Mg
Na
Ni
NO3- -N
Oil & grease
Pb
pH
PO43-
TDS
temperature
Total Coliform
Triclosan
Estimated Marginal Means of Kitchen
Estimated Marginal Means
3.00
2.00
1.00
.00
Al
BOD
Ca
COD
Cr
DO
E. Coli
EC
Fe
K
Mg
Na
Ni
NO3- -N
Oil & grease
Pb
pH
PO43-
TDS
temperature
Total Coliform
Triclosan
Estimated Marginal Means of Bath
Estimated Marginal Means
10.00
8.00
6.00
4.00
2.00
.00
Al
BOD
Ca
COD
Cr
DO
E. Coli
EC
Fe
K
Mg
Na
Ni
NO3- -N
Oil & grease
Pb
pH
PO43-
TDS
temperature
Total Coliform
Triclosan
Parameters
Error bars: 95% CI

Fig 7

Figure