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Assessing greywater management and reuse options for smallholder urban farmers and eatery operators in Mbarara City, Uganda

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Abstract

Introduction: Rapid urbanisation, climate variability, and increasing water scarcity have intensified interest in greywater reuse for urban agriculture in developing countries. However, evidence on the management, quality and reuse potential of greywater from small-scale eateries remains limited. This study aimed to assess greywater management practices, microbial contamination, and stakeholder perceptions to evaluate its suitability for reuse in urban farming in Mbarara city, southwestern Uganda.

Materials and methods: A mixed-methods approach was employed involving 80 participants (40 eatery operators and 40 smallholder farmers) across two administrative divisions. Data on greywater generation, handling and disposal were collected using questionnaires and interviews, while greywater samples from eateries were analysed for fecal indicator bacteria using standard methods, and findings were summarized using descriptive statistical analyses.

Results: Eateries generated approximately 80 L of greywater per day, with disposal identified as a major operational challenge. Microbial contamination was widespread, with coliforms detected in 87.5% of samples and faecal indicators in nearly half. Poor disposal practices were associated with environmental challenges, including odours, mosquito breeding, and drainage blockage. Smallholder farmers reported persistent water shortage and expressed strong willingness to adopt treated greywater for irrigation and urban farming.

Conclusions and implications: These findings highlight a critical gap between greywater availability and safe reuse in rapidly growing secondary cities. While untreated greywater poses clear public health risks; its consistent availability and stakeholder acceptance present significant opportunities for reuse following appropriate treatment. Strengthening decentralized treatment, hygiene practices, and policy guidance could enable safe integration of greywater into sustainable urban agriculture systems.

Keywords: Greywater management, Microbial contamination, Smallholder farmers, Urban farming, Hydroponics, Greywater reuse, Public health

1 Introduction

Rapid urbanisation, climate variability, and increasing pressure on freshwater resources have intensified global concerns regarding sustainable water management and food systems. In many low- and middle-income countries, expanding urban populations are accompanied by rising water demand, declining water quality, and inadequate wastewater management infrastructure [9, 39]. As a result, greywater generated from domestic and commercial activities has gained attention as a potential alternative water resource for non-potable applications, including urban agriculture. However, despite its growing relevance, significant knowledge gaps remain regarding the quality, management, and safe reuse of greywater in rapidly urbanising secondary cities, particularly in sub-Saharan Africa.

In sub-Saharan Africa, urban growth is among the fastest globally, exerting increasing pressure on water supply systems and food security [32]. Uganda reflects this trend, with a steadily rising urban population and increasing vulnerability to water scarcity and climate variability [17, 37, 42]. Urban households and small-scale businesses generate considerable volumes of greywater, yet this resource is largely unmanaged and often discharged untreated into the environment. While previous studies have examined wastewater reuse and urban agriculture in central Uganda and other regions [15, 18], limited empirical evidence exists on the quantity, microbial quality, disposal practices, and reuse potential of greywater in emerging secondary cities such as Mbarara. In particular, the interface between greywater management and urban farming systems remains poorly characterized.

Mbarara city, located within Uganda's cattle corridor, is experiencing rapid population growth, land fragmentation, and increasing pressure on water resources due to recurrent droughts and erratic rainfall [29]. These conditions have heightened the need for alternative water sources to support urban agriculture, particularly among smallholder farmers who operate under constrained land and water availability. At the same time, the expansion of informal and small-scale eatery businesses has led to increased generation of greywater, often disposed of through unsafe and unregulated practices. Such disposal contributes to environmental pollution, public health risks, and the degradation of urban water bodies, including River Rwizi, a key water resource for the city.

Targeting smallholder farmers and easterly operators provides acritical entry point for understanding both the supply and demand dimensions of greywater reuse. Eatery businesses represent a concentrated and consistent source of greywater, often generated in relatively high volumes within limited space, making disposal a persistent operational challenge. Conversely, smallholder urban farmers face chronic water shortages for irrigation, particularly during dry seasons, and therefore represent potential end-users of treated greywater. Understanding the practices, perceptions and constraints within these two groups is essential for designing feasible, locally appropriate greywater reuse systems.

Urban farming technologies, including hydroponics, vertical farming, and container-based systems, offer promising solutions for food production under conditions of limited land and water availability. Studies have demonstrated the potential of treated greywater to support such systems when appropriate risk-reduction measures are applied [15, 41]. In addition, nature-based treatment approaches such as phytoremediation have shown effectiveness in improving greywater quality in resource-constrained settings [44], [7]). Despite these advances, the adoption of such technologies remains limited in many African urban contexts due to gaps in knowledge, infrastructure, and policy support.

This study therefore aimed to assess the quantity, management practices, microbial quality, and reuse potential of greywater generated by small-scale eateries and households in Mbarara City. Specifically, the study sought to: (i) quantify greywater generation and disposal practices among eatery operators and smallholder farmers; (ii) evaluate the microbial contamination of greywater from eateries using fecal indicator organisms; and (iii) examine stakeholder perceptions and willingness to adopt greywater reuse for urban farming. By integrating social and microbiological perspectives, this study contributes empirical evidence to inform sustainable greywater management and supports the development of safe, low-cost reuse strategies for urban agriculture in rapidly growing secondary cities.

2 Study area, materials and methods

2.1 Description of the study area

The study was conducted in Mbarara City, a rapidly growing urban centre in Southwestern Uganda, 000 36 48′S, 300 39 30′E (Latitude: 0.6132; Longitude: 30.6582), at an average elevation of 1,147 m above sea level. The city lies within Uganda's cattle corridor, characterized by a semi-arid climate, recurrent droughts and highly variable rainfall patterns. These climatic conditions contribute to periodic water shortages, particularly during prolonged dry seasons, thereby increasing dependence on alternative water sources for domestic and small-scale agriculture. Mbarara city is the largest urban centre in the region, with an estimated daytime population of 500,000 [33], and was officially established as a city in 2020. It is administratively divided into North and South divisions (Fig. 1), both of which were included in this study. Rapid population

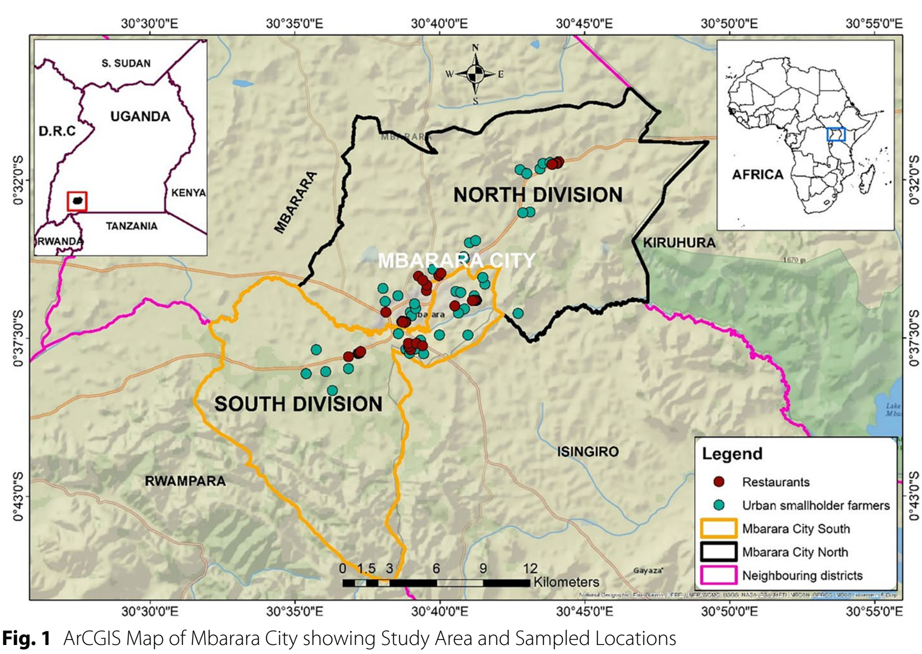

Fig. 1 ArCGIS Map of Mbarara City showing Study Area and Sampled Locations

growth, driven by rural–urban migration, has resulted in increased demand for water, expansion of informal settlements, and growing pressure on existing water supply and sanitation infrastructure. Water supply in the city is primarily provided through piped systems managed by National Water and Sewerage Corporation, supplemented by alternative water sources such as shallow wells in some areas. However, access to reliable and affordable water remains uneven, particularly for low-income households and small-scale businesses. As a result, water use efficiency is prioritized, and greywater is generated in significant volumes from domestic and commercial activities, especially from small-scale eateries that rely heavily on water for food preparation and cleaning. The city is traversed by River Rwizi, a major tributary within the Lake Victoria drainage basin and a key water source for domestic and urban use. However, inadequate wastewater management infrastructure and limited sewer network coverage have led to widespread discharge of untreated greywater into open drains, soils, and nearby water bodies. This not only contributes to environmental pollution and public health risks but also highlights the potential for capturing and reusing greywater as an alternative water source. In this context, the combination of water scarcity, high greywater generation, and limited wastewater treatment infrastructure creates both a challenge and an opportunity. While current disposal practices pose environmental and health risks, the consistent production of greywater presents a viable resource for reuse in urban agriculture, particularly for smallholder farmers facing water constraints.

2.2 Sample design and sampling

This study employed a mixed methods design which integrating qualitative and quantitative approaches to assess social perspectives, water use patterns, greywater generation, and contamination. Study participants comprised smallholder farmers and small-scale eatery operators in Mbarara City. A total of 80 participants were purposively selected, including of 40 eatery operators and 40 smallholder farmers from the North and South divisions to ensure representation of the study area. Inclusion criteria for smallholder farmers were: (i) engagement of urban or peri-urban farming activities, (ii) residence within the study divisions, and (iii) willingness to participate in the study. For eatery operators, inclusion criteria included: (i) operation of a small-scale food business with on-site water use, (ii) generation of greywater from kitchen activities, and (iii) consent to participate and allow sample collection. Participants who did not meet these criteria or declined to participate were excluded.

Purposive sampling was used to target participants with relevant experience in greywater generation and use; however, this approach may introduce selection bias and limit the generalisability of findings beyond study population. Nevertheless, the sample size was considered adequate for capturing variability in practices and perceptions, consistent with established qualitative sampling guidance [8, 43]. For microbiological analysis, 40 greywater samples were collected from eatery kitchen sinks, corresponding to one sample per participating eatery. This sample size was dimmed sufficient to characterize contamination patterns within the study setting and is consistent with similar exploratory studies assessing microbial water quality in small-scall urban systems. Sampling was conducted to capture variability across locations and operational conditions within the two city divisions.

2.3 Data collection instruments

Semi-structured questionnaires were used to collect data on household characteristics (household size, land ownership), water use patterns, monthly water expenditure, volumes of greywater generated, disposal methods and associated management challenges. The questionnaires were developed based on study objectives and informed by relevant literature on greywater management and urban water usage. Prior to data collection, the instruments were pretested in a neighbouring urban area with similar socio-economic characteristics to assess clarity, relevance, and consistency. Feedback from the pilot exercise was used to refine question wording, sequencing, and response options to improve reliability and validity. Data collection was conducted between June and September 2023 across sampled locations shown in Fig. 1. This period spans part of the dry season and early rainy season in Mbarara city, thereby capturing variability in water use patterns and greywater generation associated with seasonal changes. However, no formal stratification by season was applied. Data were collected by trained research assistants with prior experience in field-based survey. Training focussed on study objectives, ethical considerations, administration of questionnaires, and standardisation of interview procedures to minimize interviewer bias. Semi-structured interviews were conducted in the local language where necessary to ensure accurate understanding and responses.

To enhance data validity and triangulation, a post-data collection participatory validation exercise was conducted in November 2023 using a "World Café" approach. This interactive approach engaged a subset of smallholder farmers and eatery operators who had participated in the initial interviews (June–September 2023). The process enabled participants to reflect on, validate, and enrich the findings through collaborative discussion [22, 24].

2.4 Water sample collection and microbiological analysis

Greywater samples were collected from kitchen sink outlets of 40 small-scale eateries to assess microbial contamination. A single discrete grab sample (500 mL) was collected from eatery during active kitchen operation to ensure representative sampling of wastewater generated under typical conditions. Sampling was conducted once per site during the study period, with efforts made to capture variability across locations within the two city divisions. Samples were collected aseptically using sterile 500 mL glass bottles, immediately labelled and placed in insulated ice boxes maintained at approximately 4 °C to minimise microbial changes during transport. All samples were transported to the Microbiology Laboratory at Mbarara University of Science and Technology within 24 h in accordance with recommended holding times.

Sampling, preservation, and analytical procedures followed the *Standard Methods for the Examination of Water and Wastewater* [10], [5]) and World Health Organization guidelines for water quality assessment [39]. Microbiological analysis focused on faecal indicator organisms, including total coliforms, thermotolerant (faecal) coliforms, and *Escherichia coli* as indicators of sanitary quality.

Microbial enumeration was performed using the multiple-tube Most Probable Number (MPN) method. For each sample, a five-tube series was prepared using MacConkey broth. Aliquots of 10 mL were inoculated into double-strength broth, while 5 mL and 1 mL aliquots were inoculated into single-strength broth, each containing inverted

Durham tubes. Tubes were incubated at 35 °C for 24 h and examined for acid and gas production. Positive tubes were recorded as total coliforms, and bacterial densities were estimated using standard MPN tables.

For fecal coliform confirmation, aliquots from positive tubes were transferred into fresh MacConkey broth and incubation at 44.5 °C for 48 h. Tubes showing acid and gas production were considered positive for thermotolerant coliforms. Detection of *E. coli* was conducted by subculturing from faecal-coliform-positive tubes onto MacConkey agar, followed by incubation at 37 °C for 24 h. Presumptive colonies were further confirmed using the indole production in tryptone water with Kovács reagent and standard IMViC biochemical tests.

Quality assurance and quality control (QA/QC) measures were implemented throughout sampling and analysis. Sterile sampling procedures were maintained to avoid contamination, and media sterility and performance were verified using control blanks. Positive and negative control organisms were used where applicable to validate test performance. All analyses were conducted in duplicate to ensure reproducibility, and standard laboratory protocols were followed for calibration, incubation conditions, and results verification. Microbial concentrations were expressed as MPN per 100 mL of greywater. The results were subsequently integrated with socio-economic data and presented under three analytical components: smallholder farmers, eatery owners, and greywater quality.

In addition to the primary data collection phase, a follow-up participatory workshop was conducted in November 2023 to further explore emerging themes and validate preliminary findings. This interactive approach strengthened the reliability of the study by incorporating stakeholder feedback into the interpretation of results.

2.5 Data analysis (collected from human participants)

Quantitative data were analysed using SPSS Version 26. Descriptive statistics, including frequency, percentages, means and standard deviations, were used to summarize socio-demographic characteristics, water use patterns, greywater generation and disposal practices. Where appropriate, cross-tabulations were performed to compare responses from smallholder farmers and eatery operators across the two city divisions. Given the exploratory nature of the study, no inferential statistics were applied. Qualitative data obtained from semi-structured interviews were analysed using thematic content analysis. Transcribed responses were reviewed and coded inductively to identify recurring themes related to greywater management practices, challenges, perceptions and reuse potential. A coding framework was developed iteratively, and similar codes were grouped into broader thematic categories. To enhance analytical rigor, data triangulation was employed by comparing responses across participant groups (smallholder farmers and eatery operators), and aligning qualitative findings with quantitative results. Missing or incomplete responses were handled using listwise exclusion for quantitative analysis, where only complete responses were included in statistical summaries. For qualitative data, incomplete responses were retained where meaningful insights could still be extracted, while unclear or inconsistent responses were excluded from thematic interpretation. Data generated from the World Café workshop were incorporated into the thematic analysis to support triangulation and validation of key themes. Insights from participant discussions were compared with interview findings to refine thematic categories and enhance interpretive credibility. The findings are presented under three analytical components: smallholder farmers, eatery operators, and greywater samples.

2.6 Data analysis (water samples)

Microbiological concentrations of total coliforms, thermotolerant (faecal) coliforms, and *E. coli* were quantified and expressed as Most Probable Number (MPN) per 100 mL of greywater. To account for a wider range of microbial counts and improve comparability across samples, MPN values were $\log_{10}$-transformed prior to analysis. Descriptive statistical analysis, including means, ranges and standard deviations, were used to summarise microbial contamination levels across sampled eateries. In addition, the frequency and the proportion of samples testing positive for each microbial indicator were calculated to characterize contamination patterns. To assess potential public health risk, microbial concentrations were compared against relevant guideline values for wastewater reuse in agriculture, including the World Health Organisation (WHO) recommended threshold for irrigation of crops consumed raw ($\leq 10^3$ E. coli per 100 mL). The proportion of samples exceeding these guideline values was determined to evaluate compliance and inform risk interpretation. Given the exploratory nature of the study and the limited sample size, no inferential statistical tests were performed on microbial data. Instead, comparisons were made descriptively across sampling locations and categories. Results are presented using summary tables and graphical representations to illustrate variability and distribution of microbial contamination among sampled eateries.

3 Results

3.1 Smallholder farmers' demographics and water management: household characteristics; agricultural activities; water consumption and greywater generation

Characteristics of the smallholder farmers including household size, land ownership, water use, and greywater generation in North and Southern Divisions of Mbarara City are summarized in Table 1.

Slight differences were observed in mean household size between Northern and Southern divisions (Table 1), with household sizes ranging from five to six members. Variations in household size were reflected in corresponding differences in domestic water use, monthly expenditure, and volumes of greywater generated. Large households

Table 1 Socio-demographic characteristics and water-use patterns of smallholder farmers in Mbarara City

Parameter	Mbarara City North	Mbarara City South
Household size (mean SD)	6.0 ± 2.0	5.0 ± 1.0
Time spent in area (years)	6.5 ± 3.4	4.7 ± 3.8
Size of land/plot (acres)	1.5 ± 0.8	1.7 ± 0.6
Size of land used for farming (acres)	0.5 ± 0.3	0.5 ± 0.2
Amount of water used /day jerrycans (litres)	9.0 ± 2.0 (180L)	8.0 ± 3.0 (160L)
Amount of money spent on water per month (Ugandan shillings [US$])	32,030.0 ± 16076.6 [$9.2 ± $4.5]	37,000.0 ± 15,403.3 [$10.6 ± $4.4]
Amount of greywater generated /day (litres)	40 to 60L	40 to 60L

generally reported higher water consumption and greywater output, indicating a direct relationship between household size and water demand within the study area.

All participants had resided in their current locations for less than 10 years, with mean duration of residence ranging from 4.7 to 6.5 years across the two divisions. This relatively short duration of residence suggests a highly mobile urban population, likely influenced by ongoing rural–urban migration and settlement dynamics following the recent establishment of Mbarara City. Such mobility may affect long-term investment in water infrastructure and greywater management practices, as households may rely on temporary or informal water use and disposal strategies.

4 Smallholder farmers' agricultural activities and the main crops grown

Crop cultivation was the most common agricultural activity, reported by 54.7% of respondents (Table 2). Participants were allowed to select multiple activities, resulting in a total number of responses exceeding the number of respondents. This indicates that many farmers engage in diversified livelihood activities.

Farming is a multi-activity in Mbarara City although the bananas-were the most commonly cultivated crop, reported by 42.7% of respondents (Table 2). Vegetables cultivation was limited, with tomatoes being the only vegetable crop reported. Most farmers (62.5%) reported growing crops primarily for household consumption.

4.1 Challenges and greywater disposal practices (Smallholder farmers)

Three major challenges affecting smallholder farmers were identified (Table 3). These included limited water for irrigation (35.8%), prolonged drought (33.7%), and pests and diseases (30.5%). The main water source for all smallholder farmers who participated in this study was tap water supplied by the National Water and Sewerage Cooperation (NWSC). The amount of water used per day in households ranged between 160 and 180 L per day, with the North division consuming higher volumes of water than the South division. Monthly household expenditure on water ranged from 32,000 to 37,000 Uganda

Table 2 Smallholder farmers' agricultural activities and major crops cultivated in Mbarara City

	Responses	
	No	**Percent**
Agricultural activities		
Crop growing	41	54.7
Cattle rearing	9	12.0
Poultry rearing	9	12.0
Piggery	16	21.3
Total	75	100.0
Crops grown		
Banana	32	42.7
Beans	20	26.7
Maize	13	17.3
Tomatoes	10	13.3
Total	75	100.0

Table 3 Key challenges affecting smallholder farming in Mbarara City

Challenges	Responses	
	No	Percent
Prolonged drought	32	33.7
Limited water for irrigation	34	35.8
Pests and diseases	29	30.5
Total	95	100.0

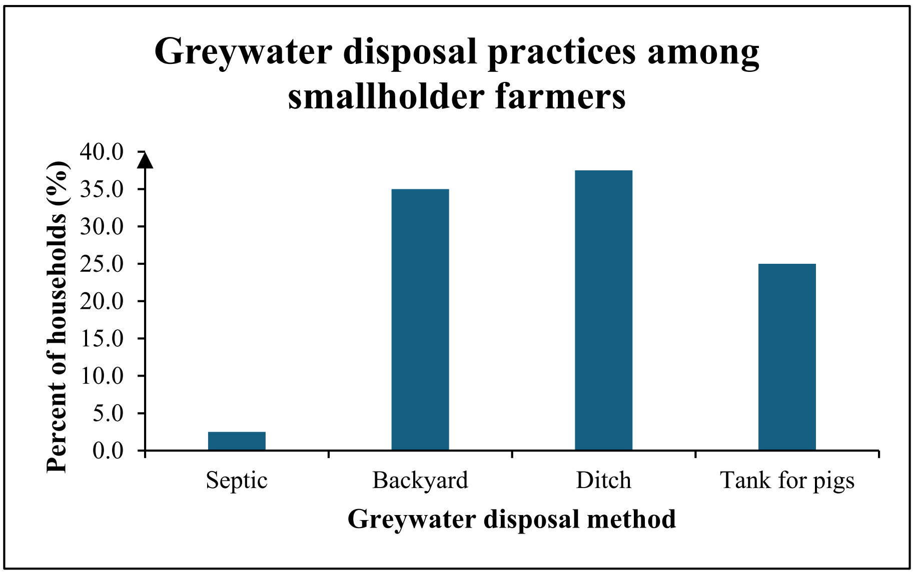

Fig. 2 Greywater disposal practices among smallholder farmers in Mbarara City

shillings (equivalent to $9.2 and $10.6, respectively). The cost of water is relatively high for average smallholder households.

Households generated approximately 40- 60 L of greywater per day in both divisions. This indicates that there is plenty of greywater that could be used to support urban farming system in Mbarara City.

Three principal greywater disposal methods were reported at household level (Fig. 2). These included discharge into open drains (35.7%), disposal in the household backyards (30.05), and reuse for piggery activities (25.0%). Only a small proportion of households (2.5%) used soak pits or septic tanks. The dominant disposal methods (ditch, backyard) contrast sharply with regulated disposal (soak pits/septic tanks, 2.5%), highlighting the environmental risk of these dominant methods.

4.2 Greywater disposal practices and associated challenges among smallholder farmers

Greywater disposal practices among smallholder farmers are presented in Fig. 2. The most common methods include disposal into open drains, discharge in household backyards, and reuse, particularly for pigs. These practices reflect the limited availability of formal wastewater management infrastructure at the household level. Smallholder farmers reported several challenges associated with these disposal methods. The most frequently cited challenges were algal growth (35.9%), mosquito breeding (34.0%), and unpleasant odours (30.1%). As illustrated in Fig. 2, these outcomes are closely linked to disposal of untreated greywater in open or poorly managed environments. These conditions may contribute to localised environmental degradation, and increased public health risks, particularly through creation of mosquito breeding sites and the deterioration of sanitary conditions around households.

4.3 Eatery operators' characteristics and greywater generation

Of the 40 eatery businesses surveyed, 45% were established after 2020 (Table 4), indicating a relatively recent expansion of small-scale food enterprises in Mbarara City. This trend reflects increasing urban demand for food services and suggests a corresponding rise in greywater generation from such establishments. The percentage could have been higher if the eateries that did not indicate/remember when they were established had responded to this question.

The majority of eateries (97.1%) relied on piped water supplied by the National Water and Sewerage Cooperation (NWSC), while only 2.9% used alternative sources such as wells. Usually, water from the well is free but has a higher risk of contamination than tap water. Monthly expenditure on water ranged from 45,000 to 55,000 Uganda shillings, exceeding that reported for smallholder farmers. Higher water expenditure was associated with increased water use intensity, which in turn contributed to greater volumes of greywater generation. Greywater generation among eateries ranged from four to eight 20 L jerricans per day (approximately 80–160 L), substantially higher than the two jerricans reported for smallholder households. Despite this higher output, most eateries operated within spatially constrained premises, particularly in South Division, limiting opportunities for on-site greywater management. This combination of high-water use and limited space appears to exacerbate disposal challenges.

4.4 Methods and challenges of greywater disposal in eateries

Greywater disposal practices among eateries are presented in Fig. 3**.** The most common methods included discharge into roadside drains, trenches, and nearby open areas, with trench disposal accounting for 22.5% of responses. These informal disposal pathways reflect the absence of connection to formal wastewater management systems. The reported disposal methods were associated with several operational and environmental challenges (Table 5). Unpleasant odour was the most frequently reported disposal issue (55%), followed by algal growth (25%) and mosquito breeding (20%). As illustrated in

Table 4 Year of establishment of eatery businesses participating in the study

Year of establishment	Frequency	Percent
2000–2005	1	2.5
2015–2020	11	27.5
2021–2025	18	45.0
Total	30	75.0
Missing System (not mentioned)	10	25.0
Total	40	100.0

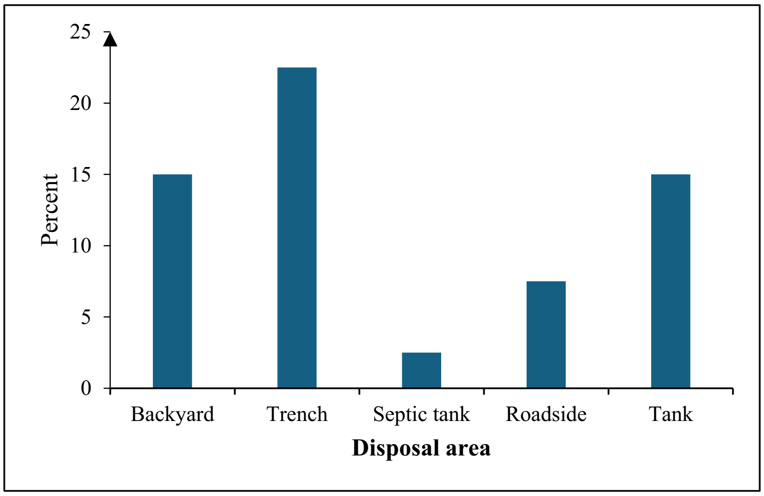

Fig. 3 Methods of greywater disposal by eatery businesses

Table 5 Challenges associated with greywater disposal

Challenges	Participants' Responses	
	N (40)	Percent
Bad smell	22	55.0
Development of algae	10	25.0
Breeding place for mosquitoes	8	20.0
Total	40	100.0

Fig. 3, the discharge of untreated greywater into open environments likely contributes to these outcomes.

Eateries with higher water use and greater greywater generation tended to report more pronounced disposal challenges, particularly where space constraints limited containment or treatment options. These findings highlight the interaction between eatery scale (as reflected by water use), infrastructure limitations, and the severity of greywater-related environmental and public health concerns.

4.5 Greywater quality and contamination (Eateries)

Detergent use among eatery businesses is presented in Fig. 4, with bar soap (42.1%) being the most commonly used cleaning agent, followed by Omo (28.9%), Magic (15.8%), and liquid soap (13.2%). The widespread use of these detergents suggests a substantial contribution of chemical components such as sodium and phosphates to greywater quality, with potential implications for both environmental discharge and reuse suitability.

4.6 Microbial Quality of greywater generated by Eateries

Microbiological analysis revealed a high prevalence of contamination in greywater samples collected from eateries (Table 8; Fig. 5). Total coliforms were detected in 35 out of 40 samples (87.5%), while only 12.5% of samples showed no detectable coliforms. Thermotolerant (faecal) coliforms were confirmed in 19 samples (47.5%), indicating

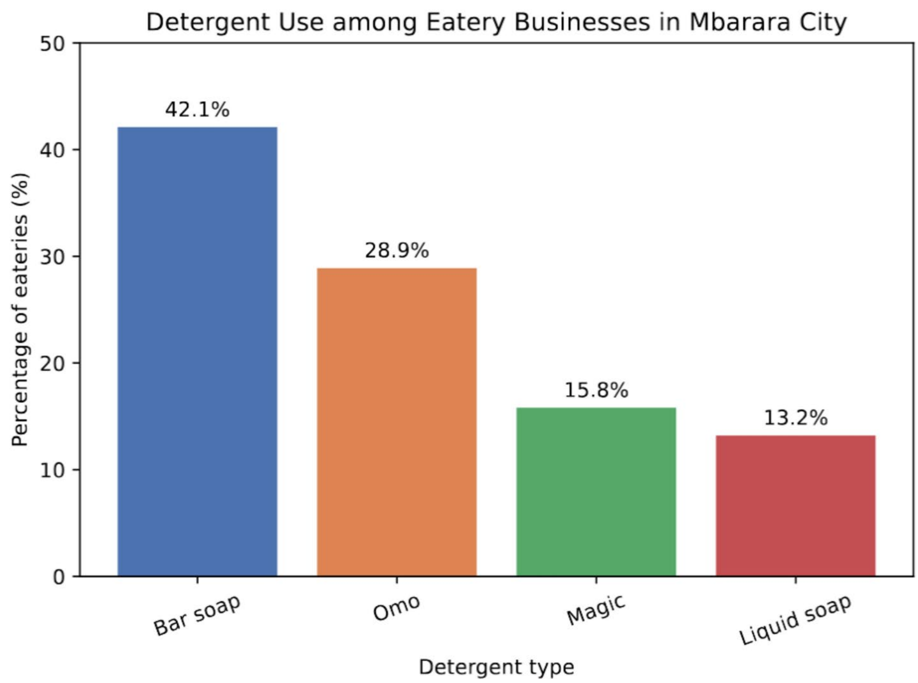

Fig. 4 Detergent use among eatery businesses in Mbarara City

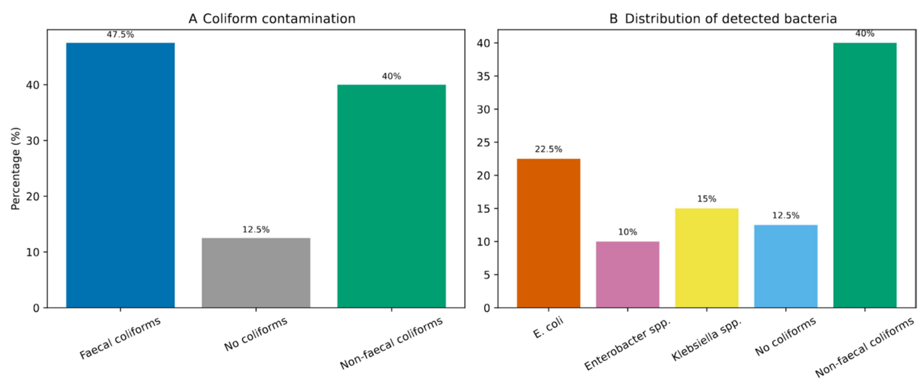

Fig. 5 Microbial contamination of greywater from eatery businesses in Mbarara City. **A** Distribution of coliform contamination categories, showing a high prevalence of faecal coliforms (47.5%) and non-faecal coliforms (40%), with only 12.5% of samples showing no detectable coliforms **B** Distribution of bacterial species isolated from contaminated samples. With E. coli detected in 22.5% of samples, followed by Klebsiella spp. (15%), and Enterobacter spp. (10%)

substantial fecal contamination. Notably, *E. coli*, a key indicator of recent fecal pollution, was detected in 22.5% of samples, while Klebsiella spp. (15%) and Enterobacter spp. (10%) were also identified. Sixteen samples (40%) were positive for total coliforms but showed no detectable faecal coliforms.

When compared with recommended microbiological limits for wastewater reuse in agriculture ($\leq 10^3$ *E. coli* per 100 mL for crops consumed raw), the presence of *E. coli* in nearly one-quarter of samples indicates that a substantial proportion of greywater may pose a potential health risk if used without treatment. The detection of fecal coliforms in almost half of the of the samples further underscores the need for caution. Overall, the findings demonstrate widespread microbial contamination of eatery-generated greywater, with high proportion of samples containing indicators of fecal pollution. These results highlight the need for appropriate treatment and risk mitigation measures prior to any reuse, particularly in urban farming systems involving direct contact with edible crops.

4.7 Qualitative results

4.7.1 Smallholder farmers

4.7.1.1 Theme 1: Water scarcity and coping strategies Smallholder farmers consistently reported insufficient water availability for irrigation, particularly during prolonged dry periods. Water shortages were described as severe and recurrent, sometimes lasting up to two weeks.

> *"Sometimes we can spend almost two weeks without enough water for the garden, especially in the dry season."*

In response, farmers adopted short-term coping strategies, including prioritising domestic use and limited reuse of greywater, mainly for livestock such as pigs. However, the reuse of greywater for crop production was largely absent.

4.7.1.2 Theme 2: Farming practices and resource constraints Most farmers practiced mixed farming, combining crop production with livestock rearing under conditions of limited land availability. Zero grazing was reported among Aa few participants as a strategy to optimize space. Despite these constraints, none of the respondents reported using hydroponic or other water-efficient farming technologies.

> *"We grow crops on small land and keep a few animals, but we don't have new methods like hydroponics."*

4.7.1.3 Theme 3: Perceptions and willingness to adopt greywater reuse Participants expressed openness to adopting greywater reuse, provide that safety and treatment concerns were addressed. Suggested approaches included chemical treatment, removal of detergent residues, and community sensitization.

> *"If the water can be cleaned and made safe, we are willing to use it for our crops."*

Farmers also emphasized the need for institutional support, including training, demonstration projects, and financial assistance to pilot reuse technologies.

> *"We need support and training to know how to treat and use this water properly."*

4.8 Eatery business operators

4.8.1 Theme 1: Greywater disposal challenges and environmental impacts

Eatery operators reported multiple challenges associated greywater disposal, including environmental pollution, unpleasant odours, slippery surfaces, and blockage of drainage systems. The accumulation of greywater also contributed to increased presence of flies, which affected hygiene and operational costs.

"The water causes bad smell and attracts many flies, and we spend money trying to control them."

Some operators also highlighted the lack of designated disposal points as a major constraint.

"Sometimes we don't even know where to pour the water."

4.8.2 Theme 2: Current greywater management practices

Greywater management practices were largely informal. Some operators reported removing solid waste particles for use as animal feed (e.g. pigs, dogs, poultry), while liquid waste was disposed of through nearby drains and open areas. The use of detergents such as Jik, and powdered soaps was widespread, with frequent cleaning undertaken to maintain hygiene standards.

"We remove the food remains for animals, but the water itself is just poured away."

4.8.3 Theme 3: Awareness and perceptions of reuse potential

Awareness of greywater reuse for agriculture was generally low among eatery operators. Most respondents were unaware of any existing practices beyond its use for feeding animals. However, there was a general willingness to participate in reuse initiatives if practical arrangements were provided.

"If there is a way to collect and use it, we are ready to cooperate."

Operators emphasized the importance of regular collection to prevent nuisance conditions within business premises.

"As long as the container is emptied quickly, we are okay to provide the greywater."

5 Discussion

This section discusses the key findings of the study, with emphasis on greywater disposal challenges, microbial contamination, reuse potential, and associated public health and policy implications. The discussion integrates social perspectives, urban farming systems, water supply constraints, greywater quality, and re-use options relevant for smallholder farmers and eatery businesses in Mbarara City. This is intended to inform applications of strategic urban farming technologies, such as hydroponics. The study identified minimal adoption of the hydroponic farming systems, despite the substantial volumes of greywater generated daily by households and eateries in Mbarara City.

5.1 Greywater generation and management practices: implications for urban agriculture

This study demonstrates that both smallholder households and eatery businesses in Mbarara City generate substantial volumes of greywater, with eateries producing markedly higher quantities (80–160 L/day). However, greywater management practices remain largely informal, characterised by direct discharge into open drains, backyards, and roadside channels. Similar patterns of unmanaged greywater disposal have been reported in other rapidly urbanising settings, where infrastructure development lags behind population growth [3, 14, 25 21]. These findings reflect a mismatch between increasing greywater generation and the absence of appropriate management infrastructure in rapidly urbanising secondary cities. From an urban agriculture perspective, this presents both a challenge and an opportunity. While current disposal practices contribute to environmental pollution, the consistent availability of greywater presents a potential alternative water source for irrigation. In water-scarce environments such as Uganda's cattle corridor, where prolonged droughts constrain conventional farming [12, 19, 35 27]), greywater reuse could support climate-resilient food production systems, including hydroponics and container-based farming [6, 11, 16]. However, realising this potential requires improved management systems and safe water reuse practices.

5.2 Microbial contamination and public health risks: pathways and mitigation

The study revealed widespread microbial contamination of eatery-greywater, with total coliforms detected in 87.5% of samples, and faecal coliforms in 47.5%. The presence of *E. coli* in 22.5% of samples indicates recent faecal contamination and potential exposure pathways for disease transmission. These findings are consistent with previous studies highlighting microbial risks associated with untreated greywater reuse [2, 26], [38]). Importantly, these contamination levels exceed World Health Organization guidelines for irrigation of crops consumed raw ($\leq 10^3$ E. coli per 100 mL) [40], indicating that untreated greywater is unsuitable for direct agricultural use. Potential exposure pathways include contaminated irrigation water, direct contact with crops, and environmental contamination from improper disposal. Despite these risks, the absence of fecal coliforms in 40% of samples and lack of detectable coliforms in 12,5% suggest that greywater quality may be improved through targeted interventions. Low-cost, decentralized treatment options, such as filtration, sedimentation, and phytoremediation offer feasible risk-reduction strategies in resource constrained settings ([7], [44]). A multi-barrier approach combining treatment, safe handling and crop selection is therefore essential to minimize public health risks.

5.3 Stakeholder perceptions and willingness to adopt greywater reuse technologies

Qualitative findings indicate that both smallholder farmers and eatery operators recognise the challenges associated with greywater disposal and express willingness to adopt improved management and reuse practices. Farmers, in particular, identified water scarcity as a major constraint and demonstrated openness to using treated greywater for irrigation. However, adoption is currently limited by low awareness, lack of technical knowledge, and absence of demonstration systems. Eatery operators, while willing to participate in reuse initiatives, emphasized operational constraints such as space limitations and the need for regular water removal. These findings highlight the importance of integrating behavioural and social dimensions into greywater interventions. Training programs, community sensitizations, and participatory approaches are critical for building trust and facilitating adoption. The role of social influence and knowledge dissemination, as suggested in adoption theory literature [1, 20, 31], is particularly relevant in this context. In addition, peer influence and social networks have been shown to significantly affect adoption decisions in agricultural contexts [34].

5.4 Challenges and opportunities for hydroponic and other urban farming systems

The study identified minimal adoption of hydroponic farming systems despite favourable conditions, including limited land availability, high water costs, and abundant greywater supply. Similar observations have been reported in other low-resource urban settings, where technological uptake is constrained by cost, knowledge, and institutional support [28], [13]). This gap suggests that technological feasibility alone is insufficient to drive adoption. Urban residents in Mbarara City exhibit high mobility and often reside in rented premises, making conventional land-based agriculture less viable. Hydroponic systems, which are modular and space-efficient, are well suited to such contexts. Previous studies have demonstrated the compatibility of treated greywater with hydroponic systems [15, 41], offering opportunities for sustainable food production. Furthermore, hydroponic systems can be adapted for both vegetable production and livestock fodder, which is relevant for smallholder farmers practicing mixed farming [36]. The findings of the study highlight the need for practical interventions including demonstration projects, training programmes, and integration of hydroponics into community-based initiatives and utilization of treated greywater for both vegetable production and livestock fodder. University-led engagement models, such as Student-Twinning Community Project [4, 23], provide a platform for bridging the gap between research and practice. However, challenges remain, including initial investment costs, technical knowledge gaps, and concerns about food safety.

5.5 Policy and institutional considerations for greywater reuse in secondary cities.

The findings underscore the need for policy and institutional frameworks to support safe greywater management and reuse in rapidly growing secondary cities such as Mbarara. Current practices characterized by unregulated disposal and lack of greywater treatment pose environmental and public health risks to rapidly growing urban populations.

Policy priorities should include:

- Development of context-specific guidelines for greywater reuse, aligned with WHO standards
- Strengthening hygiene monitoring and enforcement in eatery businesses
- Promotion of decentralized, low-cost treatment technologies
- Integration of greywater reuse into urban planning and water management strategies

In addition, multi-stakeholder approaches involving local governments, academic institutions, and communities are essential for effective implementation, as well as technology transfer and capacity building. Community-based pilot projects and participatory learning approaches can facilitate adoption and scalability of greywater reuse systems.

5.6 Study limitations and directions for future research

This study has several limitations. Data were collected from a single urban setting, which may limit the generalisability of findings to other contexts. The use of purposive sampling may introduce selection bias, particularly in capturing perceptions of participants already engaged in water-related activities. Microbiological analysis focussed on indicator organisms and did not include a broader spectrum of pathogens or physicochemical parameters.

While previous studies have demonstrated the potential of phytoremediation using aquatic plants for greywater treatment, as well as the microbial safety of crops produced in hydroponic systems [44], further research is required to strengthen the evidence base for safe and scalable reuse. Future studies should prioritise longitudinal assessments of seasonal variability in greywater quality, investigations into behavioural and socio-economic drivers influencing adoption, and the development and evaluation of community-based greywater reuse models. Such efforts would provide critical insights to support the safe integration of greywater reuse in urban agriculture systems.

6 Conclusions

This study demonstrates that water scarcity remains a critical constraint for smallholder farmers in Mbarara City, particularly during prolonged dry periods, while eatery businesses generate substantial volumes of greywater that are currently underutilized. However, the widespread detection of faecal indicator bacteria, including *E. coli* in 22.5% of samples confirms that untreated greywater poses significant public health risks and is unsuitable for direct agricultural reuse in its current form, consistent with World Health Organization guideline [39].

Despite these risks, both smallholder farmers and eatery operators expressed clear willingness to adopt improved greywater management and reuse practices. This presents an important opportunity to transform greywater from a disposal burden into a productive resource. Practical interventions should prioritise low-cost, decentralized treatment approaches, such as filtration and phytoremediation ([7], [44]); combined training, pilot demonstration projects, and community-based implementation models.

At the policy level, there is an urgent need to strengthen hygiene monitoring and enforcement in eateries, develop context-specific guidelines for safe greywater reuse, and integrate greywater management into urban planning frameworks. With appropriate treatment, routine monitoring, and institutional support, greywater reuse could contribute to climate-resilient urban agriculture, improved food security, and reduced environmental pollution in rapidly growing secondary cities.

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Author contributions
Justus Asasira (JA) conceptualized the study, acquired funding, developed data collection tools, collected data from human participants, and analysis, wrote the first draft of the manuscript and revised it until the submission stage. Godfrey Magyezi Begumisa (GMB) collected water samples, and microbial tests, analysed microbial results, acquired funding, and revised the manuscript. Pascal Amandu (PA) participated in the data collection for both human participants and water samples, acquired funding, and revised the manuscript. Jane Yatuha (JY) conceptualized the study, acquired funding, analysed data from human participants and microbial tests, and revised the different drafts of the manuscript. All authors have agreed on the final version of the manuscript.

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Data availability
Data is available on reasonable request from the corresponding author.

Declarations

Ethics approval and consent to participate
Ethical approval for this study was obtained from Mbarara University of Science and Technology Research Ethics Committee (MUST-REC), Uganda (Reference number MUST-2023–878) which follow the Declarations of Helsinki. All study procedures were conducted in accordance with the Declaration of Helsinki ethical guidelines for research involving human participants. The Declaration of Helsinki and the Belmont Report ethical guidelines that include informed consent , respect for & protection of participants, beneficence, non-maleficence, justice and community engagement were followed. Written informed consent was obtained from all participants prior to data collection. Participants were provided with information regarding the purpose of the study, the nature of their involvement, potential risks and benefits, and their right to decline or withdraw from the study at any time without penalty. To ensure confidentiality and data privacy, no personal identifiers were recorded during data collection. Responses were anonymized using unique identification codes, and all data were securely stored in password-protected electronic databases accessible only to the research team. Data were used solely for research purposes and reported in aggregate form to prevent identification of individual participants or businesses.

Consent for publication
Not applicable.

Competing interests
The authors declare that there are no competing interests.

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References
1. Al Mamun A, Naznen F, Jingzu G, Yang Q. Predicting the intention and adoption of hydroponic farming among Chinese urbanites. Heliyon. 2023;9(3):e14420. https://doi.org/10.1016/j.heliyon.2023.e14420.
2. Ali AS, Gari SR, Goodson ML, Walsh CL, Dessie BK, Ambelu A. Fecal contamination in the wastewater irrigation system and its health threat to wastewater-based farming households in Addis Ababa, Ethiopia. Environ Health Insights. 2023;17:11786302231181307. https://doi.org/10.1177/11786302231181307.
3. Amenorfenyo DK, Huang X, Zhang Y, Zeng Q, Zhang N, Ren J, et al. Microalgae brewery wastewater treatment: potentials, benefits and the challenges. Int J Environ Res Public Health. 2019;16(11):11. https://doi.org/10.3390/ijerph16111910.
4. Amutuhaire T. Higher education and social responsibility: a proposal for internationalization of university—community engagements; perspectives from Uganda. SN Soc Sci. 2023;3(9):161. https://doi.org/10.1007/s43545-023-00751-2.
5. APHA. (2017). Standard Methods for the Examination of Water and Wastewater. In E. W. Rice, R. B. Baird, & A. D. Eaton (Eds.), Public Health(23rd ed., Vol. 51, Issue 1). American Public Health Association; American Water Works Association; Water Environment Federation.https://doi.org/10.2105/AJPH.51.6.940-a
6. Behera, S., Pandey, R., Bhatt, M., & Maheshwari, S. (2023). *Vertical and Urban Vegetable Farming: Maximizing Small Spaces* (pp. 384–300). https://www.researchgate.net/publication/376379852_Vertical_and_Urban_Vegetable_Farming_Maximizing_Small_Spaces
7. Bihola, D., Pandya, D., & Mankad, A. U. (2020). Eff ect of Lead and Cadmium on the Growth Parameters and Protein Content of Coleus blumeiBenth and Heavy Metal Extraction Capacity. International Journal of Science and Research (IJSR), 9(10,), 426–430.https://doi.org/10.21275/SR20930085432
8. Blair J, Conrad FG. Sample size for cognitive interview pretesting. Public Opin Q. 2011;75(4):636–58. https://doi.org/10.1093/poq/nfr035.
9. Boretti A, Rosa L. Reassessing the projections of the World Water Development Report. Npj Clean Water. 2019;2(1):15. https://doi.org/10.1038/s41545-019-0039-9.
10. Bridgewater LL, Baird RB, Eaton AD, Rice EW, American Public Health Association, American Water Works Association, et al. Standard methods for the examination of water and wastewater. 23rd edition. American Public Health Association; 2017.
11. Bwengye E, Nagawa GM, Tumwesigye W. Diversity of the on-farm crop dry spell adaptation technologies in Isingiro Town Council, Isingiro District, Uganda. African J of Climate Change and Res Sustain. 2023. https://doi.org/10.37284/ajccrs.2.1.1275.
12. Byakatonda J, Openy G, Sempewo JI, Mucunguzi DB. Over a century evidence of historical and recent dryness/wetness in sub-humid areas: a Uganda, East African case. Meteorol Appl. 2021;28(5):e2028. https://doi.org/10.1002/met.2028.
13. Christofi , A., Margariti, G., Salapatas, A., Papageorgiou, G., Zervas, P., Karampiperis, P., Koukourikos, A., Tarantilis, P. A., Kaparakou, E. H.,Misiakos, K., & Makarona, E. (2023). Determining the Nutrient Content of Hydroponically-Cultivated Microgreens with Immersible SiliconPhotonic Sensors: A Preliminary Feasibility Study. Sensors, 23(13), 5937.https://doi.org/10.3390/s23135937
14. Czarnota J, Masłoń A, Pajura R. Wastewater treatment plants as a source of malodorous substances hazardous to health, including a case study from Poland. Int J Environ Res Public Health. 2023;20(7):5379. https://doi.org/10.3390/ijerph20075379.
15. Eregno FE, Moges ME, Heistad A. Treated greywater reuse for hydroponic lettuce production in a green wall system: quantitative health risk assessment. Water. 2017;9(7):454. https://doi.org/10.3390/w9070454.
16. FAO. (2001). *URBAN AND PERI-URBAN AGRICULTURE: A briefing guide for the successful implementation of Urban and Peri-urban Agriculture in Developing Countries and Countries of Transition*. https://www.fao.org/fileadmin/templates/FCIT/PDF/briefing_guide.pdf

17. Global Green Growth Institute. (2023). *Uganda's Rapid Population Growth and Waste Management Challenges: A Look at Mukono Municipality—Global Green Growth Institute*. https://gggi.org/ugandas-rapid-population-growth-and-waste-management-challenges-a-look-at-mukono-municipality/
18. Gumisiriza MS, Kabirizi JML, Mugerwa M, Ndakidemi PA, Mbega ER. Can soilless farming feed urban East Africa? An assessment of the benefits and challenges of hydroponics in Uganda and Tanzania. Environ Chall. 2022;6:100413. https://doi.org/10.1016/j.envc.2021.100413.
19. Hasahya Emmanuel, Krishna Thakur, Michel M. Dione, Susan D. Kerfua, Israel Mugezi, & Hu Suk Lee. 2023. *Analysis of patterns of livestock movements in the Cattle Corridor of Uganda for risk-based surveillance of infectious diseases*. 10. https://doi.org/10.3389/fvets.2023.1095293
20. Kemper TD. Status, power and ritual interaction: a relational reading of Durkheim, Goffman and Collins. Routledge; 2016. https://doi.org/10.4324/9781315610740.
21. Kinuthia GK, Ngure V, Kamau L. Urban mosquitoes and filamentous green algae: their biomonitoring role in heavy metal pollution in open drainage channels in Nairobi industrial area, Kenya. BMC Ecol Evol. 2021;21(1):188. https://doi.org/10.1186/s12862-021-01913-7.
22. Löhr K, Weinhardt M, Sieber S. The "World Café" as a participatory method for collecting qualitative data. Int J Qual Methods. 2020;19:1609406920916976. https://doi.org/10.1177/1609406920916976.
23. Mbarara University of Science and Technology. Mbarara University of Science and Technology strategic plan 2020/2021—2024/2025. Mbarara University of Science and Technology; 2022.
24. Monforte J, Netherway J, Smith B. The world café is an unmethod within co-produced research. Qual Res Psychol. 2023;20(3):398–419. https://doi.org/10.1080/14780887.2023.2239728.
25. Montalvo T, Higueros A, Valsecchi A, Realp E, Vila C, Ortiz A, et al. Effectiveness of the modification of sewers to reduce the reproduction of *Culex pipiens* and *Aedes albopictus* in Barcelona, Spain. Pathogens. 2022;11(4):423. https://doi.org/10.3390/pathogens11040423.
26. Moriarty MJ, Semmens K, Bissonnette GK, Jaczynski J. Internalization assessment of *E. coli* O157:H7 in hydroponically grown lettuce. LWT. 2019;100:183–8. https://doi.org/10.1016/j.lwt.2018.10.060.
27. Nimusiima A, Basalirwa CPK, Majaliwa JGM, Otim-Nape W, Okello-Onen J, Rubaire-Akiiki C, et al. Nature and dynamics of climate variability in the uganda cattle corridor. African J of Environ Sci and Tech. 2013;7:8. https://doi.org/10.5897/AJEST2013.1435.
28. Pomoni DI, Koukou MK, Vrachopoulos MG, Vasiliadis L. A review of hydroponics and conventional agriculture based on energy and water consumption, environmental impact, and land use. Energies. 2023;16(4):4. https://doi.org/10.3390/en16041690.
29. Richey AS, Thomas BF, Lo M-H, Reager JT, Famiglietti JS, Voss K, et al. Quantifying renewable groundwater stress with GRACE. Water Resour Res. 2015;51(7):5217–38. https://doi.org/10.1002/2015WR017349.
30. Ritchie, H., & Roser, M. (2023). Urbanization. *Our World in Data*. https://ourworldindata.org/urbanization
31. Singh N, Sinha N, Liébana-Cabanillas FJ. Determining factors in the adoption and recommendation of mobile wallet services in India: analysis of the effect of innovativeness, stress to use and social influence. Int J Inf Manage. 2020;50:191–205. https://doi.org/10.1016/j.ijinfomgt.2019.05.022.
32. Statista. (2023). *Africa: Urban population 2000–2026*. Statista. https://www.statista.com/statistics/1267863/number-of-people-living-in-urban-areas-in-africa/
33. The Monitor. (2023). *Housing threatens food security in Mbarara | Monitor*. https://www.monitor.co.ug/uganda/news/national/housing-threatens-food-security-in-mbarara-4469914
34. Tran-Nam Q, Tiet T. The role of peer influence and norms in organic farming adoption: accounting for farmers' heterogeneity. J Environ Manage. 2022;320:115909. https://doi.org/10.1016/j.jenvman.2022.115909.
35. Twongyirwe R, Mfitumukiza D, Barasa B, Naggayi BR, Odongo H, Nyakato V, et al. Perceived effects of drought on household food security in South-western Uganda: coping responses and determinants. Weather Clim Extremes. 2019;24:100201. https://doi.org/10.1016/j.wace.2019.100201.
36. Ulrico J. López-Chuken. (2012). *Hydroponics – A Standard Methodology for Plant Biological Researches: Hydroponics and Environmental Clean-Up*. InTech Janeza Trdine 9, 51000 Rijeka, Croatia.
37. UN-HABITAT. (2023). *A Better Quality of Life for all in an Urbanizing World, Uganda Country Brief*. https://www.cgap.org/sites/default/files/publications/Uganda%20CGAP%20Smallholder%20Household%20Survey%20Report.pdf
38. Wang, Y.-J., Deering, A. J., & Kim, H.-J. (2020). The Occurrence of Shiga Toxin-Producing E. coli in Aquaponic and Hydroponic Systems.Horticulturae, 6(1), Article 1.https://doi.org/10.3390/horticulturae6010001
39. WHO. (2022). Guidelines for drinking-water quality: Fourth edition incorporating the fi rst and second addenda. World Health Organization.https://doi.org/10.3390/horticulturae6010001
40. WHO. (2006). *WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater*. https://iris.who.int/bitstream/handle/10665/78265/9241546859_eng.pdf
41. Widiyanti E, Karsidi R, Wijaya M, Utari P. Information needs and behaviour on climate change for sustainable farming among farmers. IOP Conference Series: Earth and Environ Sci. 2020;423(1):012024. https://doi.org/10.1088/1755-1315/423/1/012024.
42. Worldometer. (2023). *Uganda Population (2024)—Worldometer*. https://www.worldometers.info/world-population/uganda-population/
43. Wutich A, Beresford M, Bernard HR. Sample sizes for 10 types of qualitative data analysis: an integrative review, empirical guidance, and next steps. Int J Qual Methods. 2024;23:16094069241296206. https://doi.org/10.1177/16094069241296206.
44. Yatuha, J., Asasira, J., Begumisa, G., & Amandu, P. (2024). *Exploring greywater hydroponic vegetable growing and phytoremediation capacity of coleus plants for urban farmers in Mbarara city Uganda | East African Journal of Science, Technology and Innovation*. https://eajsti.org/index.php/EAJSTI/article/view/1038

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