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Enhancing Harvested Rainwater Quality Through Nanofiltration and Storage Practices in a Rural Community

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Abstract: Water scarcity remains a persistent global challenge, particularly in rural communities where untreated harvested rainwater is often the primary source of water for domestic use. This study investigated cost-effective strategies to improve the quality of harvested rainwater in a selected rural community in South Africa. A sequential mixed-methods approach was adopted to explore the community's existing rainwater harvesting practices, associated challenges, and perceptions of rainwater harvesting. The quantitative part of the study gathered data from 221 households through convenience sampling and was analysed using inferential statistics. The qualitative part of the study gathered insights from 16 interviews using convenience-based voluntary sampling and was analysed thematically. The results revealed that the majority of the households collected and stored rainwater using rooftop harvesting systems combined with plastic storage tanks. The harvested rainwater was primarily used for cooking, drinking, and cleaning. However, contamination from inadequate storage conditions, lack of filtration systems, and exposure to environmental pollutants frequently resulted in health-related concerns surfacing within the community. The study proposes using a simple wood-based nanofiltration system as a low-cost sustainable intervention to improve water quality. In addition, the study recommends promoting hygienic practices to reduce contamination risks and improving storage practices to preserve water quality. By advocating for accessible filtration technologies and encouraging safer water storage practices, the study contributes to the advancement of safe rainwater harvesting and sustainable water management in rural communities.

Keywords: Rainwater harvesting, storage practices, contamination, nanofiltration, hygiene, health.

1. Introduction

Approximately half of the global population resides in rural areas, where they face significant socio-economic challenges, including limited access to essential resources. This issue is particularly severe in regions such as Asia and Africa, where access to safe and clean drinking water is severely constrained, and communities often depend on unreliable and unsafe water sources (Ross et al., 2022). The rapid population growth and urbanisation in these areas have intensified the demand for water, while climate change has exacerbated the situation by increasing the frequency of droughts and generating unpredictable weather patterns that affect water availability. Moreover, inadequate funding for infrastructure projects and governance issues have impeded efforts to enhance water systems (Umukiza et al., 2023). In light of these challenges, there is an urgent need to transcend short-term solutions and adopt proactive water management strategies. As highlighted by Nwokediegwu et al. (2024), water is essential for life and development, and addressing global water security necessitates comprehensive, adaptable policies that support effective, long-term sustainable management.

Rainwater harvesting (RWH) is an ancient technique that has gained renewed interest as a sustainable solution for addressing water scarcity, particularly in rural regions with limited access to reliable water sources (Fiorentino et al., 2021; Mao et al., 2021). This practice, which entails the collection and storage of rainwater from rooftops or other surfaces, has shown to be an adaptable and effective method for

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supplementing local water supplies, especially during periods of drought or water shortages (Mogano & Okedi, 2023; Owusu & Asante, 2020). However, the methods employed in collecting and storing rainwater in these rural regions often lack consistency and proper safety protocols, which may lead to contamination issues (Khayan et al., 2019). Studies have raised concerns regarding the microbial safety of untreated rainwater, revealing that it can harbour a range of microorganisms, including bacteria that pose health risks (John et al., 2021; Bae et al., 2019).

Despite these risks, there exists a widespread misconception that harvested rainwater (HRW) is inherently pure, leading many to believe it is safe for direct consumption without further treatment (Latif et al., 2022). In rural households, for instance, where interruptions to water supply are common, the community frequently relies on HRW for drinking, cooking, and sanitation. These systems are employed not only in rural villages but also in agricultural and urban areas, where water shortages remain a persistent issue (Lebek & Krueger, 2023).

In South Africa, the historical underdevelopment of rural infrastructure has left many communities dependent on traditional water collection methods. The disparities created by past socio-economic policies have intensified inequalities in water access, limiting the growth of modern water infrastructure and making rainwater harvesting (RWH) a critical resource for many households (Garcia-Avila et al., 2023). These disparities are deeply rooted in historical policies, including those from the apartheid era, which systematically restricted access to essential services such as water in rural and non-white communities. Colonial legacies further contributed to uneven development, with infrastructure investment concentrated in urban areas, predominantly benefiting certain demographic groups while neglecting others (Matimolane et al., 2023). As a result, enhancing the safety and efficiency of RWH systems has become a focal point for improving water security in these regions.

One potential method to enhance the safety of harvested rainwater is through the use of advanced treatment technologies, such as nanofiltration. Previous studies have shown that nanofiltration has significant potential for removing harmful microorganisms and chemical contaminants from harvested rainwater (Sharma, 2021; He et al., 2019; Li & Mitch, 2018). However, the practical application, feasibility, and acceptance of nanofiltration in rural communities, such as Umkomaas, remain insufficiently explored. Furthermore, it is unclear whether this technology is suitable, affordable, or culturally acceptable in these contexts. Therefore, it is essential to first examine existing rainwater harvesting practices within the community, assess local perceptions of health risks associated with untreated rainwater, and explore the potential of nanofiltration as a viable treatment option (Raimondi et al., 2023). Based on these considerations, this study aims to investigate the following:

- What rainwater harvesting practices and storage conditions are commonly used in the rural Umkomaas community, and how do these practices affect the quality of harvested rainwater?
- How do residents of Umkomaas perceive the health risks associated with using untreated harvested rainwater, and what strategies do they use to cope with any health risks?
- How effective and feasible is nanofiltration as a treatment method for improving the quality of harvested rainwater in rural communities?

2. Literature Review

This literature review examines key developments in rainwater harvesting, storage, and treatment methods, emphasising their impact on water quality and public health. It begins with an overview of harvesting and storage systems, followed by a discussion of traditional and advanced purification techniques, including nanofiltration.

2.1 Rainwater harvesting and storage systems

The rooftop rainwater harvesting (RWH) technique is the easiest and most widely practised RWH method worldwide, particularly in rural areas that depend on rainwater for their livelihood (Tengan & Akoto, 2022; Alim et al., 2020). The primary advantage of rooftop harvesting is the ease of collecting rainwater and its potential for high storage capacity for domestic use. However, this technique also presents disadvantages, such as contamination from heavy metals, gases, and faecal matter from birds and animals, which can pose health risks (Nwogu et al., 2024; Mbua et al., 2024). The type of roofing material significantly influences the quality of the harvested rainwater, as some materials may facilitate the survival of harmful microorganisms before runoff (Anabtawi et al., 2022; Mao et al., 2021). Common roofing materials include metal sheets, ceramic tiles, rock slate, and cement; however, thatch and unsealed roofs are generally unsuitable for rainwater collection (John et al., 2021). Metal roofs, for example, can leach heavy metals like zinc, copper, and lead into the collected rainwater. The use of lead fittings in roofing joints is particularly concerning due to the potential for hazardous lead levels in the water (Khayan et al., 2019). Additionally, the safety of rainwater harvested from asbestos roofs is debated, given that asbestos materials may contain harmful toxins (Latif et al., 2022).

Rainwater storage systems are integral to RWH setups, as they allow for the efficient collection and preservation of water for future use. Various studies have emphasised the importance of selecting appropriate storage materials and maintaining the cleanliness of storage units to ensure water quality and safety (Matimolane et al., 2023; Zhang et al., 2021). Typically, storage systems include tanks made from materials such as plastic, metal, earthenware, and cement, each offering distinct advantages and challenges in terms of durability, cost, and influence on water quality (Ertop et al., 2023). The type of storage material can significantly impact microbial growth and chemical leaching. Plastic and metal tanks, while cost-effective and widely available, may sometimes encourage microbial proliferation or leach contaminants like heavy metals into stored water (Anabtawi et al., 2022). For instance, rainwater stored in materials such as polyvinyl chloride, stainless steel, and Portland cement has shown a higher susceptibility to microbial growth, highlighting the need for careful material selection (Nwachukwu et al., 2024). Regular maintenance, including cleaning and disinfection, is essential to prevent sediment buildup, algae growth, and biofilm formation, which can degrade water quality (Raimondi et al., 2023). Innovative solutions, such as the semi-automated cleaning device developed by Chaurasiya et al. (2019), offer chemical-free maintenance options that reduce microbial contamination and enhance safety. These advancements are particularly valuable in resource-limited settings where routine maintenance may be challenging.

2.2 Rainwater treatment and health risks

Effective treatment of harvested rainwater (HRW) is essential to ensure its safety for consumption, particularly in regions where untreated water poses significant health risks. Research examining traditional, simple, and advanced treatment methods reveals various approaches to enhancing water quality and safety, with each method presenting unique advantages and challenges (Fiorentino et al., 2021; He et al., 2020). Key approaches include straightforward methods such as boiling and chlorination, traditional filtration, solar disinfection, and the application of nanotechnology, each offering distinctive benefits for improving water quality and safety (Martinez-Garcia et al., 2022).

Boiling is one of the simplest and most accessible methods for treating rainwater, effectively eliminating bacteria, viruses, and other pathogens, thereby rendering the water safe for drinking. However, boiling may not remove chemical contaminants, and its practicality can be limited by the availability of fuel sources, particularly in resource-constrained communities (Dao et al., 2021; John et al., 2021). Chlorination is another straightforward method that involves the addition of chlorine or chlorine-based compounds to disinfect water. It is widely employed for its efficacy in killing pathogens, including bacteria and viruses, and for maintaining water safety over extended periods.

Nonetheless, concerns regarding disinfection by-products (DBPs) formed during chlorination pose potential health risks if not properly managed (Mbua et al., 2024; Nwogu et al., 2024).

2.3 Nanofiltration

Nanofiltration has emerged as a promising advanced treatment technology for improving the quality of HRW. This technique utilises specialised membranes and nanomaterials to remove contaminants at a molecular scale, providing a highly effective method for purifying water (He et al., 2019; Li & Mitch, 2018). Madgundi et al. (2023) implemented a replaceable carbon nanomesh block, combining activated carbon with substrate fibres to create a large surface area ideal for filtering out viruses, bacteria, and cysts from drinking water. Similarly, Zhang et al. (2023) developed a TpPa-wood nanofiltration membrane with a 97% efficiency rate in removing organic pollutants. The unique structure and specific chemical interactions of this membrane highlight its potential for large-scale water treatment applications, demonstrating how innovative designs can substantially improve the safety and quality of harvested rainwater.

A study by Sanchez-Ferrer and Guerrero Parra (2025) demonstrated that wood-based filtration systems can remove nanoparticles, bacteria, protozoa, nanoplastics, and microplastics from water with over 99% particle removal efficiency. The effectiveness of these filters is largely attributed to the intricate microstructure of the wood and the extended residence time of water within the filter. Specifically, beech and silver fir were found to be particularly efficient, owing to their optimal pore size range, which supports both mechanical filtration and adsorption. In addition to these developments, Jadhao et al. (2024) highlighted the environmental benefits of nanofiltration technologies, emphasising their ability to reduce chemical usage, lower energy consumption, and minimise waste generation. Their work supports the view that nanofiltration systems are not only cost-effective but also contribute to long-term economic savings and public health improvements.

3. Methodology

This study employed a mixed-methods approach to address the inherent limitations of using a single research method, aligning with the recommendation by Asenahabi (2019). By combining methods with distinct strengths and weaknesses, the mixed-methods design provided a more comprehensive understanding of the research problem. Specifically, the study integrated both quantitative and qualitative data collection and analysis to examine the prevalence of rainwater harvesting practices, as well as the underlying motivations and concerns related to water quality within the community. The quantitative component involved the development and administration of a structured survey questionnaire, while the qualitative component consisted of semi-structured interviews to provide deeper contextual insights.

The study utilised an explanatory sequential mixed-method design, where the quantitative data was collected first, followed by the collection of qualitative data (Creswell & Creswell, 2018). This method was selected to avoid repeated engagement with the participants and to ensure the research was completed within the stipulated timeframe. Additionally, the sequential design allowed the quantitative findings to inform the focus of the qualitative phase, where interview questions were designed to explore the participants' reasons behind the choices made in the survey, ensuring a deeper understanding of the data.

3.1 Sampling

The target population for the study consisted of 514 households in the rural Umkomaas sub-place community that do not have access to piped water. With a 95 percent confidence level and a five percent margin of error, the sample size for the quantitative part of the study was determined to be 221 households, with one adult member from each household participating in the survey (Adam, 2020). A convenience, non-probability sampling technique was employed, whereby participants were selected based on their availability and the researcher's convenience. Although convenience sampling offers advantages such as cost-effectiveness and reduced time consumption, it is susceptible to sample bias and limited representativeness (Golzar et al., 2022). To mitigate these limitations, data were collected at various times of the day to enhance sample diversity and improve representativeness.

During the survey interactions, participants were informed about the opportunity to take part in follow-up face-to-face interviews as part of the qualitative phase of the study. Sixteen individuals voluntarily agreed to be interviewed, making the sampling method for the qualitative phase a form of convenience-based voluntary response sampling (Golzar et al., 2022; Creswell & Creswell, 2018). This approach allowed the researcher to gather in-depth insights from participants who were not only accessible but also willing to share more detailed perspectives related to the survey topics. The number of interview participants was considered sufficient, as the data collected would reach saturation, allowing for the necessary conclusions to be drawn (Subedi, 2021).

3.2 Questionnaire design and interview guide

The survey questionnaire was designed to collect data on RWH techniques, water storage conditions, and issues related to untreated water in the rural Umkomaas community. It contained closed-ended questions that were tailored to be simple, easy to understand, and quick to complete, ensuring a high response rate from the respondents. The face-to-face interview guide was developed with open-ended questions to further explore the information provided by selected participants from the survey and to obtain a deeper understanding of the issues raised (Asenahabi, 2019).

The researcher generated cover letters for both the survey questionnaire and face-to-face interview guide to inform participants about the study's purpose and objectives. The cover letters also indicated that participation in this study was voluntary, with anonymity and confidentiality being ensured. All relevant documentation, namely the final survey questionnaire, face-to-face interview guide, letters of information, and consent, was translated into IsiZulu before the study was carried out. This was because the target population was more fluent in IsiZulu compared to the English language.

3.3 Data collection

The survey questionnaires were administered first and retrieved by the researcher, with the support of a team of research assistants. These research assistants were recruited from the local municipality to assist in recruiting participants, administering, and collecting the survey questionnaires. Participants were approached in their homes, on the streets, and at other approved gatherings within the community. For participants who could not read or write, the questions were read aloud to them, and their responses were recorded by the research assistant. The study achieved a 100% response rate for the survey questionnaires.

Face-to-face interviews were conducted with those survey participants who confirmed their willingness to take part in the interview phase of the study shortly after completing the survey. During the face-to-face interviews, conversations were recorded with a recording device for later transcription and analysis. All 16 participants who voluntarily agreed to be interviewed were informed of the recording, and their consent was obtained before proceeding. The study also achieved a 100% response rate for the interview phase. The reason for collecting the data in this sequence was to allow the qualitative phase to build on the quantitative findings, thereby providing deeper insights into the specific practices and perceptions identified in the survey.

3.4 Data analysis

The quantitative data for this study were analysed using the Statistical Package for Social Sciences (SPSS) (version 25). The Pearson chi-square goodness of fit test was employed to determine whether the observed frequencies of a single categorical variable significantly differed from the expected frequencies. This test is based on the calculation of the chi-square statistic, which measures the discrepancy between observed and expected frequencies. Statistical significance is established when the calculated chi-square value exceeds the critical value, or when the p-value is less than 0.05 (Turhan, 2020). A significant result suggests that the observed data deviate from the expected distribution, indicating potential factors influencing the distribution.

Thematic analysis was used to analyse the qualitative data. This method systematically identifies and organises patterns within qualitative datasets (Nolan-Cody et al., 2024). The process involved several stages: first, familiarisation with the dataset through repeated reviews; next, the generation of initial codes, which were organised into patterns based on similarities. Subsequently, the codes were grouped to identify themes, which were then reviewed for consistency. The final step involved defining and naming the themes and sub-themes. Excel was used to manage and organise the themes efficiently due to the volume and similarity of the dataset. The analysis was interpretative, incorporating key themes from the audience inclusion theory alongside other emergent themes identified during data collection, as suggested by Nolan-Cody et al. (2024). This approach ensured a comprehensive understanding of the qualitative data and its relevance to the study questions.

To ensure a comprehensive understanding of the research findings, the quantitative and qualitative data were integrated in the interpretation phase through methodological triangulation. This approach allowed insights from each dataset to inform and complement the other, providing a more holistic view of the research problem (Creswell & Creswell, 2018). According to Dawadi et al. (2021), triangulation employs a variety of theories, data collection methods, and data sources to provide different perspectives on the topic under study, as a means of cross-checking the results. It is a process that enhances the credibility and validity of the research findings by reducing potential biases and reinforcing the consistency of the conclusions (Asenahabi, 2019).

3.5 Reliability, validity and trustworthiness

For the quantitative part, the study incorporated construct validity to evaluate the processes of RWH and treatment, and content validity to ensure that the aspects measured included HRW and the technologies used for its treatment. In terms of reliability, the study adopted the test-retest reliability analysis. This was done to verify the consistency and stability of the results over time, ensuring that the measurements were reliable and free from bias (Mohajan, 2017). According to Jason et al. (2015), the kappa statistic is preferred for measuring agreement because it accounts for the possibility of chance agreement, making it more robust than using only percentage agreement. Furthermore, Sainani (2017) indicates that a kappa value between 0.6 and 1 demonstrates good to excellent reliability. In this study, the reliability test was conducted by administering the survey to the same participants, with a two-week interval between assessments. This timeframe was chosen to minimise the impact of external factors and allow sufficient time for any potential changes in responses to become evident. The calculated kappa value of 0.737 confirmed that the quantitative measuring instrument has high reliability, meaning it achieved consistent results across repeated assessments.

For the qualitative component, the study ensured trustworthiness by applying the criteria of credibility, dependability, confirmability, and transferability (Nowell et al., 2017). Dependability was ensured through triangulation and the maintenance of an audit trail that documented all research activities and decisions, thereby enhancing the transparency and consistency of the research process. Credibility, which relates to the accuracy and truthfulness of the findings, was achieved through prolonged engagement with participants and member checking, allowing participants to validate and clarify preliminary interpretations (Nowell et al., 2017). To ensure confirmability, the researcher engaged in reflexivity and peer debriefing to minimise bias and maintain objectivity, ensuring that findings reflected the participants' perspectives rather than the researcher's own assumptions. Lastly, transferability was addressed by providing rich, thick descriptions of the study context, enabling readers to assess the applicability of the findings to other settings while acknowledging that the ultimate judgment of transferability lies with the reader (Creswell & Creswell, 2018).

3.6 Ethical considerations

Ethical clearance for the study was obtained from the Institute Research Ethics Committee of a University of Technology situated on the East Coast of South Africa. The researchers were accountable to this committee for ensuring ethical compliance throughout the study. Additionally, formal permission was obtained from the chief of the rural Umkomaas community before recruiting residents to participate in the study.

For both the survey and interviews, participant confidentiality and anonymity were maintained by using pseudonyms to protect those involved in the project. Each participant was required to sign an informed consent form prior to taking part in the study. Participants were informed of their right to anonymity and their right to withdraw from the study at any time without any adverse consequences, and they were assured that their participation would be entirely voluntary.

4. Results and Discussions

This section presents the findings of the study in two parts. It begins with a quantitative analysis of the survey data to provide measurable insights into the key variables of the study. This is followed by a qualitative analysis that shares community members' lived experiences and perceptions, offering deeper context to the survey results. The qualitative findings provide a broader understanding of patterns and trends that complement and validate the quantitative results, thereby contributing to a more comprehensive interpretation of the study.

4.1 Quantitative analysis

This section presents the quantitative analysis of household demographics, rainwater harvesting practices, and related health concerns in the Umkomaas community. The statistical findings for these key areas are presented below.

4.1.1 Section A – Demographic profile of Umkomaas households

The results for the number of people living in a household and the age range of people living within a household is presented in Figure 1.

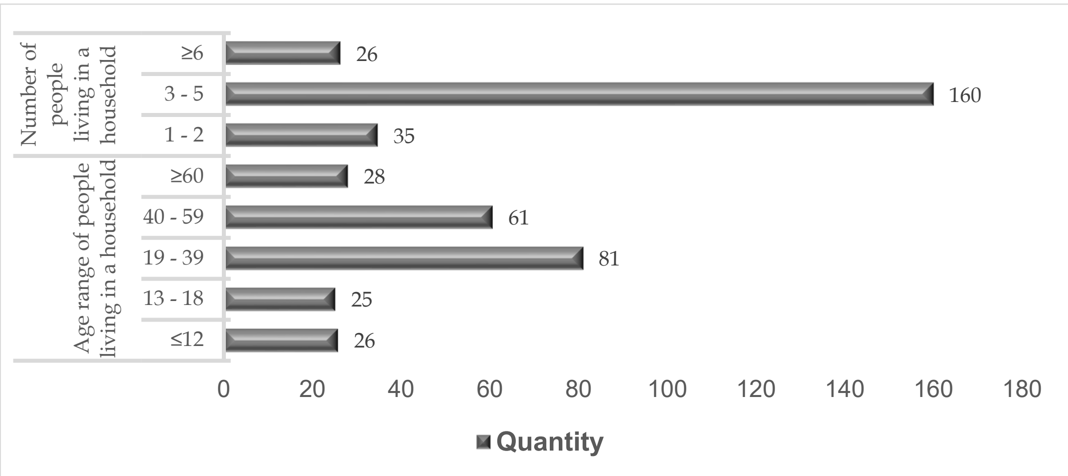

Figure 1*: Number of people and age range of people living in a household*

As shown in Figure 1, most households consist of 1 to 2 residents, while a large proportion have between 3 and 5 residents, and a smaller number have six or more residents. The weighted average household size is therefore approximately four residents. The majority of households with 3 to 5 residents reflect a common trend towards moderate-sized domestic units. This observation supports the idea that household size influences water consumption, as suggested by Alim et al. (2020). The modal age group in the community is between 19 and 39 years, followed by those aged 40 to 59 years. These two age groups indicate that rural Umkomaas is a community largely composed of energetic youth and working-age adults. The data also reveal the presence of other age groups, including children aged 0 to 12 years, teenagers between 13 and 18 years, and senior citizens aged over 60 years. These findings suggest that most households in rural Umkomaas are made up of individuals in active age groups, which is likely to correlate with higher usage of HRW, as noted by Tengan and Akoto (2022).

4.1.2 Section B – Rainwater harvesting systems

The quantitative results for the survey are presented in Table 1.

***Table 1**: Quantitative results from survey*

Question	Category	Frequency	degrees of freedom (df)	Chi Square Critical Value (0.05)	Chi Square Calculated value
1) RWH technique	Roof Harvesting	136	2.0	5.991	78.470
	Deep Pit	45			
	Non-Roof Harvesting	40			
2) Roofing material	Metal	120	4.0	9.488	176.750
	Other	33			
	Thatch	32			
	Tiling	32			
	No Response	3			
3) Storage container	Plastic Jojo Tank	116	2.0	3.991	56.760
	Plastic Container	80			
	Metal Drum	25			
4) Cleaning frequency	Weekly	55	4.0	9.488	87.040
	Monthly	35			
	Quarterly	36			
	Yearly	90			
	Others	6			
5) HRW uses	Household Cleaning and Laundry	77	3.0	7.815	40.530
	Cooking and Washing	70			
	Drinking	57			
	Farming and Irrigation	16			
6) Frequency of health-related concerns	Monthly	122	3.0	7.815	166.310
	Quarterly	78			
	Yearly	20			
	Others	1			
7) Type of health-related concerns	Diarrhoea	49	5.0	11.071	23.090
	Abdominal Pain	48			
	Skin Rashes	45			
	Others	35			
	Dehydration	27			
	Vomiting	16			

The responses to Question 1 in Table 1 show that most respondents use the roof harvesting technique, while fewer utilise the deep pit and non-roof harvesting techniques. The low adoption of deep pit and non-roof methods suggests that they are less practical or feasible (Ertop et al., 2023). The distribution of preferences among these rainwater harvesting techniques was found to be statistically significant [$\chi^2(2df) = 78.470, p < 0.05$]. This indicates that the observed distribution differs significantly from what would be expected by chance alone, highlighting the influence of various factors in the respondents' adoption of specific RWH techniques. The prevalence of the roof harvesting technique within the community can be attributed to its simplicity, cost-effectiveness, and practicality, especially in regions that have unreliable clean water sources. However, it is important to note that basic and opportunistic methods employed by rural South African households can compromise the integrity of the rainwater harvesting system, as highlighted by Matimolane et al. (2023).

For Question 2, respondents show a clear preference for metal roofing materials, while thatch and tiling materials are less favoured. Other roofing materials also account for a small portion of the responses. The distribution of preferences among these roofing materials was statistically significant [$\chi^2(4df) = 176.750, p < 0.05$], indicating that the observed distribution significantly deviates from what would be expected by chance alone. Metal roofing is likely favoured due to its durability, ease of installation, and clean collection surface, while thatch and tiling are less popular because of installation and maintenance challenges, as well as contamination risks (Raimondi et al., 2023).

Question 3 shows that most respondents store harvested rainwater in plastic JoJo tanks, while others opt for plastic containers or metal drums. The chi-square test for independence revealed a statistically significant difference in storage container preferences among the respondents. [$\chi^2(2df) = 56.760, p < 0.05$]. This statistical result indicates that the distribution of storage container preferences is not random and is influenced by specific factors. For instance, the respondents' choices are driven by considerations such as cost-effectiveness, ease of installation, and the perceived safety of plastic containers. This is consistent with previous studies indicating that plastic containers are favoured for their durability, resistance to corrosion, ease of handling, and affordability (Garcia-Avila et al., 2023). However, the use of general plastic containers and metal drums, as opposed to the purpose-built JoJo tanks, suggests that some respondents resort to more readily available, though potentially less ideal, storage solutions.

Question 4 reveals that respondents differ in their cleaning practices, with most cleaning their containers annually, while others clean weekly, quarterly, or monthly. The chi-square goodness of fit results [$\chi^2(4df) = 87.040, p < 0.05$], indicate that the differences in cleaning frequencies are statistically significant. This statistical significance underlines the variability in cleaning practices among respondents and highlights the need for standardised cleaning protocols to ensure water safety. For example, the preference for annual cleaning is likely associated with the use of purpose-built JoJo tanks, which are engineered to require less frequent maintenance. Ross et al. (2022) support this observation, noting that some tanks are designed to be maintenance-free for up to five years. However, Anabtawi et al. (2022) emphasise that regular cleaning is essential to prevent the accumulation of microbial contaminants, thereby maintaining water quality. Respondents who clean their containers more frequently are probably using smaller storage options, such as large buckets or drums, which may not be ideal for long-term water storage.

Question 5 reveals that a significant number of respondents use harvested rainwater for household cleaning and laundry, followed by cooking and washing, drinking, and farming and irrigation. These figures illustrate the varied uses of harvested rainwater in the respondents' daily activities. The chi-square goodness-of-fit test results [$\chi^2(3df) = 40.530, p < 0.05$] indicate statistically significant differences in how rainwater is utilised across these categories. The combined percentage of respondents using harvested rainwater for cooking, washing, and drinking (57.8%) highlights its role in activities involving direct consumption, emphasising the need to ensure that the water meets potable standards (Dao et al., 2021). The significant role of harvested rainwater in both domestic and agricultural contexts in rural areas is further supported by the findings of Das et al. (2024) and Matimolane et al. (2023).

The results for Question 6 reveal that most participants reported health-related concerns on a quarterly basis, with some noting such concerns annually, while a smaller proportion reported them monthly. The statistically significant result [$\chi^2(3df) = 166.310, p < 0.05$] indicates that these patterns are unlikely to have occurred by chance and may be potentially associated with contextual factors such as water quality, usage practices, and the condition of storage and treatment methods used for harvested rainwater. However, this association does not imply a causal relationship, as it is based on the participants' perceptions. This observation aligns with the findings of Osayemwenre and Osibote (2021), who reported that roof-collected rainwater often contains contaminants exceeding WHO guidelines, which are known to pose health-related risks. Similarly, Tengan and Akoto (2022) documented the presence of pathogens, heavy metals, and other pollutants in untreated harvested rainwater, suggesting a possible link between water quality and the frequency of health-related concerns.

The different types of health-related concerns reported for Question 7 also indicate a statistically significant association $[\chi^2(5df) = 23.090, p < 0.05]$, which is believed to be linked to untreated harvested rainwater. While this finding offers insight into community perceptions, it is also based on self-reported data and does not establish a causal relationship. This observation aligns with findings from Mbua et al. (2024), who identified similar health-related concerns in Cameroon due to the consumption of untreated harvested rainwater. Moreover, Nwokediegwu et al. (2024) and John et al. (2021) emphasise that untreated harvested rainwater can serve as a pathway for pathogens, thereby exacerbating health risks related to waterborne diseases.

4.2 Qualitative analysis

The qualitative interview questions were designed to provide an in-depth understanding of how the existing rainwater harvesting practices, as identified in the survey, affect the daily living conditions and health perceptions of the residents of the Umkomaas community. The thematic analysis for interview items A to G is presented below:

4.2.1 Theme A – Reasons for choosing rainwater harvesting techniques

Interview item A uncovers a theme that explains participants' preference for a particular rainwater harvesting technique. This theme indicates that participants primarily selected their preferred method based on factors such as ease of maintenance, ease of installation, and the availability of materials for constructing the harvesting system. Moreover, the perception that rainwater collected from rooftops is safer before it contacts the ground may also influence this preference (Lebek & Krueger, 2023). See the statements below:

> *Participant 7: "Roof harvesting technique is simple to implement, easy to maintain and to install. It is user friendly."*
>
> *Participant 6: "We actually use the roof technique as it enables us to store high quality level of water than any other harvesting technique."*
>
> *Participant 3: "Roof technique because it costs less, reducing water bills and demand."*
>
> *Participant 5: "We use the non-roof harvesting water technique because it helps to reduce storm water."*

These views were consistent with the responses to Question 1 in the quantitative survey, where many participants selected roof harvesting based on its practicality, cost-effectiveness, and suitability to local conditions. By integrating these two sets of data, the study was able to triangulate the findings and confirm that the preference for roof-based systems is closely linked to the economic and environmental factors of the rural Umkomaas community. Further triangulation is evident in responses to Question 2 of the quantitative survey, where respondents favoured certain roofing materials based on durability, ease of maintenance, and initial installation costs. The type of roofing material was found to significantly influence the quality of harvested rainwater, thereby reinforcing the importance of practical and environmental considerations in decision-making (Bae et al., 2019).

4.2.2 Theme B – Condition assessment of storage tanks

Interview item B reveals that the storage condition of containers is the main theme, with three sub-themes related to the physical condition of the containers, water quality concerns, and maintenance practices. Below are some excerpts from the transcripts:

> *Participant 7: "Plastic jojo tank, its green in colour, not exposed to rust and it consists of 8000 volume of litres which lasts longer when its full".*
>
> *Participant 2: "It's greenish".*
>
> *Participant 4: "Greenish outside, and inside they are muddy on the bottom."*
>
> *Participant 8: "We clean the JoJo tank before we store water inside. When the water from the rain finishes, we clean it and wait for the next rain. It's made of plastic."*

Participants described various conditions of their storage containers, noting issues such as muddiness, green discolouration, and sediment accumulation, often linked to the materials used and the frequency of cleaning. These qualitative insights were consistent with the responses to Question 4 of the quantitative survey, where many participants expressed a preference for frequent cleaning and proactive maintenance of their containers. This triangulation confirms that regular cleaning practices and awareness of container conditions are central to ensuring water quality in the rural Umkomaas community. This practice aligns with findings by Matimolane et al. (2023), who observed similar cleaning frequencies in other rural communities in South Africa.

4.2.3 Theme C – Environmental factors affecting storage

Interview item C explored how storage containers are managed and the environmental conditions in which the containers are stored. The emerging sub-theme highlighted the importance of storage location and safety, with several participants noting that the placement of tanks is often influenced by the tank's size and the available space. See the comments below:

> *Participant 6: "There are no trees around the storage container in this case, jojo tank. We need to ensure that the area is cleaned and not dirty as may happen that dust can get inside the plastic jojo tank when it is completely exposed or not covered."*
>
> *Participant 11: "There is grass and soil, it gets muddy if there is rain."*

This qualitative finding aligns with Question 3 of the quantitative survey, which focused on the types of storage containers used and the contextual factors influencing their selection and placement. Participants indicated that some tanks are strategically located in concealed or less accessible areas due to space constraints, safety concerns, the positioning of roof gutters, and aesthetic considerations. This highlights the importance of proper storage site planning and the implementation of adequate protective measures, such as covering the containers or placing them on elevated platforms, to reduce contamination risks and maintain water quality. This is supported by Nwachukwu et al. (2024) and Mbua et al. (2024), who caution that inadequate placement and poor maintenance of storage systems can significantly compromise the safety of harvested rainwater.

4.2.4 Theme D – Strategies for water scarcity

Interview item D explored what happens when harvested rainwater runs out and there is no rain for extended periods. See some of the transcripts below:

> *Participant 6: "When harvested water from the rain runs out and there is no rain, our plants die because of dehydration or not getting enough water. There is no water for household cleaning, laundry, cooking and washing. We therefore depend on rivers and lakes sometimes for irrigation and washing."*
>
> *Participant 7: "We collect water from the nearby dams and rivers using our containers. Sometimes the water tank from the municipality does provide water in such instances."*

> *Participant 10: "When the water is finished, plants and agriculture suffer, and we use the available alternatives of any available water such as a river."*

The responses revealed that participants often rely on alternative water sources, such as municipal water or rivers, during periods of water scarcity. However, the availability and reliability of these alternatives were inconsistent. The theme of community resilience also emerged, with participants noting how they share water resources or seek assistance from neighbours during dry spells. Additionally, a few respondents mentioned government interventions to supply water during droughts, although these efforts were often perceived as insufficient. These findings suggest the need for better strategies and support systems to ensure access to alternative water sources during periods of rainwater shortage. As Matimolane et al. (2023) suggest, ensuring reliable access to water alternatives is crucial for improving community resilience in rain-dependent regions.

4.2.5 Theme E – Seasonal health-related concerns

Interview item E aimed to explore seasonal patterns of health-related concerns potentially linked to the consumption of harvested rainwater. The qualitative responses revealed that some participants reported health-related concerns during spring, while others attributed these concerns to the winter season, often due to the use of alternative sources such as river water. A portion of respondents did not associate health-related concerns with any specific season. See the comments below:

> *Participant 6: "I can say around September and November."*
>
> *Participant 12: "During winter, because we go and fetch water from the river, and it's cold and the water is not clean."*

These qualitative insights align with the findings from Question 6 of the quantitative survey, which examined the frequency of reported health-related concerns in the community. This triangulation of data demonstrates that seasonal environmental changes may influence public health by affecting water quality. Khayan et al. (2019) support this, noting that seasonal fluctuations can significantly impact water quality and, in turn, community health. Similarly, Osayemwenre and Osibote (2021) emphasise that peaks in waterborne illnesses often correspond with periods of heavy rainfall or prolonged drought.

4.2.6 Theme F – Perceptions of rainwater health-related concerns

Interview item F explored the participants' perceptions of health-related concerns in relation to the consumption of harvested rainwater and their practices concerning water treatment. Several participants believed that consuming untreated rainwater contributed to health-related concerns such as abdominal pain and diarrhoea. See some of the transcripts below:

> *Participant 6: "Yes, this is because no family member suffers abdominal pain if there is no rainwater stored. So, it is highly possible that they fall sick because of this water."*
>
> *Participant 14: "I can say sometimes it's the water. Some of us would have diarrhoea, and we wish to have tap water."*

These qualitative insights were supported by responses to Question 7 in the quantitative survey, where a notable proportion of participants reported various health-related concerns following the consumption of untreated rainwater. This triangulation of data highlights a commonly perceived link between untreated harvested rainwater and the associated health-related issues. However, while these findings reflect community concerns, this study does not establish a causal relationship, as the conclusions are based on participant perceptions and self-reported experiences. These insights are consistent with previous studies by Singh et al. (2022) and Martinez-Garcia et al. (2022), which underscore the health risks associated with consuming untreated rainwater, particularly in settings with limited filtration. Furthermore, symptoms such as diarrhoea or skin rashes may indicate exposure to waterborne pathogens like Cryptosporidium spp., as noted by Mbua et al. (2024), reinforcing the importance of implementing proper water treatment measures.

4.2.7 Theme G – Perceptions of rainwater safety and quality

Interview item G aimed to understand the participants' comfort levels and perceptions of safety regarding the quality of their harvested rainwater. While some participants expressed uncertainty or discomfort due to concerns about contamination, others reported feeling compelled to use the water despite these safety concerns because alternative water sources were unavailable. The sub-themes that emerged included trust in water quality, factors influencing comfort levels, and how these perceptions guided household decisions regarding water use. See the comments below:

> *Participant 14: "Unfortunately, I can't choose but I use this water. The safety and comfort does not matter because I rely on this water."*
>
> *Participant 2: "No, because it needs to be purified and maybe 1 don't have the ingredients to purify water."*
>
> *Participant 7: "Yes, because we boil them before drinking."*
>
> *Participant 15: "No, I'm not comfortable because this harvested water is not healthy."*

In addition, many participants indicated that they used traditional methods, such as boiling or chlorination, to improve water safety. While these methods can help reduce certain health risks, they have limitations. For instance, boiling requires a significant amount of time and energy, and chlorination does not always eliminate all types of contaminants (Nwogu et al., 2024). These insights reflect the rural Umkomaas community's limited access to advanced and reliable water treatment technologies. Although community members are aware of the health risks, they are often constrained by accessibility and affordability, which hinders their ability to adopt safer water treatment options. Overall, the findings highlight the need for greater public awareness about the risks of consuming untreated rainwater and for practical education on safer treatment methods.

5. Conclusion, Recommendations and Limitations

This study set out to examine rainwater harvesting (RWH) practices in the rural Umkomaas community and to explore how nanofiltration technologies could be leveraged to improve the quality of harvested rainwater (HRW) for domestic use. The research addressed critical challenges, including the widespread consumption of untreated water, the use of suboptimal storage containers, inconsistent cleaning practices, and the potential health-related concerns perceived by residents. The findings of this study reveal that RWH remains a vital water source for the rural Umkomaas community due to the absence of a reliable municipal supply. However, reliance on untreated HRW, poor storage containers and practices, and inadequate treatment methods poses notable risks to household water safety. Although based on perceptions, the findings reflect strong community concerns about the link between water quality and health-related issues. These insights underline the need for practical, affordable interventions tailored to the community context. The introduction of a low-cost, wood-based nanofiltration membrane system emerges as a viable solution for decentralised water treatment, with the potential to significantly enhance water quality at the household level in rural settings. The study contributes to existing knowledge by bridging the gap between traditional RWH practices and emerging water treatment technologies within a rural African context. It also demonstrates how community perceptions and local practices can inform the design of more effective, context-sensitive water interventions.

The study recommends the implementation and evaluation of wood-based nanofiltration systems for the community. Given the potential of wood-based nanofiltration membranes as a low-cost solution for improving harvested rainwater quality, future research should prioritise pilot implementations within rural communities. These trials should assess practical performance indicators, including filtration efficiency, flow rate, community acceptability, long-term durability, and ease of maintenance. Particular attention should be given to evaluating dual-filtration configurations, whereby membranes are positioned at both the inlet and outlet of storage tanks, to determine their effectiveness in removing microbial contaminants and chemical pollutants under real-use conditions. In addition, the study promotes the adoption of improved storage infrastructure, such as sealed plastic tanks that are elevated and positioned in shaded areas to minimise contamination and inhibit algae growth. Moreover, community-focused training on proper maintenance and regular cleaning of storage systems is recommended to ensure sustained water safety.

The study was limited to a single rural community, which may restrict the generalisability of the findings to other geographical areas or cultural contexts. Additionally, the proposed wood-based nanofiltration system was not tested or implemented during the study. A further limitation was a lack of awareness regarding water treatment technologies among participants, which constrained the depth of technical discussions during the fieldwork and may have influenced the scope of the findings.

6. Declarations

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