THE APPLICATION OF NANOTECHNOLOGY TO IMPROVE THE QUALITY OF HARVESTED RAINWATER IN A SELECTED RURAL COMMUNITY

by

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ABSTRACT

Water scarcity remains a global challenge, with millions of people lacking access to clean and safe drinking water. In many rural communities, there is a widespread belief that rainwater collected from rooftops is naturally pure and safe for consumption without treatment. This reliance on untreated rainwater raises concerns regarding water-related health risks, particularly in regions with limited access to water treatment infrastructure. The aim of this study was to explore the use of nanotechnology to enhance harvested rainwater quality in the rural Umkomaas community in South Africa (SA).

The study adopted a mixed-methods research approach, collecting quantitative data through a structured questionnaire from 221 households that use rainwater harvesting systems, alongside qualitative insights from 16 interviews. Participants were selected through convenient sampling to gain a comprehensive understanding of the community's experiences and challenges regarding rainwater harvesting systems. Descriptive and inferential statistics were used to analyse the quantitative data, and thematic analysis was applied to the qualitative data. The results revealed roof harvesting was prevalent due to its simplicity, with plastic tanks commonly used for storing rainwater. The primary uses of harvested rainwater included household cleaning, cooking, and drinking. Participants reported frequent occurrences of illnesses such as abdominal pain and diarrhoea, linked to the consumption of contaminated or untreated rainwater. The contamination resulted from poor storage conditions, lack of filtration, and exposure to environmental pollutants.

The study advocates for nanotechnology application as a viable solution to address contamination issues, proposing a dual nanofiltration system that incorporates filters at both storage container in- and outlets. This approach includes wood-based nanofiltration membranes due to their unique material properties, which make them particularly well-suited for water filtration applications. By integrating nanotechnology into rainwater harvesting systems, this study presents an approach for enhancing public health outcomes and demonstrates the potential for sustainable practices that align with the broader goals of water security and community resilience. The research implications extend beyond the rural Umkomaas community, offering valuable insights for similar communities facing water scarcity and quality challenges globally.

DECLARATION

I, Akpan Blessing George, hereby declare that the research work presented in this dissertation is my original work and all the materials used are appropriately acknowledged and referenced. A reference list is attached to the dissertation.

I also confirm that the dissertation has not been submitted in any of its parts or entirety for any degree in any other institution of higher learning internationally or locally.

Akpan Blessing George

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DEDICATION

To God, the source of my inspiration, the beginning and the end of all wisdom.

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LIST OF ABBREVIATIONS

AFDB	African Development Bank
CDC	Centre for Disease Control
COF	Covalent Organic Framework
COGTA	Cooperative Governance and Traditional Affairs
DBP	Disinfection By-Product
GAC	Granular Activated Carbon
HRW	Harvested Rainwater
HRWSS	Harvested Rainwater Storage Systems
IREC	Institutional Research Ethics Committee
ISO	International Organization for Standardization
KZN	KwaZulu-Natal
PICO	Population, Intervention, Comparison, and Study Design
PEER	Partnerships for Enhanced Engagement in Research
PNF	Payamavaran Nanofanavari Fardanegar
PVC	Poly Vinyl Chloride
RWH	Rainwater Harvesting
SA	South Africa
SDG	Sustainable Development Goal
SF	Sand Filtration

SCL	Sunlight/Chlorine
SLR	Systematic Literature Review
SPF	Solar Photo Fenton
SODAOP	Solar-driven Advanced Oxidation Processes
TWSS	Tap Water Storage Systems
UV	Ultraviolet
WHO	World Health Organization

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CHAPTER ONE – INTRODUCTION

1.1 Introduction

Water stands as an essential resource for humanity and its surrounding ecosystems. Considering its paramount importance, humans have persistently employed strategies leveraging technology to maintain water quality and suitability for human consumption, with nanotechnology emerging as a notable innovation in this endeavour (Kubala 2020: 1; Sharma 2021: 2). This chapter, therefore, discusses the background of the study and elaborates on the research problem. It clearly defines the study aim and objectives and outlines an overview of the research methodology and geographical study location. The chapter also offers insight into the rest of the chapters contained in this dissertation.

1.2 Background of Research

Approximately 1.5 billion people worldwide suffer from water-related diseases yearly due to bacteria, viruses and heavy metals commonly found in untreated drinking water (Bidhuri, Taqi and Khan 2018: 199). This is mainly due to the scarcity of water supply and the poor quality of treated water made available to humanity in many parts of the world (Askham and Vander Poll 2017: 1). According to the World Water Assessment Programme, water scarcity refers to the absence of sufficient water availability or not having access to safe water supplies. It is an issue that relates to all aspects of human development, including health, agriculture, education, economics, and even peace and stability (Santos 2020: 1).

In terms of the poor quality of water, Figoli, Dorraji, and Amani-Ghadim (2017: 119) point out that toxic contaminant depletion, such as heavy metals and persistent organics from industrial and agricultural activities in water supplies, have reduced the availability of clean and usable water for human consumption and food industries. Conventional water treatment processes, for example, boiling operations, filtration methods and the inclusion of chemical substances, such as chlorine, do not remove all pollutants from the water purification process, and also form toxic disinfection by-products (DBPs) in the water (Surendhiran, Sirajunnisa and Tamilselvam 2017: 374).

Since its invention in 1974, Nanotechnology has been widely accepted, and extensively used in countries such as China, India, Europe and the United States to purify drinking water, groundwater, sewage water, and wastewater, as well as different contaminated water sources (Bhati and Rai 2017: 23423; Ratna and Bin 2017: 2). The advancement of nanotechnology provides excellent capabilities to enhance the performance of existing water treatment processes and promotes the potential to develop new techniques for water purification (Figoli *et al*. 2017: 119).

Although this technology has proven effective in water purification processes over recent years, it is still being explored in SA, a country affected by severe drought conditions, with a poor record of water conservation, outdated and inadequate water treatment infrastructure, and lasting concerns regarding the quality and degradation of the already limited volume of available water (Viljoen and van der Walt 2018: 484; Mogano, and Okedi 2023: 273; Maharaj and Friedrich 2024: 80). In the past, a large portion of South Africans were denied access to essential services provision due to the apartheid and colonial governments that kept people separated from each other, evicted people from their ancestral lands and denied them participation in the nation's economy (Clark and Worger 2016: 73). These policies directly impacted the livelihood of people from various communities and forced them to rely on alternative sources of government amenities, such as the provision of electricity and supply of water.

Rainwater harvesting (RWH) has become an alternate source of water supply for people living in the rural areas of SA (Owen and Goldin 2015: 541). It is a technique that involves the collection and storage of rainwater in a tank, container, deep pit, or reservoir, for use in various applications such as laundry, farming, household cleaning, and drinking. Sánchez, Cohim and Kalid (2015: 120) state although rainwater is usually free from contaminants, its exposure to the atmosphere and methods of collection and storage over time result in the water being contaminated and becoming hazardous to human health.

SA has signed the 17 United Nations (UN) 2030 Sustainable Development Goals (SDGs), as indicated by the UN (2015). The UN SDGs comprises a collection of global goals that encourage governments throughout the world/UN to promote the well-being of their citizens of all ages in the respective country towards sustainable development and to live healthy lives. This study, therefore, focuses on assessing the possibility of using nanotechnology to achieve SDG 3, which is to provide for good health and well-being of citizens and SDG 6, which is to provide access to clean water and sanitation for sustainable development.

1.3 Problem Statement

According to the 2017 World Bank Report, an excessive number of South Africans are very poor and do not have access to basic social services such as electricity and pipe-borne water (World Bank 2017). Even though the South African constitution approves water as a human right, millions of citizens remain disconnected from the national water infrastructure, as reported by Viljoen and van der Walt (2018: 1). This has resulted in an inadequate supply of potable water to rural communities in SA.

The demand for water has increased substantially over the years, yet the water supply sources have become infrequent, thus, surface water assessment and modelling related to RWH in catchment areas have become a necessity, as indicated by Askham and Vander Poll (2017: 1). One such area is the Umkomaas district, located in the south coast area of the KwaZulu-Natal (KZN) Province, SA. Residents living in the rural, inland parts of this small coastal town are mainly farmers and depend on municipal water tanker supplies, stagnant water, local rivers, and rainwater for their domestic activities (Makhaye 2022: 3). The rural Umkomaas community is severely affected by drought conditions and pollution; therefore, they depend primarily on the RWH technique as their alternate and convenient source of water supply to meet their daily water needs (Schreiner, Mungatana, and Baleta 2018: 21).

While this rainwater is relatively free from impurities, Celik *et al.* (2017: 270) advise the contaminants collected by the rain through the atmosphere deteriorate the rainwater quality during the harvesting process, storage conditions and household use. Dust particles, micro-organisms, heavy metals such as lead and sulphur ions, and gasses such as nitrogen oxides, carbon oxides and sulphur oxides cause contamination of the atmosphere. These pollutants found in rainwater emerge from the emission of vehicles and industries, roof materials used for collecting the rainwater, and the condition of the storage containers (Khayan *et al.* 2019: 1; Igbinosa and Aighewi 2017: 189).

Due to SA being an industrialised nation, atmospheric pollution contributes to ozone layer contamination, thereby also tainting the rainwater. In addition, the environmental pollution and contaminated litter in the catchment areas are supplementary sources of rainwater contamination, potentially leading to health risks when consumed by humans (Sánchez *et al*. 2015: 121). The contamination and health risks associated with this technique remain a concern, therefore, it becomes imperative to consider alternate methods, such as nanotechnology application to improve the harvested rainwater (HRW) quality, as indicated by Yaqoob *et al.* (2020: 495).

1.4 Aims and Objectives

The aim of this study was to explore the application of nanotechnology to improve the quality of HRW in a selected rural community.

The objectives of the study were:

- To examine the existing RWH processes in rural Umkomaas through a survey.
- To conduct interviews exploring how the current RWH practices identified in the survey affect the daily living conditions and health perceptions among residents in the rural Umkomaas community.
- To investigate the role of nanotechnology in wastewater treatment and identify the various elements to be considered for improving HRW quality.
- To propose a process using nanotechnology to improve the quality of HRW.

1.5 Research Questions

- What are the existing RWH processes in the rural Umkomaas community?
- How does the current RWH practices influence the daily living conditions and health perceptions of residents in rural Umkomaas?
- What is the role of nanotechnology in wastewater treatment, and what elements should be considered to enhance the quality of HRW?
- What nanotechnology-based process can be proposed to improve the quality of HRW in the rural Umkomaas community?

1.6 Research Methodology

This study employed a mixed methods approach, incorporating the collection and analysis of both quantitative and qualitative data (Bryman 2012: 628). The mixed methodology was selected to provide a comprehensive understanding of the research problem and effectively address the study objectives. A survey questionnaire constituted the quantitative aspect of the study, while interviews comprised the qualitative aspect.

The target population for the study was 514 households in the rural Umkomaas sub-place community who do not have access to pipe-borne 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: 95). A convenience, non-probability sampling technique was employed, whereby respondents were selected based on their availability and the researcher's convenience (Guest, Namey, and McKenna 2017: 61). For the qualitative part of the study, 16 participants were considered sufficient, as the data collected would reach saturation, allowing for the necessary conclusions to be drawn (Subedi 2021: 1).

The survey questionnaire and interview schedule were designed to collect data on RWH techniques, water storage conditions, and issues related to untreated water in the rural Umkomaas community. The questionnaire was tailored to be simple, easy to understand, and quick to complete to ensure a high response rate from the respondents.

Data were collected through questionnaires, interviews, and a review of literature sources. The collection of data is the systematic approach of gathering information from various sources to ensure the research questions are answered (Wagner 2012: 269; Taherdoost 2021: 11). The questionnaires were administered and retrieved by the researcher, with the support of a team of research assistants. These research assistants were recruited from the local municipality to help in recruiting participants, administering, and retrieving the questionnaires. Participants were approached in their homes, on the streets, and at other approved gatherings within the community.

Both quantitative and qualitative data were collected concurrently to avoid repeated engagement with the participants and to ensure the research was completed within the stipulated timeframe. For participants who could not read or write, the questions were read out to them, and their responses were recorded by the research assistant. During the face-to-face interviews, conversations were recorded with a recording device for later transcription and analysis. All participants were informed of the recording, and their consent was obtained before proceeding.

Pilot testing of the questionnaire was conducted with 20 people from the target population to identify any flaws in the measurement instrument. During this phase, it was noted some participants were unable to read and understand English. Consequently, the main study questionnaire was provided in both IsiZulu and English to accommodate all participants. The 20 individuals who participated in the pilot testing were excluded from the main study.

Bhandari (2023: 2) explains that construct validity assesses whether a test measures the concept it is intended to measure, while content validity seeks to determine whether the test is fully representative of what it aims to measure. This study incorporated construct validity to evaluate the processes of RWH and treatment, and content validity to ensure 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, to ensure the measurements were reliable and free from bias (Mohajan 2017: 59).

For both the survey and interview, participant confidentiality and anonymity were maintained by using pseudonyms to protect those participating in the project. Each participant was required to sign an informed consent form prior to participating in the study. Participants were informed of their right to anonymity and the right to withdraw from the study at any time without any adverse consequences. They remained assured their participation would be on a voluntary basis.

1.7 Delimitations and Geographical Location

The study was conducted in the rural Umkomaas community of the Ugu District in KZN, SA. Umkomaas, a coastal town located along the south coast, was established when a harbour was built in 1861 to facilitate sugar exports (Healy 2023: 1). As illustrated in Figure 1.1, the town is situated alongside the uMkhomazi River, also known as the Mkhomazi or Umkomaas.

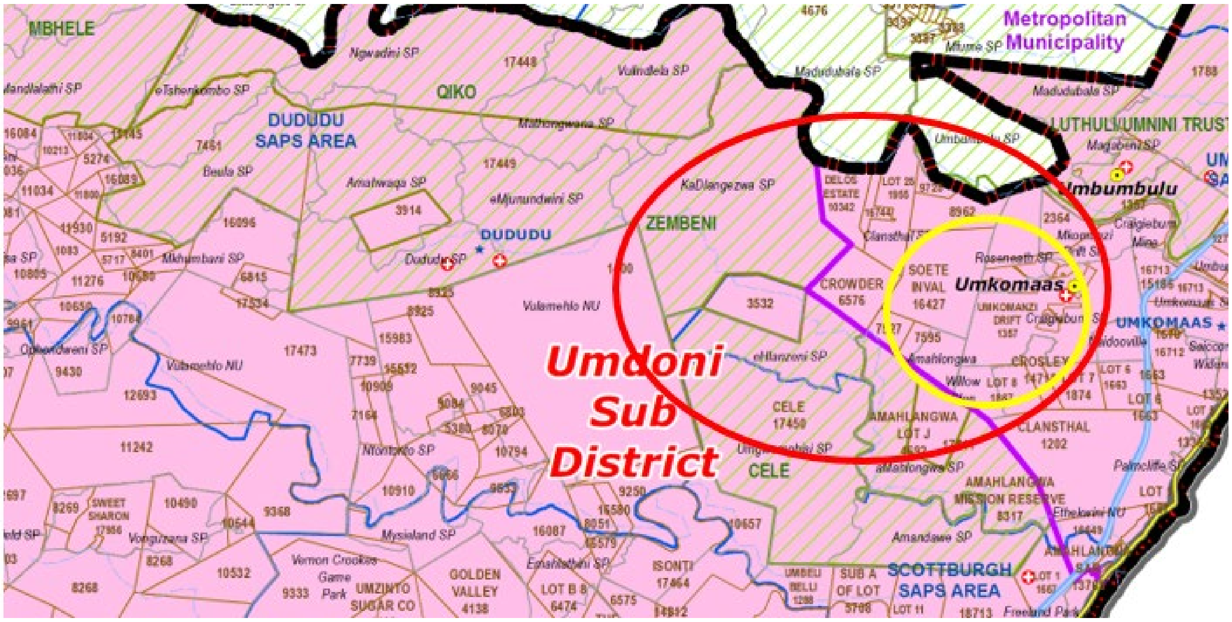

Figure 1.1: Map of Umkomaas

Source: Adapted from SA, Department of Justice (2021)

Historically, Umkomaas thrived due to the successful dredging of Durban Harbour's sandbar and the arrival of the railway, which facilitated transportation and trade. The town is renowned for its exceptional diving opportunities, golf courses, raft races, and canoeing, as well as various other sports activities. Additionally, the Empisini Nature Reserve has attracted tourists, offering a forested area with a waterfall, bush walks, and diverse wildlife, including hippopotamuses (Seeff 2020: 1). However, the region also faces environmental challenges. A significant number of local industries have contributed to pollution and environmental contamination, impacting water quality and public health (Wansi 2022: 1).

This study specifically focused on the rural Umkomaas community, and while the findings may provide valuable insights, they are not exhaustive of all RWH practices in SA. The researcher believes the findings from this study could apply to neighbouring rural communities, villages and towns that utilise untreated rainwater. Furthermore, the study implications may extend to the broader South African context, where similar environmental and health challenges persist.

1.8 Significance of the study

The study addresses the challenge of water scarcity in rural communities, positioning RWH as a practical and sustainable solution. While RWH provides an essential water source, the consumption of untreated HRW poses significant health risks due to the presence of contaminants. To address this, the study explores nanotechnology as an innovative treatment method to enhance water quality.

By recognising that effective RWH extends beyond collection, the study highlights the importance of proper storage, routine maintenance, and accessible treatment techniques. It contributes to research on RWH and offers targeted recommendations for policymakers and community leaders to support informed water management decisions. By empowering rural communities with the knowledge and skills needed to maintain and treat their water sources, the study promotes the adoption of sustainable water treatment technologies, reinforcing long-term water security.

1.9 Structure of dissertation chapters

The dissertation is divided into five chapters, and a brief description of the contents of each chapter follows:

Chapter One: This chapter generally introduced the study, its background, context, and problem statement. It set out the study aims, objectives, and delimitations. This chapter served as a guide through the research problem and outlined the intention to solve the problem.

Chapter Two: This chapter discusses the literature framework of rainwater and nanotechnology, to provide an overview of existing research findings and theories in the area of study. It covers previous research on rainwater, RWH, its importance in cases of water shortage, and the role of nanotechnology in water quality management, along with nanotechnology application in water purification.

Chapter Three: This chapter will detail the research methodology; mixed methods and associated techniques are explained in this section. This method was utilised to define and determine whether the research problem was adequately covered.

Chapter Four: Chapter Four presents the results and analysis, showing the statistical analysis of data obtained from the fieldwork. It entails processing data into meaningful results that are easy to interpret and understand.

Chapter Five: Chapter Five summarises the findings, presenting conclusions drawn from the study findings and possible recommendations for further research.

1.10 Summary of Chapter

This chapter provided the background and context of the study, clearly defining the problem statement along with its aim and objectives. The chapter also outlined the research methodology, describing the approaches used for data collection and analysis, ensuring the study's objectives are systematically addressed. Furthermore, the study's delimitations were discussed, establishing the scope and boundaries to maintain focus and relevance. The next chapter will present a literature review on RWH processes, water quality challenges, and the role of nanotechnology in water treatment.

CHAPTER TWO - LITERATURE REVIEW

2.1 Introduction

SA is faced with a range of challenges associated with water management, and water scarcity is predicted to severely impact the country by 2030 (Fisher-Jeffes, Armitage, and Carden 2017: 81). To avert the predicted future water crisis, the SA needs to find ways to reduce its reliance on conventional surface water schemes. It is important to note the water crisis is a global challenge, not unique to SA and the African continent. The causes of this global water crisis are somewhat linked to water pollution, ecological imbalance, urbanisation, and global warming, as well as groundwater depletion due to illegal bore wells (Schleifer 2017: 2). This chapter, therefore, presents a synopsis of relevant literature reviewed on the water crisis in Africa, in SA, and in rural areas. Furthermore, this chapter discusses RWH, water treatment, nanotechnology, and water management.

2.2 Water Crisis in Africa

Blessed with abundant natural resources, the continent of Africa remains the world's poorest and most under-developed continent, bedevilled with a lack of access to clean drinking water, constant conflict, and bad governance (World Health Organization (WHO) 2017: 2; UN 2015: 1; Shemer, Wald and Semiat 2023: 612). Water scarcity is an issue that relates to all aspects of human development, including health, agriculture, education, as well as economics, and even peace and stability (UN 2015: 1). All these issues are interlinked and overlap; therefore, any step towards improving access to clean drinking water in Africa has the potential to solve many developmental barriers as well (Pradeep 2017: 327; Yildirim, Alim, and Rahman 2022: 2).

According to Mnisi (2020: 1), Africa is the second-driest continent in the world and suffers from severe water scarcity, stress and crisis. Pradeep (2017: 327) emphasised Sub-Saharan Africa (SSA) water availability assessments are highly uncertain, due to inadequate observation networks, which is expected to worsen in the future. Therefore, the African Development Bank (AFDB) highlights the need to safeguard the future from impending disasters, considering the adverse effects of climate change on water resources, the environment, and socio-economic development in Africa

(AFDB 2019: 12-13; Pradeep 2017: 328). Ross, Alim and Rahman (2022: 251) further accentuated that the water crisis is exacerbated by natural phenomena such as global warming and climate change, leading to both physical and economic water scarcity.

2.2.1 Water Crisis in SA

Water scarcity is a serious problem in SA, which has led to the country being described as water scarce (du Plessis 2022: 2; SA Government 2016: 2; Ndeketeya and Dundu 2019: 163; Mogano, and Okedi 2023: 273; Matimolane *et al.* 2023: 276; Maharaj and Friedrich 2024: 80; Lebek and Krueger 2023: 114). SA ranks as one of the 30 driest countries in the world, with an average rainfall of approximately 40 percent, which is less than the world annual rainfall average (Winter 2018: 1; Dzvene *et al.* 2022: 1; Umukiza *et al.* 2023: 42). Statistics show SA has an average annual rainfall of less than 500mm, whereas the world average rainfall is 850mm. In addition, SA has limited value, where regional and local rainfall distribution varies considerably, with water security threatened by recurring droughts; water use is also poorly regulated and managed (SA Government 2016: 2; Winter 2018: 2).

Since 2013, provinces such as KZN, Gauteng, Western Cape and Eastern Cape have experienced drought and water shortages, resulting in water restrictions in urban areas and in the agriculture sector (du Plessis 2022: 2; Prins *et al.* 2022: 3; Umukiza *et al*. 2023: 42; Mogano and Okedi 2023: 273). Different levels of water restrictions are placed on entire provinces, large municipalities and numerous smaller towns (Prins *et al*. 2022: 3; Ndeketeya, and Dundu 2019: 163). A reliable supply of water at an acceptable quantity and quality is essential for the future development of SA; however, unreliable rainfall and growing demand are increasing water stress levels (Mnisi 2020: 1; Umukiza *et al*. 2023: 42). In addition, while crisis-proofing in SA's water security can be imperative at this stage, it is not clear how this can be attained (Prins *et al*. 2022: 3; du Plessis 2022: 2).

There is no universal agreement on how water security is measured; however, these measurements can be assessed through water availability, quality, and use, as well as access and equity in water management, and the effect and frequency of floods and droughts (Lawford *et al.* 2013: 633; Ziti, Chapungu, and Nhamo 2024: 1). SA is a water-stressed country, as indices show regions of high-water demand, particularly in the country's southwestern, eastern, and northern parts (Karodia and Khan 2015: 5). By 2035, water demand is expected to exceed supply by 10 percent. Moreover, when planned water schemes are not carried out, the Institute for Security Studies estimates this gap could increase to 21 percent (Winter 2018: 2; Mnisi 2020: 2).

The severity of the water crisis, combined with significant population pressure in the Western Cape Province, has exposed flaws within existing water resource governance structures and institutional arrangements in SA (Rawlins 2019: 3; Mogano and Okedi 2023: 273). Equity in water allocations in the country is part of post-apartheid water reform and has become a highly contested space within the rural and urban spheres (Rawlins 2019: 1; Matimolane *et al*. 2023: 276). From the discussion above, it is evident the severity of the water shortage in SA has historical connotations, hence, constitutes a significant challenge to livelihood and economic development. As a result, economic activities and daily lives are affected, which highlights the need for equality in water distribution in order to address apartheid inequalities.

2.2.2 Water crisis in rural areas

Most rural dwellers in SA struggle to source water for their daily needs, which include but are not limited to walking very long distances in search of water (Mnisi 2020: 2; Matimolane *et al*. 2023: 276). Due to the stress associated with sourcing water, these rural dwellers are usually unable to obtain the quantity of water required for their daily use. This creates an avenue for poor hygiene and possible dehydration, which, in turn, can lead to diverse health conditions (Viljoen and Van der Walt 2018: 486; Dzvene *et al*. 2022: 1).

For the purpose of this study, this review will identify a few examples of rural communities in KZN, SA and their water crises. The study focus is on the rural areas of Umkomaas, a coastal town on the KZN south coast, in SA, where most rural residents are farmers and depend on rainwater for domestic activities. These residents are severely affected by drought, because they do not have access to pipe-borne water. During periods of no rainfall, they depend on their dams, rivers, and municipal tankers for water supply, which is usually limited (Naidoo 2021: 2). This drought also cuts across other KZN rural areas.

Another example is Umzinyathi, where Pieterse (2015: 1) highlighted the dependency of residents on rainwater and local lakes and rivers for water needs, however, the lakes and rivers have recently dried up. According to Pieterse (2015: 1), an article published in the Citizen stated Lake Merthley was at a 27 percent volume level and is the only water source that supplies the Greytown area. Furthermore, as of 2022, the water situation in Ugu and other municipalities in KZN has not seen any significant improvement (Umdoni Municipality 2022: 92). Mlondo (2023: 1) reported that certain regions in KZN have experienced continuous water outages lasting up to three weeks, a situation that was also observed in 2021. In addition, the Buffalo River and other surrounding small dams that used to supply water to the Dundee and Nguthu districts dried up. As a result, water had to be supplied through augmentation releases from the Ntshingwayo Dam (Pieterse 2015: 1).

To address this anomaly, the authorities are expected to prioritise the severe water shortage. Similarly, it will prevent the outbreak of diseases from untreated water consumption (Bidhuri *et al*. 2018: 199).

To further bolster the ongoing water crisis in the rural areas, News 24 in October 2019 reported the residents in Umvoti asked the Cooperative Governance and Traditional Affairs (COGTA) department spokesperson, Sipho Hlomuka, to intervene in the Umvoti Municipality amid fears over the ongoing water crisis in the area. Mbili (2022: 1) highlights the situation, quoting a pensioner in the area who urged the local government to intervene, saying:

> *"I have to walk about 10 km to fetch water from the Tugela River. Our officials and local government need to intervene. A water tanker from Umzinyathi District Municipality delivers water to certain areas in the ward. It does not come to our area, and as a result, we are always left out".*

It has, therefore, been established that the water crisis is a serious problem in rural Umkomaas and, by extension, the larger SA. The problem of the water crisis has been identified to have roots in the apartheid past; unfortunately, post-apartheid governments have not done enough to address the problem, thereby ameliorating the sufferings of citizens, particularly in rural Umkomaas and other parts of KZN (Bablins 2021: 29; Rawlins 2019: 4). It is, therefore, deemed appropriate that collaborative efforts are implemented to provide potable drinking water to all communities within KZN and the entire SA.

2.3 Rainwater harvesting (RWH)

RWH is a technique that involves the collection and storage of rainwater in a tank, container, deep pit or reservoir, for various applications such as laundry, farming, household cleaning and drinking (Pradhan and Sahoo 2019: 2; Vartan 2022: 1; Anabtawi *et al.* 2022: 1). In its broadest sense, RWH can be defined as the "collection of runoffs for its productive use" (Raimondi *et al.* 2023: 1). These authors argue runoff may be harvested from roofs and ground surfaces, as well as from intermittent or ephemeral watercourses. The act of gathering and organising rainwater in a systematic way for later use is referred to as "rainwater harvesting" (Nadupuru and Shewale 2023: 1; Singh *et al.* 2022: 161).

In the RWH process, rain droplets are collected or harvested for either its economic advantage or domestic application (Lee and Kim 2023: 107). The storage of collected rainwater in containers (plastics, concrete, metallic and earthen tanks) for agricultural or domestic purposes has been a regular practice among rural dwellers, peasants, and low-income families, in many developing countries and water scarce communities or nations. However, proper harvesting of rainwater, preventing losses through evaporation, seepage, hydrological studies, and engineering intervention, as well as treatment, and proper storage of HRW for portable use/ or application has been challenging among both urban and rural dwellers in many developing countries (Singh *et al* 2022: 171, Senevirathna, Ramzan, and Morgan 2019: 190). RWH, particularly rooftop, surface runoff, catchment, and conveyances or metallic guttering, have all made HRW a source of concern, due to pollutants encountered in the collection and storage process (Vanacker 2021: 50).

Rainwater has been ascribed as of one of the purest natural water sources (Singh *et al.* 2022: 170, Vialle *et al.* 2015: 178, Vialle *et al.* 2012: 2). Although it is a relatively clean source of water supply, compared to groundwater or water from rivers or lakes, it appears the contamination from the atmosphere, the process of harvesting and the storage conditions directly impact the rainwater quality and causes it to become polluted and non-potable (Khayan *et al*. 2019: 1).

Contamination from the atmosphere is caused by dust particles, micro-organisms, heavy metals such as lead and sulphur ions, and gasses such as nitrogen oxides, carbon oxides and sulphur oxides. These pollutants found in the rainwater emerge from the emission of vehicles and industries, roof materials used for collecting the rainwater, and the condition of the storage containers (Khayan *et al*. 2019: 1; Igbinosa and Aighewi 2017: 189; Mao *et al.* 2021: 2). The three techniques commonly used for harvesting rainwater include the roof harvesting, deep pit, and non-roof harvesting techniques (JKCement.com 2023: 3; Nwogu, Ubuoh, and Kanu 2024: 1; Mbua, Efande, and Sunjo 2024: 31).

2.3.1 Roof harvesting technique

The roof harvesting technique is the easiest and most widely practised RWH technique around the world, particularly in rural areas that depend on rainwater for their livelihood (Joji and Jacob 2023: 3; Gwenzi *et al.* 2015: 108). RWH systems for the roof harvesting technique can be installed through basic plumbing skills, such as connecting all the outlets from a building's terrace through a pipe that joins a tank to store the water (Novak, Van Giesen, and DeBusk 2014: 118). The advantage of this technique is the relatively easy process to collect the rainwater and yield a high storage volume capacity for everyday use.

The disadvantage of the rooftop harvesting technique, however, is that the water contains heavy metals, gases, and in some cases, contaminants from bird or animal faeces that may present a risk of cervical lymphadenitis and other associated health diseases to children and people with immune-compromised systems (Igbinosa and Aighewi 2017: 190; Al-Khatib *et al.* 2019: 2; Nwogu *et al*. 2024: 2; Mbua *et al*. 2024: 31). This is mainly attributed to the different roofing materials that may influence the survival of faecal bacteria on the rooftop prior to run-off during rainfall. It is, therefore, not recommended for children and people with immune-compromised systems to consume untreated rainwater from the rooftop harvesting technique, as they may be exposed to additional risks of gastrointestinal infections such as typhoid and cholera (Hamilton *et al.* 2017: 290). Al-Khatib *et al*. (2019: 2) explain the heavy metals found in rooftop HRW increase the risk of children developing cancer over time, particularly when this water is continuously consumed.

Roofs are composed of different materials, and in most cases, these materials are suitable for use as rainwater catchment surfaces, with the exclusion of roofs made from materials such as grasses and stems (Anabtawi *et al*. 2022: 1). Roofing materials commonly used for roofing houses are metal sheets, ceramic tiles, rock slate and cement, and these roofing materials directly impact the quality of HRW (Tengan and Akoto 2022: 2; John *et al.* 2021: 3; Chubaka *et al.* 2018: 1). For example, metals such as zinc, copper, and lead can be present at quite high levels in rainwater that has contact with metallic roofs and fittings. Lead materials are sometimes used as roofing joints, and this may result in hazardous levels of lead in collected water. Therefore, lead fittings are not recommended for roofing.

Paint on roofing materials may also release toxins, which can cause risks to health and an unpleasant taste in the water. The contents and suitability of paints should thus be checked before a roof is painted (Stewart *et al.* 2016: 3). Likewise, the safety of rainwater harvested from asbestos roofs has been queried, because asbestos is made from reinforced cement, which contains toxins potentially harmful in the long-term (Ojo 2019: 735; Stewart *et al*. 2016: 5; Latif, Alim, and Rahman 2022: 2). These conditions compromise the quality of HRW, making it unsuitable for human consumption (Melidis *et al.* 2007: 15).

2.3.2 Deep Pit harvesting technique

The deep pit harvesting technique is practised in erosion-prone communities, such as the south-eastern states of Nigeria (Eseoghene 2019: 18). It is often used to control flooding by digging catchment pits or trenches to collect the run-off water from their heavy annual rainfall conditions and loose topsoil. Similarly, India uses the deep pit harvesting technique to prevent flooding and drought by collecting the HRW to increase the groundwater level to safety conditions (Bommala 2018: 1; Ertop *et al.* 2023: 7). This technique is also used in the agricultural sector to increase soil water storage, soil fertility and subsequent crop yield, as indicated by Tamagnone, Comino and Rosso (2020: 1). The disadvantages of the deep pit harvesting technique is that the pit always remains open and therefore presents a risk of drowning, and becoming a breeding environment for mosquitoes and other water-related pathogens that can cause illnesses such as malaria (Bommala 2018: 1).

2.3.3 Non-roof harvesting technique

The non-roof harvesting technique is a method that collects rainwater directly from the atmosphere by installing a storage container at 1.5 meters above the ground to avoid rain splash and reduce surface contamination (Imarhiagbe and Osarenotor 2020: 2). The significance of this technique is that the rainwater quality is not compromised with possible rooftop contaminants caused by bird or animal faeces. However, the disadvantage of this technique is the lower yield, with less rainwater collection volume than roof harvesting (Madgundi *et al.* 2023: 1085; JKCement.com 2023: 2).

Imarhiagbe and Osarenotor (2020: 2), in their study in Edo, Nigeria, identified the level of the analysed heavy metals found in non-roof-HRW was relatively above the predefined acceptable limits of the WHO and, therefore, deemed it unsafe for human consumption. In addition, these authors conducted a health risk assessment on the non-roof-HRW and declared it a public health concern when continuously ingested.

It can be inferred from the above, whether adopting rooftop RWH, the deep pit technique, or the non-roof harvesting method, each approach offers different ways of collecting rainwater for human consumption. However, all these methods face challenges that pose significant risks to humans when the HRW is not properly treated. Therefore, new innovative technologies should be developed to ensure safe treatment of this water prior to consumption.

2.4 Water treatment processes

The processes for treating water are divided into two parts: the preliminary treatment process, also known as screening, and the main treatment process (Singh *et al*. 2022: 167). The preliminary treatment process involves any physical, chemical, or mechanical application used on the water before it undergoes the main treatment process. The basic steps of water treatment include coagulation, precipitation, filtration, and disinfection (Centre for Disease Control and Prevention (CDC) 2022: 1; Dudziak and Kudlek 2019: 142).

The purpose of the preliminary treatment process is to ensure any materials are removed that will interfere with the behaviour pattern of the water throughout the main treatment process

(Pakharuddin *et al.* 2021: 4). The larger screens are used to remove particles such as rocks, sticks, leaves, or any other debris found in the water. In addition, smaller screens are used to remove the algae and other visible contaminants from the water. Al-Mahallawi (2014: 5), through his findings, indicates all objects are removed by physical size separation at this stage of the process.

The main water treatment process consists of water softening, which is the replacement of hard ions such as calcium ions (Ca^{2+}) and magnesium ions (Mg^{2+}) by sodium ions (Na^{+}), and demineralisation, which is the complete removal of the dissolved minerals (Idrica 2022: 1; Hayani *et al.* 2016: 3875). Water softening is used primarily as a pre-treatment method to reduce the water hardness prior to reverse osmosis and nanofiltration (Dudziak and Kudlek 2019: 142). Demineralisation is, furthermore, also known as deionisation. It can be achieved by using two resins, whereby the water is initially passed through a bed of cation exchange resin in hydrogen ion form (H^{+}). The cations in the water are then taken up by the resin, while hydrogen ions are released. Following this, the water passes through the second anion exchange resin in the hydroxide form (OH^{-}), where the anions are exchanged for hydroxide ions, which react with the hydrogen ions to form water (H2O) (Al-Mahallawi 2014: 89).

Deionisation helps produce safe, acceptable, clear, colourless, and odourless water. Before supplying water to consumers, water treatment is essential to improve water quality, preventing disease spread (CDC 2022: 1; Dudziak and Kudlek 2019: 142). Water treatment can eliminate potential or certain harmful substances in the water and possibly prevent contaminated water consumption that could cause potential health risks. Therefore, it is important to establish a water treatment facility with sufficient capacity to remove pollutants prior to being supplied to consumers.

2.5 Nanotechnology

Nanotechnology is an innovative scientific advancement introduced earlier in this century to revolutionise industries and address challenges in science and technology (Thiruvengadam, Rajakumar and Chung 2018: 1). It is the design, production and application of structures, devices, and systems at the nanoscale (Bayda *et al.* 2019: 2; Thiruvengadam *et al*. 2018: 1). This is achieved through nanoscience, which is the study of structures and materials on an ultra-small scale and the unique and interesting properties these materials demonstrate (Bayda *et al*. 2019: 2). Nanoscience is a cross-disciplinary field spanning various domains, including chemistry, physics, biology, and medicine, as well as computing, materials science, and engineering, to provide a better understanding of our world (Soriano *et al.* 2018: 107). According to Mansoori (2017: 1), nanoscience delves into the study of nanomaterials and their properties, and nanotechnology utilises these materials and properties to generate novel structures.

Another important aspect of this technology is nanomaterials, which are natural or manufactured objects with at least one external dimension in the nanoscale (in the range of 1-100 nm) and a specific surface area by volume greater than 60 $m^2\ cm^{-3}$ (Szczyglewska, Feliczak-Guzik, and Nowak 2023: 3; Joudeh and Linke 2022: 2; Altammar 2023: 1). When nanomaterials have all dimensions in the nanoscale, they are referred to as nanoparticles. These particles exist in the natural world and are also created through human activities. Due to their sub-microscopic size, nanoparticles have unique material characteristics, and manufactured nanoparticles may find practical applications in a variety of areas, including medicine, engineering, catalysis, and environmental remediation (Gavrilescu *et al.* 2018: 153).

2.5.1 Benefits of Nanotechnology

One nanotechnology advantage is that it is engineered by nanomaterials specially designed for certain purposes or functions that make them unique and offer advantages non-achievable by any other form or chemical state of the same material (Malik, Muhammad and Waheed 2023: 2). Examples of some particle forms in the nanoscale are nanorods, nanotubes, nanopores, and nanoshells, as well as nanospheres, nanodrives, nanobelts, and nanorings, along with quantum dots, fullerenes, liposomes, and nanocapsules, in addition to dendrimers. Nanoscale machines were invented and designed to be controlled by the computer in order to perform specialised jobs (Malik *et al*. 2023: 2). Another advantage of nanotechnology is its wide use in food packaging, agricultural production, medicine delivery, and cancer treatment, in addition to pharmaceuticals, water purification and wastewater treatment (He, Deng and Hwang 2019: 2; Biswas *et al.* 2022: 2). According to Malik *et al*. (2023: 1), as a technological revolution and innovation, nanotechnology has significantly improved humanity in several ways, and through this technological innovation, wastewater treatment could be achieved.

2.5.2 Challenges of Nanotechnology

In every human domain, it is glaring that along with the positive changes brought by nanotechnology, there are also disadvantages, such as toxic effects on human health and environmental security (Aithal and Aithal 2016: 18). The mechanisms of nanotoxicity are not yet clearly understood in theory, but toxic effects produced by nanoparticles have been recognised for lung inflammation, heart problems, skin reaction and weak immune systems (Viswanath and Kim 2016: 191).

Gavrilescu *et al.* (2018: 154) noted humanity has been exposed to airborne nanosized particles throughout their evolutionary stages. However, only with the Industrial Revolution did such exposures increase dramatically, because of anthropogenic sources such as internal combustion from engines. The expanding field of nanotechnology increases the number of sources for human exposure to nanoparticles in different ways, such as inhalation, which affects the respiratory tract (Omlor *et al.* 2015: 2; Kumah *et al.* 2023: 2). Ingestion, which affects the gastrointestinal tract, is injected, thereby affecting blood circulation, while dermatologically, it affects the skin. Nanoparticles are present in some consumer products, thereby exposing humans to their side effects (Sonwani *et al.* 2021: 4).

Nanomaterials can also cause air, water, and soil pollution. All of these are too small to be easily detected, thereby making nano-pollution another unwanted, man-made, environmental impact, with undefined long-term effects (Aithal and Aithal 2016: 18). Gavrilescu *et al*. (2018: 153) suggest larger and multicentre studies are needed to determine human reactivity and the fate of nanoparticles in the environment, before large-scale nanotechnology is completely accepted.

From the above, it has been clearly revealed the emergence of nanotechnology has brought about a massive revolution on several fronts, including the treatment of wastewater, medicals, and food processing. Hence, it supports the application of nanotechnology in the treatment of HRW for healthy human consumption.

2.6 Water Quality Management

Water quality management is the process of controlling the quality of water through its concentration level, the state of the organic and inorganic material present in the water, and the physical characteristics of the water (Krenkel 2012: 8). These attributes are mainly monitored by conducting on-site measurements and examination of the samples at the location source of the water supply.

A key implication barrier is understanding the analyses and results of a specific water sample specimen are only valid for that specific location and point in which the sample was extracted, since the physical properties of the water can change at any given time. Therefore, among the main reasons for a water quality management programme, is to gather sufficient data by means of regular sampling and analysis, in order to assess the spatial and temporal variations in the water (Roy 2019: 201; Singh *et al*. 2022: 164).

2.6.1 Water quality control and management standards

The application of water for its different uses in industry or human consumption is defined by its chemical, physical, or biological characteristics, as indicated by Roy (2019: 201). Therefore, water quality control measures and management standards have been developed and put in place to ensure the appropriate water quality level is used for its prescribed application. The use of water quality standards is a legal process for defining specifications of surface- and wastewater reuse, where these standards are generally based on the risk assessment of human health (Rock *et al.* 2019: 617; Shemer *et al*. 2023: 612; Chubaka *et al*. 2018: 1; John *et al*. 2021: 3; Latif *et al*. 2022: 2).

One such standard is the International Organisation for Standardization (ISO) (2007) quality management standard, which provides guidelines for the management of drinking water and wastewater services, such as on-site systems, distribution networks, and treatment facilities, quality criteria of the service and performance indicators. This international standard has a well-defined management system, intended to facilitate dialogue between stakeholders, enabling them to develop a mutual understanding of the functions and tasks essential to managing water utilities (ISO 24512: 2007).

The WHO (2017: 8) recommends implementing surveillance and quality control measures similar to the ISO guidelines for the ISO 24512: 2007 standard, to ensure the safety of drinking water by taking the drinking water supply characteristics into account, from catchment areas through to end consumers. However, since many aspects of drinking water quality management are often outside the direct responsibility of the water supplier, a collaborative multi-agency approach must be adopted, to ensure agencies responsible for specific areas within the water cycle are directly involved in water quality management (AFDB 2019: 20; Rock *et al*. 2019: 617). This makes consultation with governing authorities a necessity in managing the drinking water quality requirements; by monitoring and reporting the results and creating appropriate emergency response plans and communication strategies when risks are identified (WHO 2017: 8).

2.7 The role of nanotechnology in water quality management

Due to the challenges such as toxic DBPs associated with conventional water treatment processes, Dasgupta, Ranjan, and Ramalingam (2017: 597) discovered the application of nanoscale zero-valent iron for the treatment of distillery wastewater. This treatment helps remove any contaminants in the water that potentially pose hazards to humans when consumed.

The various pilot-scale and laboratory studies over recent years have also demonstrated wastewater quality can be improved through nanotechnological systems that incorporate basic separation processes such as reverse osmosis, microfiltration and nanofiltration (Li and Mitch 2018: 1687). Nanotechnological systems are also known for their excellent adsorption properties, enhanced photocatalysis, and high reactivity (Guerra *et al.* 2018: 3). As rightly observed, Madhura *et al.* (2018: 66) argued the use of these nanotechnological systems for wastewater treatment has enabled organisations to generate a sustainable level of water quality for the environment and economic development.

2.7.1 Quality assurance of nanomaterials

Nanomaterials are expected to have high-quality attributes, and the easiest method for conducting inspection on the quality of the nanomaterials is determined by customer loyalty and the competitive displacement of the various nanomaterials, as indicated by (Ferris 2015: 2). This is because each specific nanomaterial is created to be unique and a small change in its characteristic can severely impact the expected results from the nanomaterials (Khan, Saeed and Khan 2019: 909).

As nanomaterials increase in production volume for different applications, there is a growing challenge in determining how to ensure the product quality characteristics of the nanomaterials. Various techniques are available, such as sampling of the end-product of the nanomaterials, nano-analysis of the atomic structures of the target material, nanoscale characterisation expertise by laboratories, and simultaneous fabrication and inspection methods that can be used to ensure acceptable product quality requirements of the nanomaterials (Ferris 2015: 2). These techniques are employed according to the uniqueness of the nanomaterials to ensure quality.

2.7.2 Nanotechnology and water treatment

The WHO (2023: 2) reports that water contamination by pollutants has become one of the most critical health problems worldwide. Discharging inadequately treated municipal wastewater in developing countries has been the major cause of environmental pollution (Schweitzer and Noblet 2018: 261; Lin, Yang and Xu 2022: 2). The current effort to supply society with high-quality drinking water though cheaper technology is crucial for growing economies. In addition, the role nanotechnology is playing in the remediation of pollution, drinking, and wastewater treatment, has proven to be promising (Madhura *et al*. 2019: 65).

The advantage of using nanotechnology in water purification processes is it enhances the multi-functionality and usefulness of treatment systems, while reducing reliance on physical and chemical methods (Westerhoff *et al.* 2016: 1241). Some nanotechnology approaches in water treatment include nanofiltration, nano adsorbents, silver nanoparticles, and silver-magnetic nanocomposite, along with nanocavitation. For example, the Payamavaran Nanofanavari Fardanegar (PNF) organisation in Iran implemented a nanotechnology project in the Ardabil Province that purified drinking water that contained heavy metals at a lower cost than conventional purification methods. A member of the board of directors at PNF, Ali Rakhsha, stated that nano-cavitation technology oxidises AS III (Trivalent arsenic) into AS V (Pentavalent arsenic), since the alumina sorbents highly adsorb this material (FarsNews Agency 2015: 1). The life of these alumina sorbents increased two or three times more than the conventional purification method, and because no chemical oxidant was used in the product, the operational process cost was reduced. Chemical oxidants decrease the performance of the sorbents; in eliminating their use the nanotechnology project ensured the resultant effect was a lower cost during the purification process (FarsNews Agency 2015: 1).

2.8 Water treatment processes using nanotechnology

There are different techniques for water treatment available in nanotechnology. These techniques involve using adsorption, membrane separation processes or the application of nanomaterials, photocatalysis, and, in some cases, a combination of some of these techniques, to purify the wastewater (Yaqoob *et al*. 2020: 496).

2.8.1 Nanofiltration

Nanofiltration is a filtration process in which a fluid is passed through a membrane that acts as a sieve to separate the impurities. The membrane blocks the impurities in the fluid and only allows the fluid and certain monovalent ions to pass through, trapping undesirable materials on the other side of the membrane (Sharma 2021: 2; Carbotecnia 2022: 1). Some common applications for nanofiltration, according to Carbotecnia (2022: 2), include the purification process of dairy products and the drinking water filtration process, as well as reduction in colour, tannins, and turbidity. Nanofiltration membranes are potent in separating inorganic salts and small organic molecules. It is also known to be successful in water and wastewater treatment, desalination, pharmaceuticals, and biotechnology, in addition to food applications (Mohammad *et al.* 2015: 228; Barnes, Collin, and Ziff 2009: 25; Vieira, Weeber, and Ghisi 2013: 67; da Costa *et al.* 2021: 1).

The drawback is that Nanofiltration membranes are slightly more expensive than other membranes (Yang *et al.* 2019: 1). Figure 2.1 demonstrates a flow chart for the application of nanofiltration in wastewater treatment.

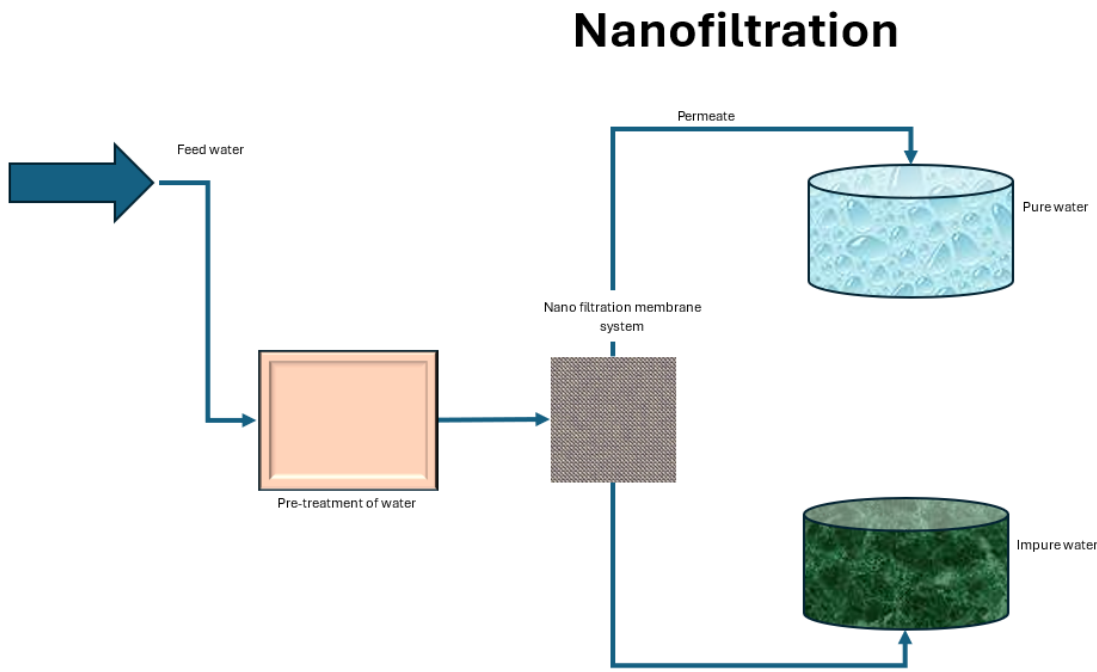

Figure 2.1: Flow chart of nanofiltration process

Source: Researcher's own construction

As illustrated in Figure 2.1, water first enters the pre-treatment tank for initial screening. It then moves to the nanofiltration membrane system, where the primary treatment takes place. The nanofiltration membrane system effectively removes contaminants as small as one nanometre in size. Subsequently, the treated water is transferred to the pure water tank, while the by-product is directed to the impure water tank.

Nanofiltration can cater for both domestic and industrial water treatment. In nanofiltration, the nano filters trap debris and bacteria, while the nanomaterials on the filters target contaminants such as viruses, pesticides, copper and fluorides (Westerhoff *et al.* 2016: 1241; Figoli *et al*. 2017: 119). The nanofiltration process is not only limited to HRW and wastewater but also includes dairy and many other products (He *et al.* 2019: 2).

2.8.2 Application of Nanomaterials

Nanomaterial applications, such as metal oxide, metal nanoparticles, carbon nanotubes, and zeolite, can be effectively used in the field of wastewater purification due to their miniature size and large surface area properties. These nanomaterials have strong adsorption capacities and reactivity on heavy metals, organic pollutants, organic ions, and bacteria (Madhura *et al*. 2019: 69).

Inorganic nanoparticles such as zinc oxide and copper oxide are cheaper, widely available, less toxic to mammalian cells, and stable, as well as more environmentally friendly (Spirescu *et al.* 2021: 2). Nano metal oxides, including zinc and copper oxides, have demonstrated antibacterial activity (Pandey and Dahiya 2016: 19). It is envisaged that nanocomposites of silver with each of these metal oxides will create a potent and yet more cost-effective inorganic antibacterial material (Buonsanti and Zheng 2021; Spirescu *et al*. 2021: 2). Therefore, the nanocomposites to be created would be separated into silver with copper oxide and silver with zinc oxide nanocomposites. The harmonious combination of these nanocomposites would enhance their antibacterial potential (Pandey and Dahiya 2016: 20; Spirescu *et al*. 2021: 2). Hence, each elemental composition of the nanocomposite will activate its own antibacterial activity through the production of associated ions, acting as antibacterial agents.

Use of silver nanoparticles, a method in nanotechnology, is often employed for water treatment, as they are highly toxic to micro-organisms, resulting in effective microbial defence against fungi, bacteria, and viruses. The silver nanoparticles method has been extensively used to disinfect drinking water, due to its exorbitant effectiveness in the purification process (Madhura *et al*. 2019: 76). Silver nanoparticles have also been proven effective water filters in domestic water treatment processes, because of their intense and wide-spectrum antimicrobial activity and low toxicity to humans (Madhura *et al.* 2019: 75; Gadkari *et al.* 2018: 229).

2.8.3 Nano-adsorption

Adsorption is a surface phenomenon whereby molecules of a substance (adsorbate) adsorb on a solid surface (adsorbent) (Kumar *et al.* 2014: 1845). Certain factors that affect the adsorption process are temperature, the nature of the adsorbate and adsorbent, the presence of other impurities, as well as particle size, contact time and the chemical environment (Motitswe, Badmus and Khotseng 2022: 2). Nanomaterials have proven excellent adsorbent materials due to their exotic properties, such as the uniqueness of their miniature size, catalytic potential, high reactivity, and larger surface area, along with a substantial number of active sites for interaction with various impurities. These properties undoubtedly contribute towards their exceptional adsorption capacities that can be used for wastewater treatment in industrial applications (Kumar *et al*. 2014: 1845; Raimondi *et al*. 2023: 1; Rifai *et al.* 2024: 1).

Nanotechnology plays a vital role in applying nanomaterials and nanofiltration in the treatment and purification of HRW and wastewater (Yulistyorini, Idfi, and Fahmi 2018: 2). Despite the cost of treatment and the technology, nanotechnology continues to be beneficial in water treatment and purification.

2.9 Summary of chapter

This chapter provided an overview of previous research on RWH, outlining the various methods used to collect and store rainwater and emphasising its importance in addressing water shortages, particularly in rural SA communities. It highlighted the role of RWH as an alternative water source for household use, while acknowledging challenges related to water quality due to inadequate storage and contamination risks. Additionally, the chapter explored the application of nanotechnology in water treatment, focusing on its potential to improve the quality of harvested rainwater by removing pollutants and pathogens. The next chapter details the research methodology employed in conducting this research.

CHAPTER THREE - RESEARCH METHODOLOGY

3.1 Introduction

This chapter outlines the research design and methodology adopted for this study, detailing the target population and sampling strategy used to gather relevant data. It explains the data collection procedures, including the research instruments employed to capture both qualitative and quantitative information. The chapter further describes the data analysis techniques applied to interpret the findings, ensuring they align with the study's aim and objectives. Ethical considerations guiding the research process are also discussed. Lastly, it presents the steps followed in the Systematic Literature Review (SLR) process to critically analyse existing studies and identify research gaps relevant to this study.

3.2 Research Design

The purpose of conducting research is to predict results, test a theory, and provide a clear and meaningful understanding and explanation of social phenomena (Abutabenjeh and Jaradat 2018: 238). The research design defines, measures, and structures the data collection processes in the research (Eller, Gerber and Robinson 2018: 92). It is primarily focused on the logical framework of the study, which starts with the research problem and highlights the questions the research intends to answer (Sileyew 2019: 3; Wagner 2012: 55; Garner, Wagner and Kawulich 2016: 10).

The central research question in this study is: How do RWH practices, storage conditions, and treatment methods affect the quality of HRW and its impact on community health, and can the application of nanotechnology provide a viable solution for improving water quality in rural communities?

To address this question, a mixed-methods approach was deemed appropriate as it integrates both quantitative data (collected through surveys) and qualitative data (obtained via interviews) to provide a comprehensive exploration of RWH practices in the selected community. The research process involved identifying the core problem, conducting a detailed literature review, selecting appropriate methodologies for data collection and analysis, and finally, presenting the findings through discussion, concluding with recommendations for practical solutions.

3.2.1 Research Methodology

The research methodology is the study of methods used in carrying out research (Wagner 2012: 271; Garner *et al.* 2016; Abutabenjeh and Jaradat 2018: 247). It enables the researcher to report how details of the study were obtained and allows others to evaluate and analyse the study.

Wagner (2012: 273), Garner *et al*. (2016: 103-105) and Abutabenjeh and Jaradat (2018: 248) explain qualitative research is used for the interpretation of phenomena, in terms of the impact it has on the study participants. In contrast, quantitative research focuses on describing social phenomena through a systematic numerical analysis, such as the application of statistical calculations. The quantitative research method is a strategy that emphasises quantification in collecting and analysing data from the respondents (Bryman 2012: 160). The advantage of quantitative research is that the findings are likely to be generalised to an entire population or a sub-population, since it involves a larger, randomly selected sample. It provides the respondents with the opportunity to respond to the questions at their convenience.

The qualitative research method is a process of real investigation that seeks an in-depth understanding of social phenomena through the eyes of the participants. The advantage of qualitative research is it allows the researcher to understand participant experiences by asking questions that cannot easily be put into numbers (Yadav 2021: 680; Abutabenjeh and Jaradat 2018: 248).

3.2.2 Mixed Research Methods

According to Bryman (2012: 628), the mixed research method combines both quantitative and qualitative research in a single project and has become an increasingly used and accepted approach to conducting social research. All research methods individually are flawed, but these limitations can be mitigated through mixed research methods (Turner, Cardinal and Burton 2017: 2). This is made possible since it combines the use of multiple methods that do not share the same failures, which can enhance what is known regarding a given research question. When multiple methods are applied, the imperfections in each method tend to cancel one another (Turner *et al*. 2017: 2).

This study has, therefore, been designed to incorporate a mixed-methods approach, combining the benefits of both quantitative and qualitative techniques. A survey questionnaire was developed and distributed for the quantitative segment, whereas semi-structured interviews were utilised for the qualitative aspect of the study. Data obtained from mixed methods research were validated through methodological triangulation (Dawadi, Shrestha and Giri 2021: 28).

3.2.3 Triangulation

The use of a variety of theories, data collection methods, and data sources to provide different perspectives of the topic under study, as a means of cross-checking the results, is known as triangulation (Abutabenjeh and Jaradat 2018: 246; Dawadi *et al.* 2021: 27). It is a research strategy that helps increase the validity and enhances the credibility of the research findings, thereby mitigating any research biases (Bhandari 2023: 1).

At the data collection stage, triangulation provides ways of verifying or validating data accuracy and stability. During the data analysis and integration stages, triangulation is used to increase the rigour of the analysis (Wagner 2012: 1638). There are four triangulation types, namely method, investigator, theory, and data source triangulation (Moon 2019: 103; Carter *et al.* 2014: 545). This research study utilised method triangulation, as quantitative data were collected through closed-ended questions in the survey questionnaire, and additional qualitative data were gathered through interviews. The integration of results from both methods provided valuable insights and enhanced analysis rigour.

3.3 Target Population

Sileyew (2019: 8) describes a population as the entire group of individuals or units being studied. The target population refers to a clearly specified large group of cases from which the researcher draws a sample and to which the study results would be generalised. The target population for this study is the residents of the rural Umkomaas community in the Umdoni local municipality, which is one of the four local municipalities in the Ugu district of KZN. According to data from the census in SA, there are 514 households in rural Umkomaas, and none of the households have access to pipe-borne water (StatsSA 2022). The residents in this community source their water primarily through RWH or by collecting water from the Mkhomazi River. Additionally, they depend on municipal tankers for water supply when there is no rainfall.

Gathering data on the target population posed a significant challenge due to the scarcity of information in these rural areas, where access to reliable demographic data is limited. To overcome this obstacle, the researcher conducted extensive searches through various channels, including local government records, community organisations, and internet sources. Through diligent investigation, and a one-on-one interview with the Chief, the researcher was able to reach a resolution to obtain the necessary information.

3.4 Sampling methods and sample size

Sampling in a research context is the process used to select those elements that will participate in the research study (Oribhabor and Anyanwu 2019: 47). Two types of sampling techniques are used in research: probability and non-probability. The probability sampling method uses random selection, which limits the influence of personal researcher judgement and imparts confidence that the sample adequately represents the target population (Bryman 2012: 188; Graziano and Raulin 2013: 323; Nanjundeswaraswamy and Divakar 2021: 25).

Different types of probability sampling include simple random, systematic, stratified, and multi-stage cluster sampling. In the case of the non-probability sampling method, some units of the target population are allowed to be selected over others, while it also allows the researcher to determine which elements to include in the sample (Oribhabor and Anyanwu 2019: 50; Nanjundeswaraswamy and Divakar 2021: 28). The common types of non-probability sampling methods include convenience, quota, self-selection (volunteer), and snowball, as well as purposive (judgmental) sampling (Wilson, Chen and Peace 2023: 20).

A convenience non-probability sampling technique was used in this study. The sample for this study was chosen at the researcher's convenience, where the participants were often selected because they were at the right place at the right time (Guest *et al*. 2017: 61). Convenience sampling is most commonly used in research, since it is less expensive and there is no need for a list of the entire population element. Participants who met the inclusion criteria were recruited in the study (Acharya *et al.* 2013: 332). This sampling method helped the researcher achieve the target sample size for this study.

A sample size of 221 was determined as appropriate for the quantitative component of this study, based on sample size determination tables (Adam 2020: 95). This calculation employed the interpolation formula:

$$y = y_1 + (x - x_1)\frac{(y_2 - y_1)}{(x_2 - x_1)}$$

$$y = 218 + (514 - 500)\frac{(235 - 218)}{(600 - 500)} = 220.38$$

The chosen sample size ensures a 95 percent confidence level with a five percent margin of error. This study, therefore, investigated 221 households of the target population that use a RWH system as their source of water supply for their daily livelihood. One adult member from each household was approached to participate in the survey.

For the qualitative part of the study, 16 participants were selected from the same target population to participate. This sample size was sufficient to reach saturation, as highlighted by Subedi (2021: 2), referring to the point at which no new information or themes emerge. Saturation typically occurs with sample sizes ranging from 12 to 20 participants, depending on the study's scope and population homogeneity. This number of participants provided the researcher with varied, in-depth views on the subject under investigation.

A total of 221 respondents completed the survey, and 16 participants took part in the interviews, achieving a 100 percent response rate for the study.

3.5 Questionnaire Design

A questionnaire is a measuring instrument that comprises a series of questions to gather information from participants in a study. Questionnaires can be used for both qualitative and quantitative research purposes (Bryman 2016: 715).

The most common types of questioning techniques used for developing and constructing questionnaires are open- and closed-ended questions (Bhandari 2021: 2). On the one hand, open-ended questions are used for qualitative research when participants have to express their views and responses in the questionnaire. On the other hand, closed-ended questions are used for quantitative research when participants do not have to express themselves but rather make choices by selecting from a set of alternatives provided by the researcher.

The advantage of open-ended questions is this does not constrain participants' answer choices (Bhandari 2021: 2). In some cases, the participant might provide information relevant to research areas the researcher may not have considered or included in open-ended questions. At the same time, the advantage of close-ended questions is they help participants make quick decisions, therefore, the results are much easier to interpret since they are standardised and, thus, can be analysed statistically.

In this study, the research questionnaire combined a quantitative survey and a qualitative interview guide within a single document. The research questionnaire was designed to collect data on existing RWH techniques, water storage conditions, rainwater usage patterns, and associated health effects within the rural Umkomaas community. In addition to relevant literature, the research questionnaire was informed by the study's research focus, the specific context of the Umkomaas community, and insights gained from preliminary observations and discussions with community members. Considering the selected area of Umkomaas is a unique rural community, the questionnaire was designed in the simplest format that would be easy for the participants to understand and complete, thereby maximising the response rate. It combined closed-ended questions for the quantitative survey and open-ended questions for the qualitative interview guide. According to Wagner (2012: 102) and Bryman (2016: 209), interviews are known to obtain in-depth and comprehensive qualitative or quantitative information from participants in a study.

The researcher generated a cover letter for the questionnaire to inform participants of the study purpose and objectives. The cover letter also indicated participation in this study was voluntary, with anonymity and confidentiality ensured. All relevant documentation, namely the final questionnaires, letters of information, and consent were translated into IsiZulu before the study was carried out. This is because the target population is more fluent in IsiZulu compared to the English language.

3.6 Data Collection

Data collection is the systematic approach of gathering information from a variety of sources to ensure the research questions of the study are answered (Wagner 2012: 269; Taherdoost 2021: 11). For this study, data were collected through questionnaires, interviews, and a review of literature sources. The questionnaires were administered and retrieved by the researcher with the support of a team of research assistants. Research assistants were recruited in the local municipality to assist in recruiting, administering, and retrieving the questionnaires.

Participants were recruited in their homes, on the streets, and at other approved gatherings in the community. The quantitative and qualitative data were collected concurrently, owing to the difficulties of engaging the research participants severally over the same purpose. This was done to save time and ensure the research was completed within the timeframe. For participants who could not read and write, the questions were read out to them, and their responses were completed on the questionnaire by the research assistant attending the participant. For the face-to-face interview, a recorder was used to record the conversations for further transcription and analysis after the interview. Participants were informed that the interviews would be recorded, and they all consented to this.

3.6.1 Field Challenges

One of the challenges encountered during this study was the language barrier between the researcher and the participants, as they predominantly spoke IsiZulu. This issue was effectively addressed with the assistance of indigenous research assistants, well-acquainted with the community and fluent in IsiZulu.

In addition, it was observed some participants preferred providing answers to the closed-ended questions, rather than providing answers and responses to the open-ended questions. To address this, the researcher and the research assistants had to explain the importance of the interview and its significance to the study. Consequently, participants were convinced of the value of their detailed input and consented to participate in the interview.

3.7 Pretesting

Pretesting or pilot testing is a technique performed at the early stage of the research to detect whether there are any constraints or limitations in the questionnaire before it is used for the main study (Ornstein 2013: 100). A pilot test was conducted with 20 individuals from the target population. This pilot test helped the researcher refine the design, verify the wording and sequence of the questionnaire, to ensure effective responses from participants. It is important to note the 20 individuals who participated in the pilot test were excluded from the main study. Additionally, it was observed some participants struggled to read and understand certain questions independently, due to limited proficiency in English. Consequently, it was decided to include both IsiZulu and English in the final questionnaire version.

3.8 Data analysis

Wagner (2012: 269) and Kelley (2023: 2) described data analysis as the process of examining data collected from the field and then establishing how they fit together when interpreting the meaning of the results. Therefore, the quantitative data for this study were analysed using the Statistical Package for Social Science (SPSS) (version 25), while the qualitative data were analysed using thematic analysis.

3.8.1 Coding

Coding is the process of assigning labels and organising data to identify different themes and the types of relationships between them. According to Bryman (2016: 709), in qualitative research, coding is the process of breaking raw data into component parts and attributing names or labels. However, in quantitative research, codes act as tags placed on data in relation to people or units of analysis. The aim is to assign the data relating to each variable into groups, each of which is considered a category of the variable in question (Belotto 2018: 2624). Numbers are then assigned to each category to allow the information to be processed by a computer. Flick (2018: 14) also describes coding as generating concepts from raw data and apportioning data excerpts into categories. In this study, the responses from the structured interviews were identified, categorised and then grouped according to similarities due to the initial coding, which later generated a pattern leading to the themes. It was from this technique that the themes were identified and formed the basis for the data analysis.

3.8.2 Quantitative Data Analysis

Descriptive statistics and inferential statistics were the formats employed in interpreting the quantitative data and presenting results in this study.

3.8.2.1 Descriptive statistics

Descriptive statistics, as described by Wagner (2012: 269), involve summarising and explaining quantitative data both numerically and graphically. It is important to ensure the data are correctly captured by addressing missing data, incorrect values, and inconsistencies prior to analysis, as errors can impact the validity of the research results (Sharma 2019: 4; Dong 2023: 16). In this study, descriptive statistics were used to identify the frequency of the quantitative data.

3.8.2.2 Inferential statistics

Wagner (2012: 270) and Sharma (2019: 8) explain inferential statistics is a mathematical process used to determine the occurrence probability of some population characteristics from a sample. Inferential statistical analysis infers properties of a population, for example, by testing hypotheses and deriving estimates. This type of analysis infers properties of a population by testing hypotheses and deriving estimates. In the context of this study, inferential statistics were used to assess how well the theoretical distribution fits the observed categorical data, in terms of evaluating whether the proportions of outcomes match a prespecified set of population proportions, as described by Abebe (2019: 37). This approach is essential in determining whether the observed data can be generalised to a broader population, thereby providing insights into underlying patterns and relationships.

Kishore and Jaswal (2023: 41) explain the chi-square goodness of fit test is typically used to compare the observed data to expected data, based on a known distribution, checking for any significant differences. This test is particularly useful in categorical data analysis, where the aim is to determine whether the frequency distribution of certain characteristics matches what is theoretically expected. The test involves two hypotheses:

- Null Hypothesis: The data matches the expected distribution.
- Alternate Hypothesis: The data does not match the expected distribution.

Therefore, the Pearson chi-square goodness of fit test was employed in this study, 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 should the p-value be less than 0.05 (Turhan 2020: 578). A significant result suggests the observed data deviate from the expected distribution, indicating potential factors influencing the distribution.

3.8.3 Qualitative Data Analysis

The qualitative data analysis was performed using thematic analysis, which is an approach for analysing qualitative data by grouping and identifying patterns in the data collected during the research (Vaismoradi and Sherrill 2019: 1; Wagner 2012: 231). This approach involved several stages: first, the researcher familiarised herself with the dataset through repeated revisions. The initial codes were then generated and organised into patterns based on their similarities. Thereafter, the data were grouped into codes to identify core themes that matched and reviewed for consistency. The final step involved defining and naming these core themes and sub-themes. Excel was used to manage and organise the themes efficiently, due to the dataset volume and similarity. The analysis was interpretative, based on key themes from the audience inclusion theory and other prevalent themes that occurred during the qualitative data collection, as suggested by Brinkmann and Kvale (2018: 115). This process ensured a comprehensive understanding of the qualitative data to reflect its relevance to the study.

For qualitative research to be accepted as trustworthy, it is expedient that the researcher must demonstrate data analysis has been conducted in a precise, consistent, and exhaustive manner through recording, systematising, and disclosing the methods of analysis with sufficient detail to enable the reader to determine whether the process is credible (Nowell *et al.* 2017: 1).

Trustworthiness for this study was maintained through the rigorous techniques used in data collection and analysis. The data were transcribed by two independent people in different locations to minimise any form of bias. Additionally, the questionnaire and interview questions were reviewed by the researcher's supervisor before data collection began, with codes and themes generated from the data also discussed with the supervisor.

3.9 Validity and Reliability

Validity and reliability are the two most important and fundamental features in the evaluation of any measuring instrument or tool for good research. These tests are needed to present the research methodology concisely, increase transparency, and decrease opportunities to insert researcher bias, specifically in qualitative research (Mohajan 2017: 59). The trustworthiness of the qualitative and quantitative data, as well as the transparency of the conduct of the study are crucial to the usefulness and integrity of the findings.

3.9.1 Validity

Research validity refers to the extent to which the data collection method accurately measures what it intends to measure (Wagner 2012: 275). Sürücü and Maslakci (2020: 2696) add validity is established when the research accurately demonstrates a relationship between two variables and supports the credibility of quantitative studies. It is the degree to which the results are truthful; therefore, it requires a research instrument such as a questionnaire to correctly measure the concepts under study. In quantitative research, validity is the extent to which a measuring instrument measures what it is intended to measure, but in qualitative research, it refers to when a researcher uses certain procedures to check the accuracy of the research findings (Mohajan 2017: 71).

From the various types of validity checks available, this study found it appropriate to use construct and content validity. Construct validity examines whether the test or instrument measures the concept it is intended to measure (Bhandari 2023: 2). In this study, construct validity was ensured by focusing on how rainwater is harvested and treated, ensuring the instruments and methods accurately reflected these processes. However, content validity assesses whether the test comprehensively covers the content it aims to measure (Bhandari 2023: 2). This study verified content validity by thoroughly evaluating all aspects of HRW and the technologies used in the treatment process, ensuring the measurements were fully representative of these variables.

3.9.2 Reliability

Wagner (2012: 273) states reliability is the consistency with which a measuring instrument yields a certain result, when the entity being measured has not changed. It measures consistency, precision, repeatability, and trustworthiness, as well as the extent to which the research is without bias (Mohajan 2017: 59). The findings by a researcher in a quantitative study are considered reliable when consistent results have been obtained in identical situations but different circumstances, while in qualitative research, it is referred to as when a researcher's approach is consistent across different projects (Mohajan 2017: 67). The reliability calculation assists in preventing the misinterpretation of results and confirms consistency in a study.

To ensure the reliability of the measuring instrument in this study, the test-retest reliability method was employed to assess the consistency of results over time. This method involves administering the same questionnaire to the same group of participants at two different points in time and then comparing the results to evaluate the stability of the responses (Sainani 2017: 622). The test-retest reliability method is particularly useful for verifying the instrument yields consistent results under similar conditions, thereby ensuring the reliability of the data collected.

According to Jason *et al.* (2015: 4), 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: 624) indicates 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.

3.10 Ethical Protocols

For both the survey and interview, participant confidentiality was maintained by using pseudonyms to protect those participating in the project. The researcher complied with all ethical requirements as prescribed by the Durban University of Technology (DUT) Institutional Research Ethics Committee (IREC). The researcher also formally obtained permission from the Umkomaas Community Chief before recruiting the residents of the community to participate in the study.

The researcher ensured all ethical obligations were adhered to until completion of the study. Each participant was required to sign an informed consent form prior to participating in the study. Participants were informed of their right to anonymity and the right to withdraw from the study at any time without any adverse consequences. They remained assured their participation would be on a voluntary basis. In addition, participants were advised the data would be presented in such a way that their identity would not appear, and the researcher would ensure adherence.

3.11 Systematic Literature Review

A SLR is a type of investigation that evaluates and synthesises findings from various literature sources to inform practice, policy, and further research (Shuster *et al.* 2018: 2). It uses explicit and systematic methods designed to minimise bias, thus providing more reliable findings, which support the drawing of conclusions and decision-making (Deeks *et al.* 2023: 4). Essential steps in conducting systematic reviews include accommodating a diverse range of research questions, clearly defining the research question, and determining the appropriate type of review, all of which significantly impact the generation of evidence, transfer of results, and implementation of the findings (Munn *et al.* 2018: 2). By adhering to a predetermined approach and employing rigorous techniques to ensure accuracy, systematic reviews help identify trends, gaps, and weaknesses in the available evidence, thereby guiding future research in the field.

In this study, a SLR was conducted on the thematic topics generated from the quantitative and qualitative analysis regarding the use of HRW. A four-step process template was employed for the systematic review: identification, screening, eligibility, and inclusion, as recommended by Shuster *et al.* (2018: 3). The inclusion criteria were RWH techniques, storage facilities, treatment processes, and health outcomes. Conversely, the exclusion criteria included studies focusing on rainwater solely for agriculture, rainwater for urban usage, municipal water treatment, dams, and sewage water treatment. The research data were sourced from Scopus, Science Direct, and Springer Link digital databases, using the keywords and Boolean operators as follows: rainwater AND storage AND harvesting AND rural AND treatment AND process AND health AND consumption. The date range included articles published between 2014 and 2024. This selection was made to ensure the inclusion of recent and relevant studies that reflect current practices and advancements in RWH and treatment processes.

The SLR search process followed the PRISMA flow diagram as represented in Figure 3.1 below.

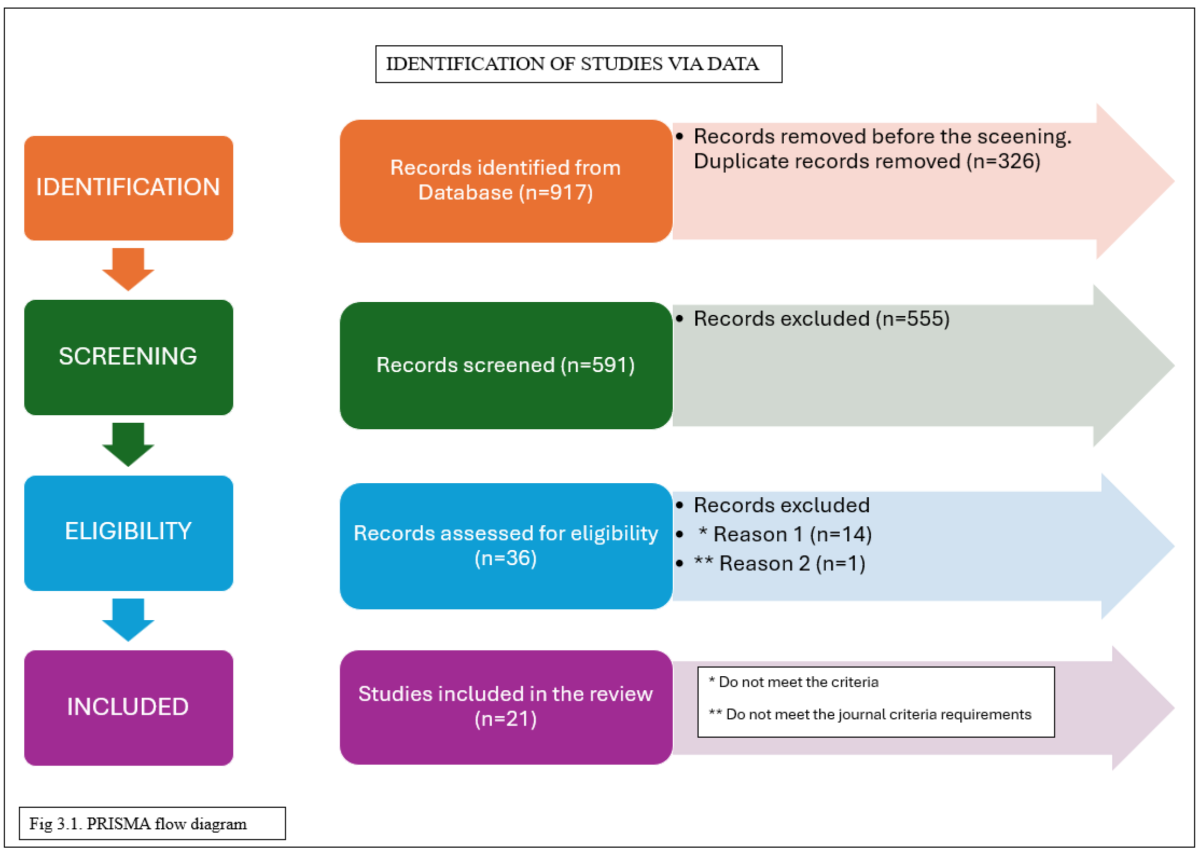

Figure 3.1: PRISMA flow diagram

Source: Researchers own construction

As Figure 3.1 shows, 917 references in total were initially identified from the databases using predefined inclusion and exclusion criteria. Thereafter, duplicates were removed, with 591 records left. The next step involved reviewing the titles and abstracts, which narrowed the remaining articles to 36. The final step entailed reading these 36 articles in full, resulting in the final inclusion of 21 articles used in this SLR analysis.

The PICO method (Population, Intervention, Comparison, and Study Design) was employed to address the diverse approaches and goals of the identified articles. A descriptive analysis was conducted to derive meaningful outcomes, with results checked for publication bias to ensure their reliability (Tufanaru *et al.* 2017: 4; Page *et al.* 2021: 5). The evaluation identified three possible outcomes: low risk, where the article is straightforward and interpretable, indicating no possibility of bias; unclear risk, where the manuscript raises questions needing further explanation by the review author; and high risk, where the results are not fully understood (Page *et al*. 2021: 7; Munn *et al*. 2018: 3).

3.12 Chapter Summary

This chapter discussed the research design and methodology. The overall research strategy was explained, with the target population and sampling discussed, providing the rationale for selection. Data collection, analysis, and approaches to coding were outlined, with reference to the use of data categories, themes, and findings. In addition, matters of ethics in research were dealt with, as well as how these principles were applied in relation to voluntary participation, avoiding harm to participants, privacy, and anonymity, as well as confidentiality. Last, the background information for the SLR was discussed in this chapter.

The data presentation, analysis and interpretation are dealt with in the chapter that follows.

CHAPTER FOUR - DATA PRESENTATION, ANALYSIS AND INTERPRETATION

4.1 Introduction

This chapter presents the results obtained from both the survey questionnaire and interviews conducted in this study. It provides a comprehensive analysis of the quantitative data and explores the qualitative insights gathered from participants. Additionally, it examines how these findings align with existing literature, offering a comparative perspective. The chapter also triangulates the results from both methods to strengthen the study outcomes and provide a comprehensive understanding of the research objectives. Lastly, it concludes with a SLR of the key themes derived from the findings.

4.2 Results of the Quantitative Survey

The quantitative part of this study was administered through a survey questionnaire to residents of the rural Umkomaas community who practice RWH. The survey sought to collect information on existing RWH systems, water storage conditions, usage patterns of HRW, and the related health effects experienced by the community.

4.2.1 Part 1 - Biographical Information

This section of the questionnaire was formulated to acquire comprehensive demographic data on households, specifically focusing on the number of occupants and their age distribution. Such information was deemed appropriate for determining household water consumption patterns.

4.2.1.1 Number of people living in a household

The results for the number of people living in a household, are presented in Figure 4.1.

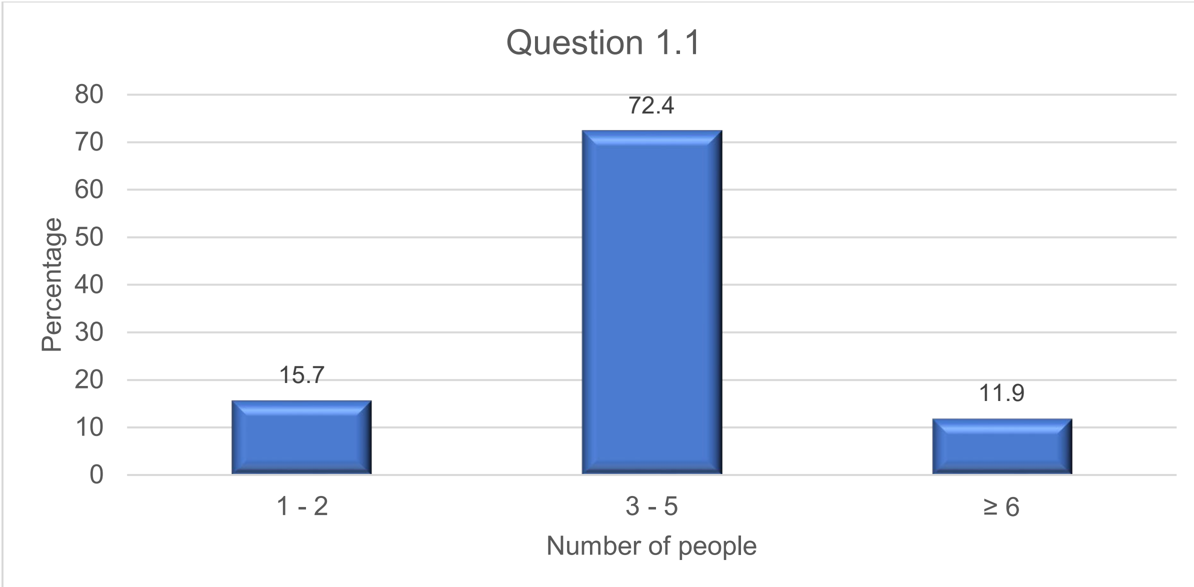

Figure 4.1: Number of people living in a household

As Figure 4.1 shows, 15.7 percent households have between 1-3 residents, 72.4 percent has between 3-5 residents, and 11.9 percent has six or more residents. The weighted average household size is, therefore, approximately four residents. The significant majority (72.4 percent) households that accommodates between 3-5 people, reflects a prevalent trend towards a moderate-size domestic unit. This observation aligns with the notion that household size influences the rate of water consumption, as suggested by various authors (Alim *et al.* 2020: 10; Mwamila, Katambara and Han 2016: 150; Islam *et al.* 2010: 3987). Moreover, this correlation extends further, indicating that larger households tend to consume water at a faster pace than smaller ones. This makes sense, since a greater number of occupants within a household are likely to require more water for basic needs and other purposes.

4.2.1.2 Age range of people living in a household

The results pertaining to the age range of people living in the community households are represented in Figure 4.2 below.

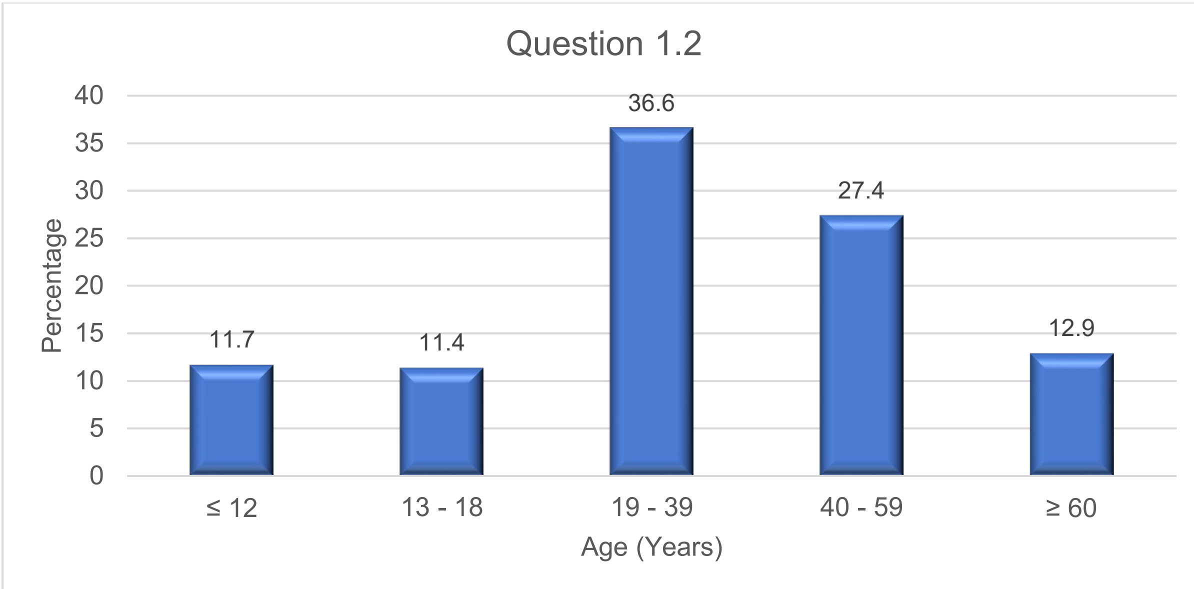

Figure 4.2: Age range of people living in a household

Figure 4.2 shows the modal average age of the community is between 19 to 39 years, accounting for 36.6 percent of the sample, followed by the age range of 40 to 59 years, comprising 27.4 percent. The reflection of these two age brackets shows rural Umkomaas is a community dominated by energetic youths and adults, within the working-class age bracket. Additionally, the data indicate the presence of other age groups within the community, including children aged 0 to 12 years (11.7 percent), teenagers between 13 to 18 years (11.4 percent), and senior citizens aged over 60 years (12.9 percent). These findings highlight that the majority households in rural Umkomaas consist of individuals within active age groups, suggesting more HRW usage, as noted by Makki *et al.* (2013: 2). Consequently, there is anticipated increased pressure on HRW in households with a higher proportion of youth/teenagers, compared to those with senior citizens, owing to their greater water consumption relative to other age groups (Tengan and Akoto 2022: 2).

4.2.2 Part 2 – Rainwater Harvesting (RWH) Processes

This part of the questionnaire was intended to investigate the RWH technique type and the predominant roofing material types commonly used in the rural Umkomaas community.

4.2.2.1 Survey Question 2.1 (Type of RWH technique)

The results pertaining to the different RWH technique types practiced, are presented in Figure 4.3.

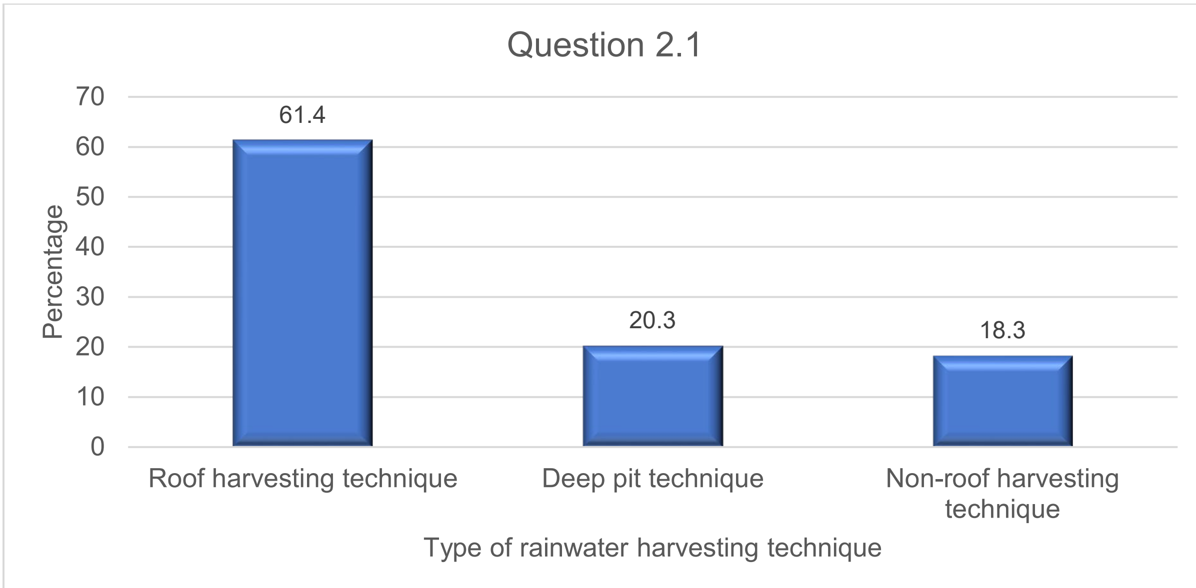

Figure 4.3: Type of RWH technique

As depicted in Figure 4.3, the majority respondents (61.4 percent) make use of the roof harvesting technique, while 20.3 percent employ the deep pit technique, and 18.3 percent practice the non-roof harvesting technique. The non-roof technique could possibly refer to direct rainwater collection in buckets before it contacts any surfaces. The low percentages for the deep pit technique and non-roof harvesting technique indicate these techniques are less prevalent among the respondents. This could be due to various reasons, including high initial investment costs, technical complexity or limited applicability in certain geographical and environmental contexts. For instance, the deep pit technique requires excavation and construction of underground storage facilities, which may not be feasible or practical in all areas (Pradhan and Sahoo 2019: 2; Gomez and Teixeira 2017: 57; Keithley *et al.* 2018: E2). The distribution of preferences among these RWH techniques was found to be statistically significant $[\chi^2(2df) = 78.470, p < 0.05]$. This indicates 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 significant majority (61.4 percent) respondents utilising the roof harvesting technique suggests a widespread adoption of this method, which is consistent with the literature that this technique is the most practiced RWH technique, particularly in areas where access to clean water sources is limited or unreliable (Tengan and Akoto 2022: 2; Alim *et al*. 2020: 7; Lye 2009: 1). This could be attributed to several factors, such as its simplicity, cost-effectiveness and suitability or various types of structures. In addition, rainwater collected from rooftops is often believed to be safer than surface water from rivers, lakes, and groundwater or from shallow wells before it comes into contact with the ground (Gwenzi *et al*. 2015: 111).

On the negative side, the roof-RWH technique has the potential risk of Escherichia coli contamination, due to the natural surroundings of the environment, as indicated by (Ahmed, Sidhu, and Toze 2012a: 5194; Ahmed, Sidhu and Toze 2012b: 6844). According to bacterial analyses, this observation is aligned with (Jesmi *et al.* 2014: 4), who found rooftop-HRW frequently does not match the bacteriological quality standards recommended for drinking water. Therefore, since the respondents in this community show a preference for the roof-RWH technique, it is important to ensure the HRW is properly treated prior to consumption, to prevent health implications.

4.2.2.2 Survey Question 2.2 (Type of roofing material)

The results pertaining to the different types of roofing materials are presented in Figure 4.4.

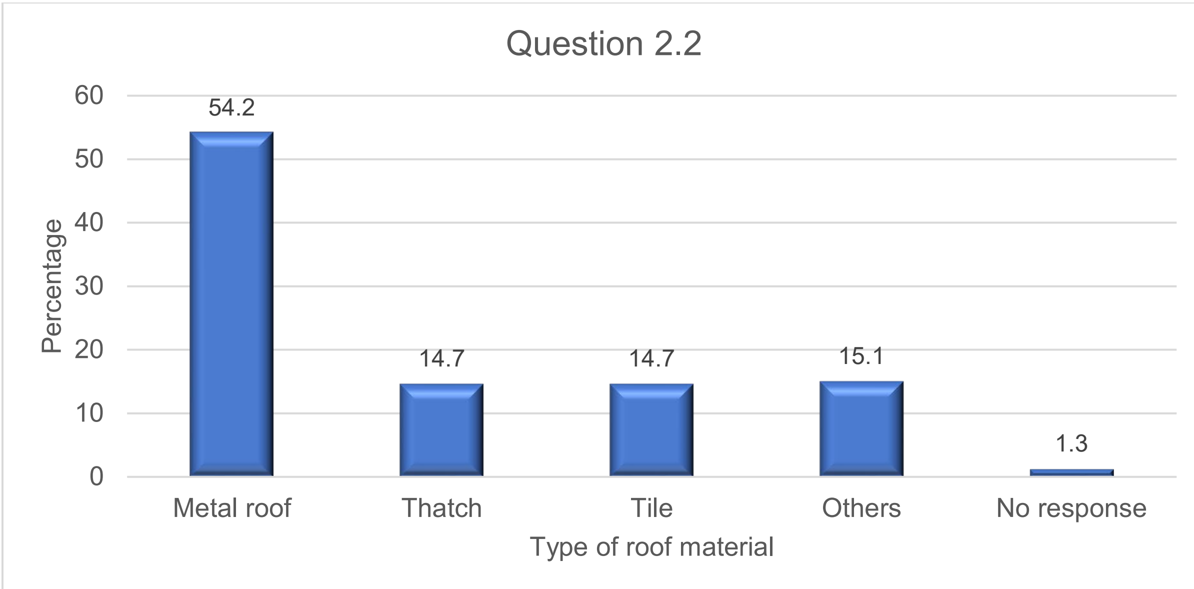

Figure 4.4: Type of roofing material

From Figure 4.4, it can be observed 54.2 percent respondents prefer metal roofing materials for RWH, while 14.7 percent respondents prefer Thatch and Tiling roofing materials. In addition, 15.1 percent respondents indicated they use some other roofing material type for RWH, demonstrating the diversity of options available in the market. Alim *et al*. (2020: 19) state factors influencing the roofing material choice for RWH include material availability, ease of construction, construction cost, and weather/climate pattern. The preference distribution among these roofing materials was found to be statistically significant [$\chi^2(4df) = 176.750, p < 0.05$]. This indicates the observed distribution differs significantly from what would be expected by chance alone, suggesting factors beyond random choice are influencing respondent preferences.

Studies have shown the type of roofing materials used for RWH can significantly impact the quality of rainwater collected (Mendez *et al*. 2010: 2; Mendez *et al.* 2011: 2050; Tengan and Akoto 2022: 2). Therefore, while metal roofing materials are the most preferred for RWH, it is imperative to consider the implications of material choice on water quality. Pollutants in HRW can originate from leaching of construction materials, organic matter, particulates, and debris, or residues from animals and birds attached to roofing surfaces (Adeniyi and Olabanji 2005: 149). These findings highlight the importance of considering both technical and environmental factors when choosing roofing materials for effective RWH systems.

4.2.3 Part 3 – Water Storage Conditions

This part of the questionnaire was intended to investigate water storage systems and maintenance conditions.

4.2.3.1 Survey Question 3.1 (Type of storage container)

The results of the container types used to store HRW are presented in Figure 4.5.

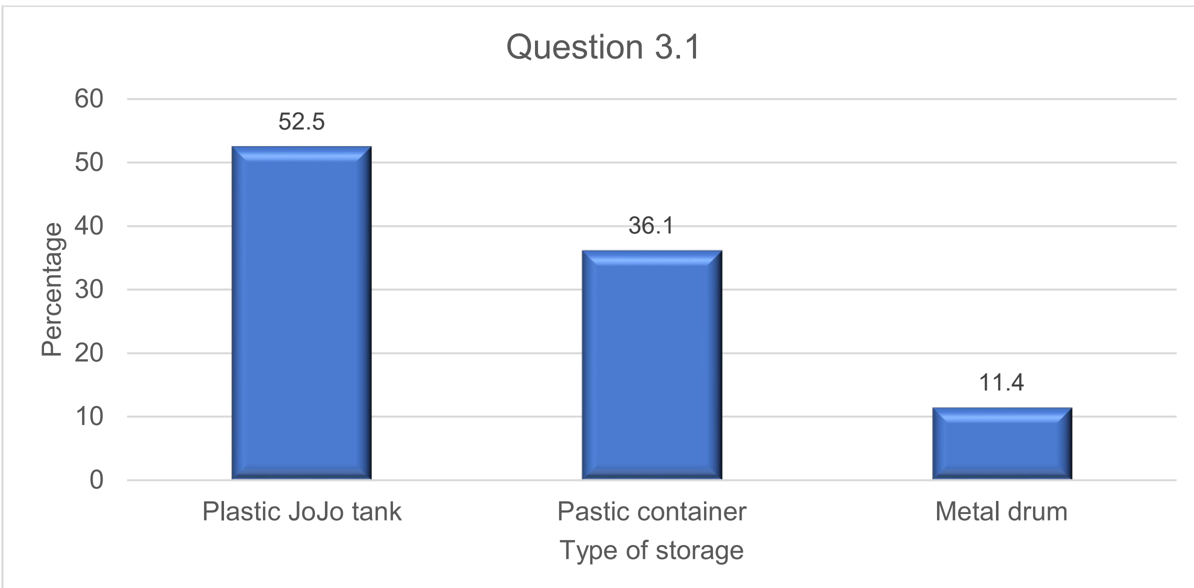

Figure 4.5: Type of storage container

From Figure 4.5, it is noted 52.5 percent respondents prefer to use plastic JoJo tanks for storing HRW. In comparison, 36.1 percent respondents use other types of plastic containers, and 11.4 percent store HRW in metal drums. The distribution of preferences among these storage containers was found to be statistically significant $[\chi^2(2df) = 56.760, p < 0.05]$. This statistical significance indicates the observed distribution of storage container preferences among respondents differs significantly from what would be expected by chance alone.

Factors such as cost-effectiveness, ease of installation, and perceived safety of plastic containers possibly contribute to this observed preference. This partiality reflects a widespread belief in the safety of plastics for water storage, as supported by previous studies (Adeniyi and Olabanji 2005:

149; Magyar *et al.* 2007: 21). Furthermore, plastic containers offer distinct advantages over metal drums in RWH systems. Unlike metal drums, which are prone to corrosion over time, plastic containers exhibit greater durability and longevity, thereby preserving the quality of stored water, as highlighted by Ertop *et al*. (2023: 7).

4.2.3.2 Survey Question 3.2 (Storage duration of HRW)

The results pertaining to the storage duration of HRW are presented in Figure 4.6.

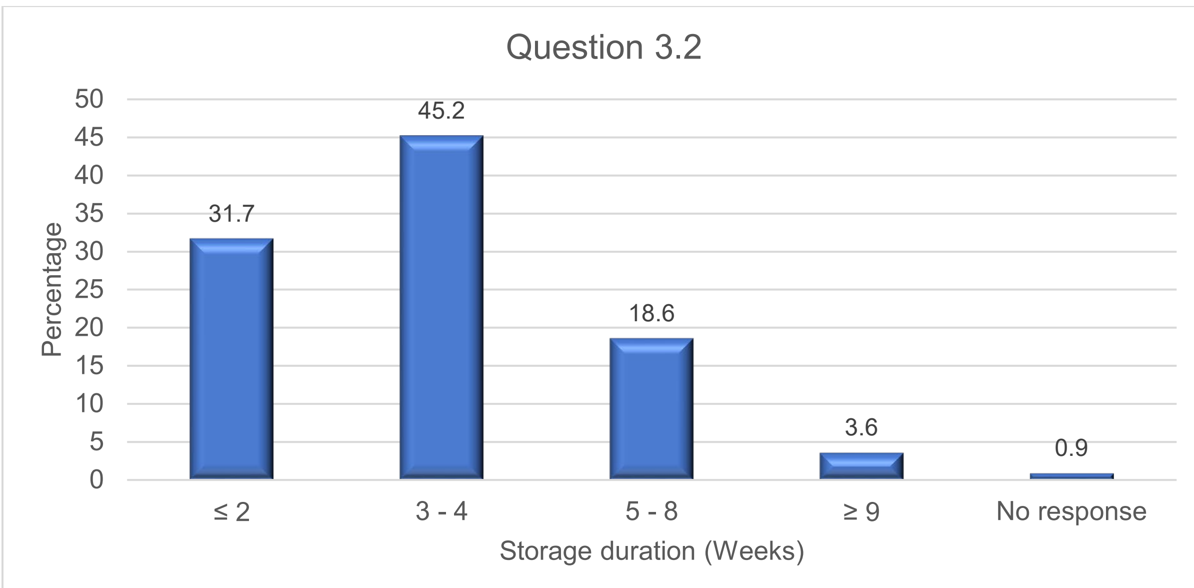

Figure 4.6: Storage duration of HRW

According to Figure 4.6, the distribution of storage durations for HRW shows 45.2 percent respondents store it for 3-4 weeks, with 31.7 percent storing it for ≤2 weeks, 18.6 percent for 5-8 weeks, and 3.6 percent for ≥9 weeks or longer. According to the respondents, the reasons for storing the HRW for a short period of time could be due to the number of people in a household using the water, and it could also depend on how quickly the quality of the HRW deteriorates. This deterioration is enhanced by dissolved solutes, such as dissolved chemicals, organics and microbes flushed with the rainwater during harvesting, negatively impacting the HRW quality and its suitability for consumption (Mendez *et al*. 2010: 2; Singh *et al*. 2022: 165; Alim *et al*. 2020: 4).

The distribution of storage durations was found to be statistically significant [$\chi^2(4df) = 155.550, p < 0.05$], indicating respondent preferences deviated significantly from an expected uniform distribution across different time periods. This statistical significance suggests factors, such as household water usage patterns, concerns over water quality degradation, practical storage considerations, and educational influences, probably contribute to the observed preferences for shorter storage durations.

4.2.3.3 Survey Question 3.3 (Cleaning frequency of storage containers)

The results pertaining to how often the HRW storage container is cleaned, are presented in Figure 4.7.

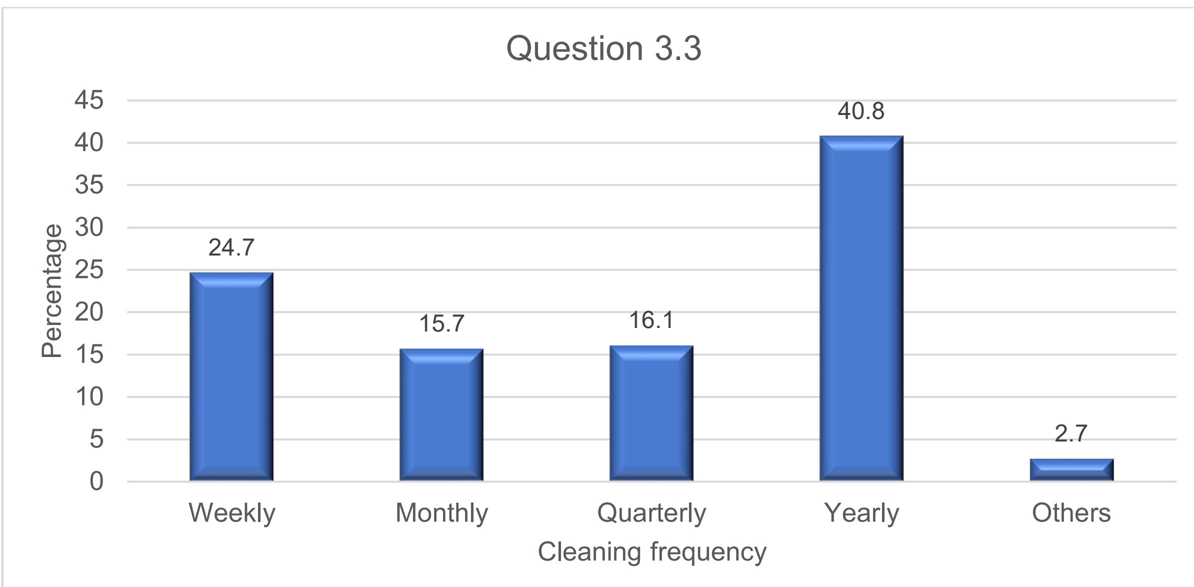

Figure 4.7: Cleaning frequency of storage containers

The data in Figure 4.7 show 40.8 percent respondents clean their storage containers annually, 24.7 percent choose to clean weekly, 16.1 percent prefer cleaning quarterly, and 15.7 percent clean their containers monthly. The chi-square goodness of fit results [$\chi^2(4df) = 87.040, p < 0.05$], indicate 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.

The irregular cleaning practices observed in this study also suggest potential health risks due to microbial contamination. This is because storing water in a container for longer periods without regular cleaning provides a breeding ground for bacterial and other microbial growth within the container (Zhang *et al.* 2021: 4; Bae *et al.* 2019: 408). Therefore, implementing regular cleaning strategies, such as using nanotechnology for tank cleaning, can mitigate these risks (Reyneke *et al.* 2020: 29).

4.2.4 Part 4 – HRW consumption

This part of the questionnaire was intended to investigate HRW consumption and its various uses within the community.

4.2.4.1 Survey Question 4.1 (Main uses of HRW)

The results pertaining to the main activities HRW is used for, are presented in Figure 4.8.

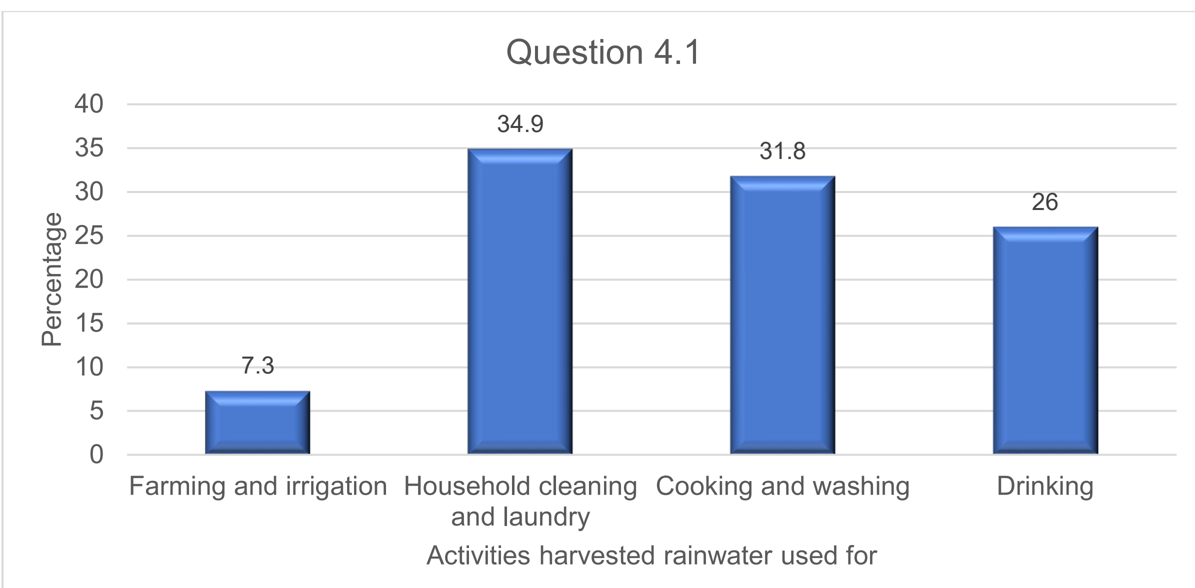

Figure 4.8: Main uses of HRW

Figure 4.8 illustrates HRW is primarily used for household cleaning and laundry (34.9 percent), followed by cooking and washing (31.8 percent), drinking (26 percent), and farming and irrigation (7.3 percent). This reveals the diverse applications of HRW among the respondents for their daily livelihood. The chi-square goodness of fit results $[\chi^2(3df) = 40.530, p < 0.05]$ indicate statistically significant differences in the distribution of rainwater uses among these categories, suggesting varied preferences and needs within the community. This could be attributed to socio-economic factors and cultural practices influencing water usage patterns.

Quality is, however, one of the main factors influencing the appropriateness of rainwater for different purposes. Though there are many uses for rainwater, such as irrigation, cleaning, laundry, and bathing, as well as toilet use (Takagi *et al.* 2019: 467; Lynch and Dietsch 2010: 46; Martinez-Garcia *et al.* 2022: 2), the focus for HRW consumption often centres on its suitability for cooking and drinking purposes. This is motivated by the more stringent standards for water quality that apply to drinking, than those for other applications, aiming to protect public health and ensure safe consumption practices.

4.2.4.2 Survey Question 4.2 (Activities HRW not used for)

The results pertaining to what activities HRW is not used for, are presented in Figure 4.9.

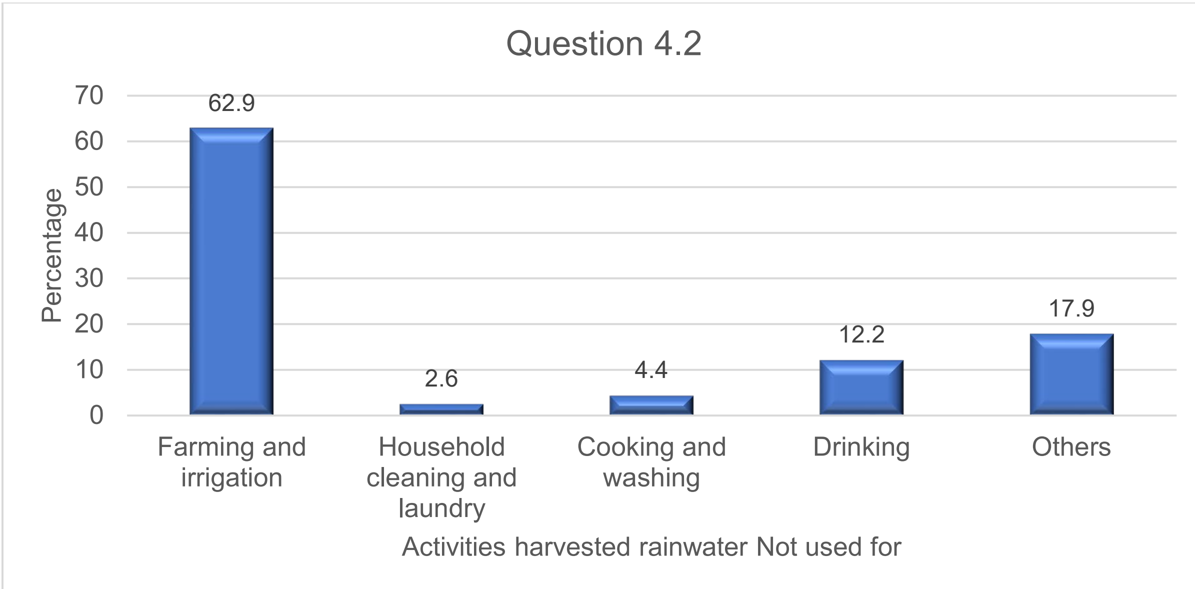

Figure 4.9: Activities HRW is not used for

Figure 4.9 shows 62.9 percent respondents would rather not use the HRW for farming and irrigation purposes, 2.6 percent would not use it to clean, 4.4 percent would not cook with the rainwater, while 17.9 percent do not define uses but classify these as other unspecified usages and 12.2 percent will not use it for drinking. The reluctance to use HRW for specific purposes may stem from cultural or practical beliefs held by respondents. This observation is supported by prior research investigating factors such as water quality, risk perception, health concerns, and financial considerations, which have historically contributed to the limited social acceptance of HRW (Rozin *et al.*2015: 5; Roebuck, Oltean-Dumbrava and Tait 2011: 356).

The statistical significance of these findings $[\chi^2(4df) = 270.920, p < 0.05]$ indicates the distribution of preferences for HRW use across these categories differs significantly from what would be expected by chance alone. This suggests the varied preferences and perceptions among respondents significantly influence their decisions regarding HRW usage. Despite its recognised suitability as a non-potable water source, compared to other alternatives for non-drinking purposes (Egyir, Brown and Arthur 2016: 161; Dobrowksy *et al.* 2014: 403), some households remain hesitant to adopt rainwater for indoor use (Mankad and Tapsuwan 2011: 381).

4.2.4.3 Survey Question 4.3 (Shelf life of HRW)

The results pertaining to how long the HRW lasts, are presented in Figure 4.10.

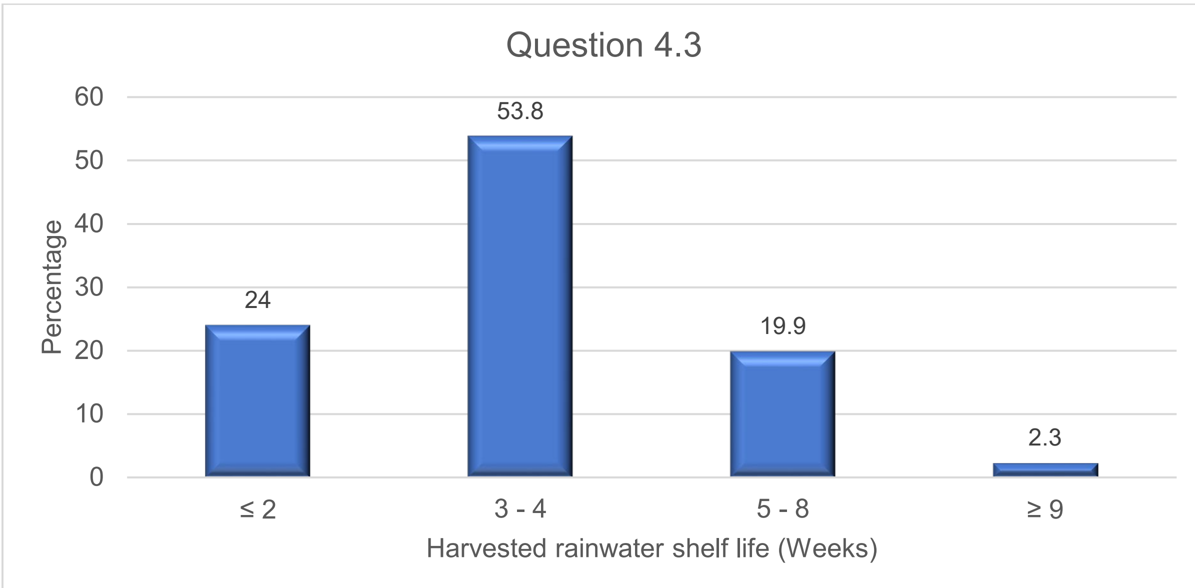

Figure 4.10: Shelf life of HRW

Figure 4.10 illustrates the majority respondents (53.8 percent) indicate their HRW lasts for up to four weeks, with 24 percent reporting a two-week duration. Additionally, 19.9 percent mention their HRW supply can last between five to eight weeks, while a small fraction (2.3 percent) report it lasting 12 weeks. The shorter storage durations reported by the respondents may be influenced by household size, as indicated by the biographical data, such as the number of household members and their age ranges. The statistical significance of these findings $[\chi^2(3df) = 121.620, p < 0.05]$ indicates the shelf life of HRW is significantly associated with household demographics.

Moreover, younger individuals, known to consume more water than those who are older (Makki *et al*. 2013: 2), likely contribute to shorter HRW storage periods. These findings echo similar results from question 3.2, where respondents also preferred shorter storage durations, possibly due to concerns over water quality deterioration. HRW quality can decline due to the presence of dissolved chemicals, organics, and microbes, introduced during the harvesting process (Despins, Farahbakhsh and Leidl 2009: 117; Alim *et al*. 2020: 18; Mendez *et al*. 2010: 2; Mendez *et al*. 2011:

2050). Without proper management, these contaminants can render the water unsuitable for consumption over prolonged periods.

4.2.5 Part 5 – Health Effect

This part of the questionnaire was intended to investigate the health effects from consuming HRW.

4.2.5.1 Survey Question 5.1 (Frequency of falling sick)

The results pertaining to the frequency of residents falling sick, are presented in Figure 4.11

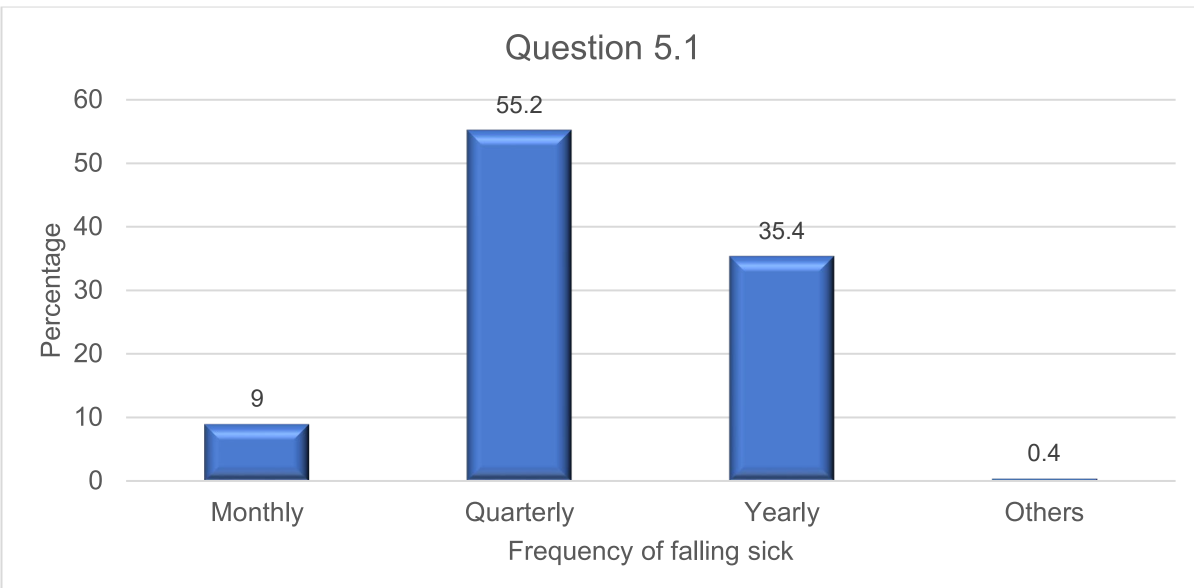

Figure 4.11: Frequency of falling sick

Figure 4.11 shows most respondents (55.2 percent) experience sickness on a quarterly basis, with 35.4 percent reporting annual occurrences, and nine percent experiencing monthly sickness. The data underscores a notable prevalence of periodic illnesses among the surveyed population. Many respondents attributed their periodic sickness to concerns over water quality, particularly regarding rainwater collected from roofs. This belief reflects a common perception that such water sources may compromise immune health due to potential contaminants.

This concern is further supported by epidemiological research that challenges the safety assumptions associated with roof-collected rainwater (Heyworth *et al.* 2006: 1053; Fiorentino *et al.* 2021: 2; Fisher-Jeffes *et al.* 2017: 81). Additionally, there was a statistically significant association between sickness frequency and concerns over water quality $[\chi^2(3df) = 166.310, p < 0.05]$. This finding underscores the strong correlation between perceived water quality issues and reported illness frequencies among survey respondents.

4.2.5.2 Survey Question 5.2 (Sicknesses associated with HRW use)

The results pertaining to the different sickness type symptoms associated with HRW use, are presented in Figure 4.12.

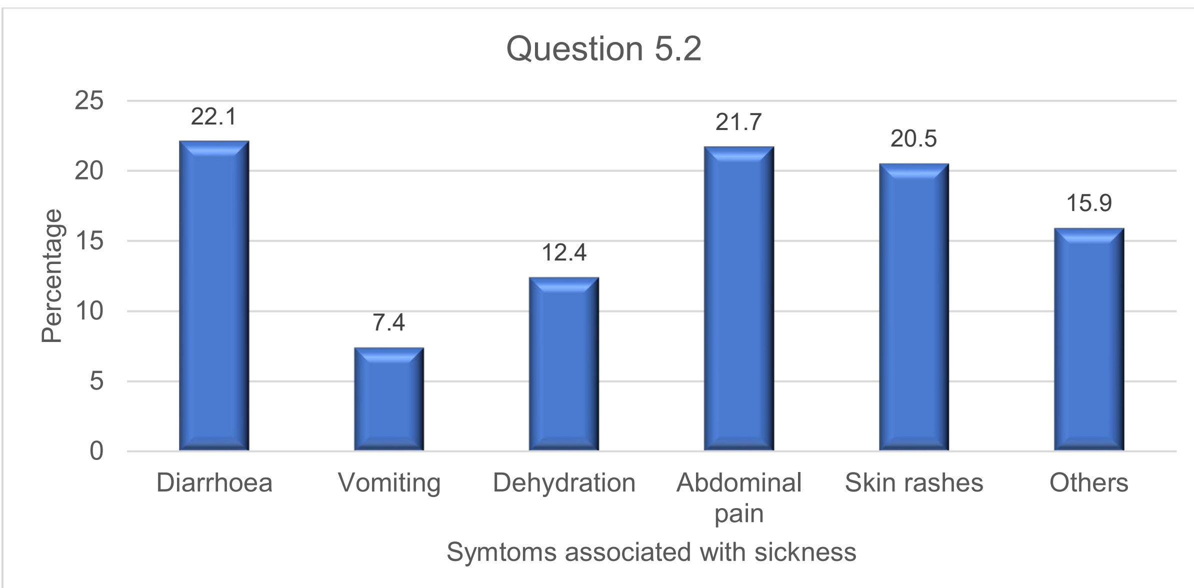

Figure 4.12: Types of sickness symptoms associated with the use of HRW

Figure 4.12 reveals significant occurrences of gastrointestinal illnesses, including diarrhoea (22.1 percent), vomiting (7.4 percent), and abdominal pain (21.7 percent). Moreover, a considerable number of respondents indicated symptoms suggestive of dehydration (12.4 percent), skin rashes (20.5 percent), and other unspecified health issues (15.9 percent). These findings are consistent with similar observations reported by Hamilton *et al.* (2017: 290). The observed statistically significant association $[\chi^2(5df) = 23.090, p < 0.05]$ underscores the link between reported symptoms and potential health risks related to rainwater quality. Consumption of contaminated water, possibly containing Cryptosporidium spp., can lead to nausea, vomiting, and diarrhoea, while Legionella pneumophila, a respiratory infection, may cause pneumonia (Dalal *et al.* 2020: 1; Azupogo *et al.* 2023: 100).

The variability in rainwater quality across different locations, as indicated by contradictory findings in past and current studies, may be attributed to differences in microbial contamination markers and assay methods. Previous research predominantly focused on conventional culturing methods, examining enterococci and E. coli in stools as indicators of pathogen presence (Martinez-Garcia *et al.* 2022: 1). The presence of E. coli in storage tanks suggests potential faecal contamination in HRW, correlating with higher levels of faecal coliforms (>1000 E. coli per 100 ml) and an increased incidence of childhood diarrhoea, highlighting significant public health concerns (Issaka 2011: 40; Ahmed *et al.* 2017: 327).

4.2.6 Chi-Square goodness-of-fit results

The goodness-of-fit results for the survey questions using the Chi-Square Test are presented in Table 4.1.

Table 4.1: Chi-Square goodness of fit results

Question	degrees of freedom (df)	Chi-Square crit. value (0.05)	Chi-Square calc. value	P value
2.1 Indicate which method is used in your household to harvest rainwater.	2.0	5.991	78.470	0.000
2.2 Indicate which of these roofing materials best describes the one that is used for the roof harvesting technique?	4.0	9.488	176.750	0.000
3.1 Indicate the type of container that is used to store the harvested rainwater.	2.0	3.991	56.760	0.000
3.2 Indicate how long the harvested rainwater is stored.	4.0	9.488	155.550	0.000
3.3 Indicate how often the storage container is cleaned.	4.0	9.488	87.040	0.000
4.1 Indicate what are the main uses of the harvested rainwater.	3.0	7.815	40.530	0.000
4.2 Indicate what the harvested rainwater is not used for.	4.0	9.488	270.920	0.000
4.3 Indicate how long the stored harvested rainwater last.	3.0	7.815	121.260	0.000
5.1 Indicate how often you or your family members fall sick.	3.0	7.815	166.310	0.000
5.2 Indicate what symptoms are commonly associated with the sickness	5.0	11.071	23.090	0.000

All questions listed in Table 4.1 show the calculated Chi-Square values are significantly higher than the critical values, and the p-values are all below 0.05, indicating strong evidence against the expected distribution. This suggests the observed distributions differ significantly from the expected distributions for each of these variables. These deviations from expected outcomes point to specific patterns in how respondents engage with RWH, suggesting these responses are not random or uniform across the community (Abebe 2019: 34).

The significant deviations observed across all variables suggest the presence of factors influencing respondent choices and behaviours. For example:

- Question 2.1 (RWH Method): The high Chi-Square value (78.470) suggests certain RWH methods are strongly preferred over others. This could reflect local practices, availability of resources, or historical preferences in the community. It is important to consider how cultural factors or local environmental conditions may shape these preferences.
- Question 2.2 (Roofing Material): The substantial Chi-Square value (176.750) for roofing material highlights a clear preference for certain materials, which may be influenced by the community's awareness of how roofing materials impact HRW quality. This could also reflect economic factors, where more affordable or durable materials dominate usage, even when they are not ideal for rainwater quality.
- Questions 3.1 and 3.2 (Storage and Duration): The high Chi-Square values for both the type of storage container (56.760) and the duration of rainwater storage (155.550) indicate distinct respondent preferences or limitations regarding storage. Economic factors may influence the choice of storage containers, while the storage duration could reflect concerns over water scarcity or storage capacity.
- Question 5.1 (Frequency of Sickness): The Chi-Square value of 166.310 reveals a strong pattern in the reported frequency of sickness among households. This is significant in understanding the health impacts associated with RWH. The deviation suggests certain groups may experience more frequent health issues, which could be related to the quality of HRW, insufficient treatment, or improper storage practices.

The significant deviations across all the analysed questions suggest factors such as cultural practices, educational awareness, economic constraints, and health concerns play a crucial role in shaping the community's approach to RWH. These patterns underline the need for tailored interventions that address the unique challenges the community faces in improving the effectiveness and safety of RWH systems. The Chi-Square results provide valuable insights into the behaviours and practices of the surveyed population, revealing areas where interventions could be targeted to enhance RWH practices and their health and environmental impact.

4.2.7 Test-retest reliability

The results of the test-retest reliability analysis are presented in Table 4.2.

Table 4.2: Test-retest contingency table of counts

	Participant 2 (Y)	Participant 2 (N)	Total
Participant 1 (Y)	7	1	8
Participant 1 (N)	0	2	2
Total	7	3	10
$* P_{obs} = 0.9$	$* P_{cha} = 0.62$		

The observed agreement ($P_{observed}$) score was 0.9, indicating that in 90 percent cases, the participants provided consistent responses across both attempts in answering the questionnaire. The expected agreement (P_{chance}) score was 0.62, indicating how much agreement is expected by chance, based on how often each response to the questionnaire was given. To quantify the level of agreement, the Cohen's Kappa (K) value was calculated through the following equation (Sainani 2017: 622):

$$K = \frac{P_{observed} - P_{chance}}{1 - P_{chance}}$$

$$K = \frac{0.9 - 0.62}{1 - 0.62}$$

$$K = 0.737$$

This calculated K value of 0.737 confirms the measuring instrument has high reliability, meaning it achieved consistent results across repeated assessments.

4.3 Results of the Qualitative Study

The qualitative interview questions were designed to provide an in-depth understanding of how the existing RWH practices, as identified in the survey, affect the daily living conditions and health perceptions among the rural Umkomaas community residents.

4.3.1 Interview Question 1

The thematic analysis for interview question 1 is presented in Table 4.3.

Table 4.3: Interview question 1 thematic analysis

Question intent	Question	Theme result	Sub-themes
To understand why participants, use specific rainwater harvesting techniques.	Why do you use the specific rainwater harvesting technique as indicated in question 2.1?	Reasons for choosing rainwater harvesting techniques.	Practicality and suitability of technique
			Cost-effectiveness
			Environmental considerations

As illustrated in Table 4.3, interview question 1 reveals a theme that explains why participants preferred a specific RWH technique over others. The theme suggests participants primarily chose their preferred method based on factors such as ease of maintenance and installation, and availability of materials for harvester construction. The choice of RWH techniques among participants is influenced by various factors, prominently highlighted in the themes of practicality, cost-effectiveness, and environmental considerations.

According to participant number 3:

"*Roof technique because it costs less, reducing water bills and demand*"

Another participant (number 6) said:

"*We use the non-roof harvesting water technique because it helps to reduce storm water*"

The qualitative responses from this question triangulated well with the responses to question 2.2 of the quantitative analysis, where respondents favour certain roofing materials based on factors such as durability, ease of maintenance, and initial installation costs.

The selection of roofing materials plays a pivotal role in determining the quality of HRW, particularly concerning contamination risks. Nadupuru and Shewale (2023: 1) indicate roofing materials, for example, asbestos and untreated metal sheets, can introduce heavy metals such as zinc into collected rainwater, impacting its quality. Conversely, materials such as polycarbonate plastics or clay tiles are noted for potentially offering better water quality outcomes due to their inert nature (Farreny *et al*. 2011: 3247). Factors influencing the selection of roof water harvesting techniques include installation costs, maintenance ease, water volume potential, and durability (Farreny, Gabarrell and Rieradevall 2011b: 686; Fuentes-Galvan, Medel, and Arias Hernandez 2018: 2; Gwenzi *et al*. 2015: 109; Alim *et al*. 2020: 13). Understanding these dynamics is crucial for optimising RWH systems to ensure both the sustainability of water sources and the health safety of users.

4.3.2 Interview Question 2

The thematic analysis for interview question 2 is presented in Table 4.4.

Table 4.4: Interview Question 2 thematic analysis

Question intent	Question	Theme result	Sub-themes
To assess the condition of storage containers.	Describe the condition of the specific storage container as indicated in 3.1 (e.g., muddy, greenish, etc.)	Condition assessment of storage containers.	Physical condition of container
			Water quality concerns
			Maintenance practices

Interview question 2 in Table 4.4 reveals the storage condition of containers as the main theme, with three sub-themes related to how participants prepare their containers for harvesting rainwater.

In the words of participant number 4:

"*Greenish outside, and inside they are muddy on the bottom*"

Participant 8 indicated:

"*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*"

These sub-themes encompass the material and type of conveyance for HRW/storage containers, methods employed for container cleaning (including modern techniques to mitigate contaminants), and the assessment of water quality and conditions within the tank. This analysis triangulated well with the responses to question 3.3 of the quantitative survey, where respondents indicated a preference for frequent cleaning of their storage containers and proactive management practices.

The condition of storage containers significantly impacts the quality and safety of HRW. Issues such as algae growth, sediment accumulation, and physical degradation of container materials are common sources of water contamination (Heyworth *et al.* 2006: 1051). Research emphasises the importance of regular maintenance practices, including cleaning and disinfection, to prevent microbial growth and maintain water clarity (Issaka 2011: 45; Leong *et al.* 2017: 64; Joji and Jacob 2023: 20). Properly maintained containers not only reduce health risks associated with waterborne pathogens but also extend the lifespan of RWH systems (Fuentes-Galvan *et al*. 2018: 2). Effective container management is essential to ensure stored rainwater remains safe for consumption and other domestic uses.

4.3.3 Interview Question 3

The thematic analysis for interview question 3 is presented in Table 4.5.

Table 4.5: Interview Question 3 thematic analysis

Question intent	Question	Theme result	Sub-themes
To describe the surrounding environment of storage containers.	Describe the surrounding area where the specific storage container is stored (e.g., left outside and not covered).	Environmental factors affecting storage.	Location and exposure
			Safety and accessibility
			Environmental contaminants

As shown in Table 4.5, interview question 3 explored how storage containers are managed and the environmental conditions that optimise RWH without compromising water quality. The sub-theme emphasises the paramount importance of storage location and safety to participants. Some noted tank location and size influence the frequency of cleaning intervals. This triangulated well with the responses to question 3.1 of the quantitative survey, which focussed on the storage container types used for HRW. In households led by women, cleaning frequency tends to be lower due to difficulties accessing the storage tanks.

Additionally, some tanks are strategically placed in concealed and less accessible areas due to space constraints, safety considerations, where the roof gutter is installed, and aesthetic preferences. The environmental context in which storage containers are situated significantly influences water quality and safety. Containers exposed to external contaminants such as airborne dust, chemical residues from nearby industries, or animal waste are at higher risk of contamination (Duruibe, Ogwuegbu, and Egwurugwu 2007: 112). This is particularly notable in the rural Umkomaas community, which is situated near an industrial site (Healy 2023: 1).

Improper storage practices, such as leaving containers uncovered or in direct contact with soil, can lead to increased levels of pollutants in HRW (Duruibe *et al*. 2007: 112). Adequate site selection and protective measures, such as using covers or elevated stands, are crucial to minimise these risks and maintain water quality standards (Roy 2019: 201). Addressing these environmental factors is essential for ensuring the integrity of RWH systems and safeguarding public health (Bae *et al*. 2019: 407; Jongman and Korsten. 2016: 961).

4.3.4 Interview Question 4

The thematic analysis for interview question 4 is presented in Table 4.6.

Table 4.6: Interview Question 4 thematic analysis

Question intent	Question	Theme result	Sub-themes
To explore alternatives during prolonged periods without rainwater.	What happens when the harvested rainwater finishes and there is no rain for a long period of time?	Strategies for water scarcity.	Alternative water sources
			Community resilience
			Government interventions

Interview question 4 in Table 4.6 highlights the importance of alternative sources of water in the event of drought or other natural phenomena that might affect rainwater. Although some participants exhibited misunderstanding of the question asked, the theme of seeking alternative water sources during periods of prolonged drought or rainwater scarcity emerged prominently from the responses.

Participant 10 said the following:

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

The dependence on RWH during extended dry spells poses significant challenges to water availability and community resilience, particularly when communities have to resort to alternative water sources, such as Mkhomazi river, municipal supplies or boreholes, during prolonged droughts (Gwenzi and Nyamadzawo 2014: 574).

The accessibility and reliability of these alternatives may vary, however, impacting water security in rain-dependent regions. For example, municipal water supplies may incur financial costs for communities, particularly in rural areas, where access to such services can be limited or costly. Boreholes, while providing a reliable water source, require significant upfront investment and ongoing maintenance to ensure sustainable water supply. Therefore, effective water management strategies, including storage capacity expansion, rainwater conservation practices, and drought contingency planning, are critical to mitigate the impact of water scarcity events (Gwenzi *et al*. 2015: 111; Ziti *et al*. 2024: 1).

4.3.5 Interview Question 5

Thematic analysis for interview question 5 is presented in Table 4.7.

Table 4.7: Interview Question 5 thematic analysis

<table>
<tr><th>Question intent</th><th>Question</th><th>Theme result</th><th>Sub-themes</th></tr>
<tr><td rowspan="2">To identify seasonal patterns of sickness related to rainwater consumption.</td><td rowspan="2">What period of the year are the residents of your household susceptible to sickness?</td><td rowspan="2">Seasonal health impacts.</td><td>Health risks associated with rainwater</td></tr>
<tr><td>Seasonal variability in sickness</td></tr>
</table>

Interview question 5, as depicted in Table 4.7, aimed to identify seasonal patterns of sickness related to rainwater consumption. The theme revealed that participants attributed sicknesses to different seasons: some reported falling sick during Spring, others during Winter, due to water collection from rivers, while some participants did not specify seasonal impacts. This finding in the qualitative study triangulated well with the findings from question 5.1 of the quantitative study, which identified the frequency of people becoming sick within the community.

Seasonal variations in sickness related to rainwater consumption highlight the complex interplay between environmental factors and public health (Hamilton *et al* 2017: 289). The peak incidences of waterborne illnesses often coincide with seasonal weather patterns, such as heavy rainfall or dry spells (Dobrowsky *et al.* 2014: 1). Factors contributing to health risks include inadequate water treatment practices, improper storage conditions, and microbial pollution sources, such as animal waste or runoff from agricultural areas (Dobrowsky *et al*. 2014: 1). Understanding these seasonal vulnerabilities informs targeted public health interventions, such as improving water treatment methods, enhancing hygiene practices, and promoting community awareness of waterborne disease risks.

4.3.6 Interview Question 6

The thematic analysis for interview question 6 is presented in Table 4.8.

Table 4.8: Interview Question 6 thematic analysis

Question intent	Question	Theme result	Sub-themes
To assess perceptions of rainwater-related sickness and treatment practices.	Would you attribute the sickness indicated in 5.2 to be related to the harvested rainwater? Please elaborate.	Perceptions of water-related health risks.	Attribution of sickness to harvested rainwater
			Water treatment practices
			Awareness of health risks

As shown in Table 4.8, interview question 6 aimed to explore participants perceptions regarding rainwater-related sickness and their practices concerning water treatment. The findings revealed a strong association between sickness and the consumption of untreated HRW among participants. This triangulated well with the response to question 5.2 of the quantitative analysis, where respondents highlighted a high incidence of gastrointestinal sicknesses associated with consuming untreated HRW. These findings underscore the significant health risks posed by consuming raw rainwater, aligning with existing studies (Lee *et al.* 2017: 401; Leong *et al*. 2017: 64) that emphasise the unsuitability of untreated rainwater for potable purposes, due to contamination risks.

The qualitative insights, furthermore, provide valuable perspectives on participants' water treatment practices. Many indicated a reliance on traditional methods, such as chlorination or boiling, to mitigate potential health hazards associated with rainwater consumption and use. While these traditional methods offer some level of protection, they are not guaranteed fully. Boiling, for example, requires significant energy and time, and chlorination might not effectively eliminate all types of contaminants, particularly chemical pollutants (Raimondi *et al*. 2023: 11). Community reliance on these traditional methods highlights the community's struggle with access to more advanced and reliable water treatment technologies. This reliance on traditional methods, despite their limitations, points to a need for improved education on water safety and increased accessibility to more effective water treatment solutions.

4.3.7 Interview Question 7

The thematic analysis for interview question 7 is presented in Table 4.9.

Table 4.9: Interview Question 7 thematic analysis

Question intent	Question	Theme result	Sub-themes
To gauge comfort levels with the quality of harvested rainwater.	Do you feel comfortable and safe with the quality of the harvested rainwater?	Perceptions of water safety and quality.	Trust in water quality
			Factors influencing comfort levels
			Decision-making on water use

As evident in Table 4.9, interview question 7 reveals participant perceptions of the quality, safety, and comfortability of the HRW and the choice they could make for their well-being, in relation to HRW consumption. Most participants said they use untreated water, because they are left with no choice, since they have limited options for water supply.

According to participant 7:

"Yes, because we boil them before drinking"

Participant 14 explained:

No, I'm not comfortable because this harvested water is not healthy"

The structured interview, in a way, exposed the participants (in this case, inhabitants of the rural Umkomaas community) to safety and public health.

Public education campaigns on water treatment methods, health risks associated with untreated water, and alternative water sources play a vital role in promoting safe water practices and mitigating health hazards (Madhura *et al*. 2019: 68). In addition to traditional methods such as boiling, the application of nanotechnology in water treatment, discussed with some of the interviewees, represents a significant advancement in addressing contamination issues. Nanotechnology offers efficient removal of pathogens and chemical contaminants, providing a more reliable and sustainable solution for water purification (Westerhoff *et al.* 2016: 1241; Bhati and Rai 2017: 23429).

Other methods commonly used for treating HRW include ozonation (Ha *et al.* 2013: 1383), metal/chemical additives (Nawaz *et al.* 2012: 21), filtration (Kim, Lee, and Kim 2005: 121; Jordan *et al.* 2008: 209), and UV treatment (Jordan *et al*. 2008: 209), solar disinfection (SODIS) (Amin and Han 2009: 420; Strauss *et al.* 2016: 5225), as well as solar pasteurisation (Dobrowsky *et al.* 2015: 1). Although these novel technologies have produced varied degrees of treatment efficiency, their cost, ease of management, and water availability, among other factors, will be critical to their successful adoption (Hamilton *et al.* 2019: 7). When creating effective rainwater treatment plans for developing nations, it is imperative that these factors influencing the water supply quality are considered.

Some people in Africa, Asia, and South America utilise SODIS, which is thought to be an affordable and simple treatment method (McGuigan *et al.* 2012: 29). In its most basic version, transparent bottles containing tainted water are placed in direct sunlight for 6–48 hours. According to Nelson *et al.* (2018: 1089), UV light inactivates microbiological pollutants, by either reacting directly with the cellular components of the microorganisms or indirectly, by generating reactive oxygen species in the water, which also damages the cellular components. The cost of installation and maintenance is affected by the choice of rainwater treatment technique.

4.4 Systematic Literature Review Investigation

Following the analysis of the quantitative and qualitative data, key focus areas such as rainwater catchment surfaces, storage systems, treatment methods, and health effects emerged as core issues influencing RWH practices in the community. These areas guided the SLR process, which aimed to contextualise the study findings by exploring how they align with or diverge from existing research.

This review provides in-depth insights into the challenges and opportunities surrounding RWH, helping to inform practical solutions for improving water quality and health outcomes. The summary of the authors' contributions to the different focus areas is presented in Table 4.10.

Table 4.10: Summary of authors' contributions to different focus areas

	Focus areas			
Authors	Rainwater harvesting catchment surfaces	Harvested rainwater storage systems	Harvested rainwater treatment	Harvested rainwater health effects
Raimondi *et al*. (2023)	X		X	
Nwachukwu *et al*. (2024)		X		
Keithley *et al*. (2018)	X			X
Chaurasiya *et al*. (2019)		X		X
Bae *et al*. (2019)	X	X		
Jesmi *et al*. (2014)				X
Samuel, and Mathew (2015)	X		X	X
Tengan and Akoto (2022)	X			
Ahmed *et al*. (2017)	X			
Ahmed *et al*. (2014)		X		
Leong *et al*. (2017)				X
Sharma (2021)			X	
Zhang *et al*. (2021)		X		X
He *et al*. (2020)			X	
Fiorentino *et al*. (2021)			X	X
Nalwanga *et al*. (2018)	X			X
Martínez-García *et al*. (2022)			X	
Lee *et al*. (2017)			X	X
Zhang *et al.* (2023)			X	
Al-Batsh *et al*. (2019)				X
Igbinosa and Aighewi (2017)			X	X

Source: Researcher's own construction

4.4.1 Roof - RWH technology

The quality of rainwater collected on roofs is significantly influenced by various factors, such as roof material design, age, condition, and their interaction with weather conditions. Studies have identified several roofing materials, including clay tiles, concrete, polycarbonate plastic, and aluminium, as well as flat gravel roofs, and galvanised metal sheets, as contributors to elevated contaminant levels exceeding WHO standards for HRW (Farreny *et al*. 2011: 3247; WHO 2011). For example, John *et al*. (2021: 3) found elevated zinc concentrations in rainwater collected from asbestos cement roofs. This was further highlighted by Fuentes-Galvan *et al*. (2018: 2) and Farreny *et al*. (2011: 3245), who noted significant variations in water quality from roofs made of flat gravel, metal sheets, polycarbonate plastic, and clay tiles in urban Spain.

Metal sheet roofs have been associated with heavy metal pollution, whereas non-metal roofs tend to have higher concentrations of other metals compared to their metal counterparts. Studies have investigated metals such as cadmium, chromium, nickel, and selenium, although in less severe quantities (Mbua *et al*. 2024: 32; Anabtawi *et al*. 2022: 1). Biofilms can mitigate metal pollutants, though green roofs may increase microbial contamination, necessitating careful consideration for rainwater collection (Singh *et al*. 2022: 165).

Raimondi *et al*. (2023: 1) conducted a study with regard to RWH, treatment and management, highlighting SDG-connected RWH benefits and limitations. The study reviewed different methods to design a RWH system, its performance impact, and analysed the most advanced technologies for rainwater treatment. They stated the importance of using paint products approved for potable water during the design of RWH systems, and why lead, zinc, copper products, and wood that absorb moisture, should be avoided. Furthermore, gutters connected to RWH systems should have protective screens to filter large debris from entering the piping. Keithley *et al*. (2018: E1) explored treatment effects on rainwater quality in urban Texas, finding differing microbial levels between green and conventional roofs.

Bae *et al*. (2019: 408) conducted experimental investigations over a two-year period to assess the impact of roofing materials on HRW quality. They found microbial contamination levels in HRW varied significantly, depending on the type of roof material used, highlighting potential health risks associated with untreated HRW. Tengan and Akoto (2022: 2) investigated the physicochemical and bacteriological parameters of roof runoff in Ghana, focusing on the influence of roofing materials on HRW quality. They observed elevated levels of heavy metals, E. coli, and faecal coliforms in rainwater collected from roofs made of aluminium, galvanised zinc metal, and asbestos, exceeding WHO standards for drinking water. Their findings underscore the critical importance of proper treatment and management practices to ensure the safety of HRW for human consumption.

Ahmed *et al.* (2017: 326) conducted a study in Australia assessing bacterial communities in HRW storage tanks. They found a high prevalence of bird faecal contaminants and other opportunistic pathogens in tanks used for drinking water storage. The study concluded most contaminants in HRW originate from roof surfaces, air pollutants, and micro-organisms from bird, insect, bat, and marsupial faeces, as well as debris in roof conveyance systems or gutters. These findings were corroborated by similar research conducted by Al-Khatib *et al.* (2019: 1).

Regular roof surface cleaning and optimising solar exposure can reduce microbial contamination. Cleaning involves removing accumulated debris, such as tree litter and animal droppings, which can introduce organic matter and pathogens to HRW. Proper cleaning schedules and methods are essential to maintain water quality over time (Nalwanga *et al.* 2018: 3648).

These studies collectively highlight the diverse methodologies and technologies in RWH, emphasising the intricate relationship between roofing materials, environmental factors, and water quality. Effective management strategies, including regular maintenance, appropriate treatment, and careful selection of materials, have been identified as crucial for mitigating risks and ensuring safe water provision. The importance of appropriate filtration and storage techniques is also stressed, in order to maintain water quality and maximise harvesting efficiency.

4.4.2 Rainwater storage systems

Ahmed *et al.* (2014: 361) investigated opportunistic pathogens (OP) in roof-captured rainwater samples from 72 storage tanks in Australia. They found a significant microbial burden in HRW due to these pathogens, correlating with bacterial indicator levels in each tank. These authors emphasised the need for regular quantitative microbial risk assessments to assess public health risks associated with these pathogens.

Nwachukwu, Ihenetu, and Obasi (2024: 2) evaluated the effect of different storage vessels on physicochemical and microbiological characteristics of rooftop HRW in Owerri Nigeria. In this study, 24 storage vessels were used (plastic container, metal tank, earthen ware pot, and block/cemented tank). The HRW was stored in the storage vessels and after some days, it was observed the storage vessel had more microbial impact on the stored rainwater samples. According to Nwachukwu *et al.* (2024: 2), six bacterial and mould organisms were isolated from the stored rainwater samples, and the bacterial organisms revealed plasmid possessed E.coli, P. aeruginosa, and Enterobacter sp., which made them resistant to antibacterial drugs. Similarly, Zhang *et al.* (2021: 4) compared opportunistic pathogen growth dynamics in harvested rainwater storage systems (HRWSS) and tap water storage systems (TWSS). They found HRWSS more susceptible to microbial growth, with storage materials such as Poly Vinyl Chloride (PVC), stainless steel, and Portland cement significantly influencing microbial load.

In India, Chaurasiya *et al.* (2019: 6) designed a semi-automated machine for storage tank cleaning. They emphasised the necessity for regular cleaning, because after a period of storing water in a tank, sediments, scales and algae are deposited in the storage tanks, which contaminates the water and makes it non-potable. These authors explain the machine was designed to promote regular cleaning, hence, it is light-weight, user friendly, and does not require the use of chemicals during cleaning.

These studies emphasise the critical role of storage conditions and materials on HRW quality. Regular assessment and proper management of storage systems are essential to mitigate health risks from microbial contamination. Furthermore, advancements in treatment technologies, along with the significance of regular maintenance and proper sanitation are necessary, to ensure the integrity and safety of stored rainwater.

4.4.3 Rainwater treatment

He *et al.* (2020: 1) conducted a study on conventional drinking water treatment technologies for surface and groundwater, focusing on the removal of dissolved organic matter and the subsequent reduction of DBPs during disinfection. They evaluated the effectiveness of these treatments in removing CX3R-type DBP precursors from rainwater and reducing the formation and toxicity of DBPs such as trihalomethanes, halo-aldehydes, haloacetonitriles, and haloacetamides during the chloramination process. The results indicated both sand filtration (SF) and granular activated carbon (GAC) effectively removed DBP precursors, with GAC outperforming SF. Conversely, no DBP precursor removal was observed during coagulation-sedimentation treatment (Surendhiran *et al*. 2017: 374).

Nalwanga *et al*. (2018: 3648) reported on a study in a rural settlement in Southern Uganda, where the quality of HRW was investigated over 12 months, using solar water disinfection technology. Their findings, based on 50 households using rooftop HRW and various storage systems, indicated while HRW generally met drinking water standards, many samples showed elevated levels of microbiological contamination, rendering the water unsafe for drinking without treatment. The study concluded that applying solar reactors could mitigate health risks associated with untreated HRW. Similarly, Martínez-García *et al*. (2022: 1) reported on using solar disinfection reactors for rainwater treatment in rural SSA communities. Their studies in Uganda and Spain demonstrated effective microbial and bacterial load reduction in HRW, supporting its potential as a safe drinking water source, underscoring the importance of continuous monitoring and technological innovation in rainwater management practices.

Fiorentino *et al*. (2021: 1) further explored advanced treatment methods for roof-HRW in Italy, using nanotechnology through solar photo Fenton (SPF) processes, including solar-driven advanced oxidation processes (SODAOP), sunlight/peroxide, and sunlight/chlorine (SCL) for disinfection. The study compared these methods with conventional disinfection processes, such as chlorination and UV-C radiation, finding SPF and SCL were more effective in reducing microbial loads in roof-HRW. This study underscores the potential of advanced treatment technologies in improving water safety.

Sharma (2021: 3) reviewed four methods through which nanotechnology can be applied in water purification purposes; Nanomembranes, Nanofiltration, Nanofabrication, and Adsorption (nanomaterials). Nanomembranes are modified with nanofibers and are used for pre-treatment. Nanofiltration is used for drinking water production, because it eliminates contaminants from ground and surface water, softens hard water, as well as removes micropollutants, and microorganisms. Nanofabrication involves nanomaterials to be fabricated using two basic methods, bottom-up or top-down, in treatment units. The use of nanomaterials as adsorbents such as Metal Nanoparticles (Silver Nanoparticles and Iron Nanoparticles), Metal Oxide Nanoparticles (Titanium oxide Nanoparticles [TiO2 NPs], Zinc Oxide Nanoparticles [ZnO NPs]), and Iron Oxide Nanoparticles, as well as Carbon Nanotubes (CNT), Nanocomposites, and Dendrimers. Despite risks associated with nanomaterials, due to high reactivity, using nanotechnology in water purification presents no problems related to human health and environment, as reported by Sharma (2021: 5).

Samuel and Mathew (2015: 114) designed, developed and evaluated a drinking water filtration mechanism for roof-RWH systems with low initial expenditure, zero power needed, no maintenance cost and self-dependent operation. This study employed the use of natural resources such as sand and gravel, three forms of charcoals, which acted as adsorbents, viz, (coconut) shell charcoal, wood charcoal and anthracite, to test as filter media. Similarly, Zhang *et al.* (2023: 5) developed a TpPa-wood nanofiltration membrane through the natural state of massive covalent organic frameworks (COFs) that effectively removed organic pollutants from water. The efficiency of the TpPa-wood membrane is high, at 97 percent, with a treatment rate of 600 L m^{-2} h^{-1}. The success rate was achieved due to inherent micropores of the synthesised COFs, chemical interaction between COFs and cellulose in wood, mechanical characteristics of wood, and low-tortuous wood channels.

Overall, these studies underline the importance of effective treatment and regular monitoring of rainwater intended for consumption. They highlight the significant role of filtration methods and the potential health risks associated with untreated HRW. Despite meeting some drinking water standards, HRW often requires additional treatment to ensure safety, particularly in rural areas. Innovations in solar water disinfection and nanotechnology offer promising advancements for improving HRW quality and highlight the need for continuous improvement in water treatment technologies.

4.4.4 Rainwater Health Effects

Lee *et al.* (2017: 400) conducted a case study in rural Vietnam to assess the quality parameters of HRW for drinking purposes. They analysed 23 samples from two HRW systems and found, while all samples met standard water quality parameters, microorganisms were detected in HRW not treated with ultraviolet (UV) light. Post-UV sterilisation analysis revealed no traces of microorganisms, leading to the conclusion that UV sterilisation is highly effective but potentially cost-prohibitive for rural areas, particularly in SSA. Similarly, Leong *et al*. (2017: 64) performed a longitudinal assessment of HRW quality under tropical climatic conditions. Their findings indicated, while HRW generally met water quality standards, microbial analysis and some physicochemical parameters, such as ammonia and pH, were exceptions. The study emphasised the necessity of disinfection strategies before HRW can be safely used for potable purposes, highlighting that consuming untreated HRW poses health risks. Furthermore, the study revealed HRW collected during the wet season had higher concentrations of suspended solids, turbidity, and microbial loads than during the dry season, suggesting seasonal variations significantly impact water quality.

Al-Batsh *et al*. (2019: 585) evaluated the quality of HRW in the Yatta area of Palestine, as part of a project by the U.S. National Academy of Sciences supported by the Partnerships for Enhanced Engagement in Research (PEER) programme. They concluded, even though the water's physicochemical quality met the country's drinking water standards, 99 percent collected water samples were contaminated with total coliforms and 52 percent with faecal coliforms. The study emphasised consuming untreated water could lead to significant health issues, highlighting the global nature of this concern.

Jesmi *et al*. (2014: 4) explored the bacterial and chemical characteristics of rooftop-HRW stored in ferrocement tanks in underdeveloped nations. They found, whereas most physicochemical parameters were within WHO recommendations, bacterial analyses indicated 50 percent samples did not meet bacteriological quality standards for drinking water. E. coli was found in 50 percent rainwater samples from rural and urban communities and 20 percent from individual households. The study also noted bacterial isolates exhibited strong resistance to multiple antibiotics, posing additional health risks.

Igbinosa and Aighewi (2017: 3) assessed the quality of rooftop-HRW in Ugbihioko, Nigeria, comparing their findings against WHO drinking water standards. They found, although temperature met WHO criteria, pH, turbidity, sulfate, and chloride, as well as nitrate concentrations varied widely and often fell short of standards. Heavy metals, such as copper and iron, exceeded the maximum allowable concentrations, while electrical conductivity, sodium, and potassium remained below. The presence of selenium and lead in some samples highlighted further health concerns.

These studies draw attention to the significant health risks associated with untreated HRW. The authors identified waterborne diseases and microbial contamination as primary concerns, accentuating the importance of water quality testing and hygiene education. A common theme across these findings is the necessity of implementing effective treatment methods and regular monitoring to ensure water safety for consumption. Whether through advanced disinfection technologies, for example, nanotechnology and solar reactors, or conventional methods, such as chlorination, addressing these microbial and chemical contaminants in HRW is crucial. Collectively, these studies emphasise the global nature of this issue and the urgent need for sustainable solutions to ensure safe drinking water, particularly in rural and underdeveloped regions.

4.6 Chapter Summary

This chapter presented an analysis of the study conducted on HRW across the different residents who harvest rainwater, in the rural Umkomaas communities of the KZN province of SA. The chapter further discussed the results of the quantitative survey and qualitative study, the triangulation of the quantitative and qualitative results, and the main themes generated. A SLR was carried out on the main themes generated from the study. The study is summarised in the next chapter, with recommendations offered, along with a proposed nanotechnology-based filtration process developed in response to the study aim and objective, and the study limitations outlined, with future research topics proposed.

CHAPTER FIVE - SUMMARY, RECOMMENDATIONS AND CONCLUSIONS

5.1 Introduction

This chapter discusses the main research findings of this study and draws inferences concerning its objectives. Additionally, it offers recommendations, outlines the study limitations, and suggests directions for future research. The importance of this study lies in its potential to provide sustainable solutions for water scarcity in rural communities. By addressing the quality of HRW through nanotechnology, this research contributes to improving the safety and usability of rainwater for household purposes. It highlights the necessity of efficient and effective RWH and storage methods to ensure a reliable and safe water supply.

5.2 Summary of Research Objectives

The research was guided by the following objectives:

- To examine the current RWH processes in the selected rural Umkomaas community through a survey.
- To conduct interviews exploring how current RWH practices identified in the survey affect the daily living conditions and health perceptions among residents in the rural Umkomaas community.
- To investigate the role of nanotechnology in wastewater treatment and to identify the various elements to be considered for improving HRW quality.
- To propose a process using nanotechnology to improve the quality of HRW.

Objectives 1 and 2 were fulfilled through a combination of survey data and interviews investigating current RWH practices in the rural Umkomaas community. Chapter 4 presented detailed findings from these efforts, offering insights into prevalent methods, challenges, and resident preferences. The combination of quantitative survey data and qualitative interview insights provided a comprehensive understanding of how these practices influence daily living conditions and health perceptions.

Objective 3 focused on exploring the role of nanotechnology in improving rainwater quality, particularly in wastewater treatment. This part of the investigation drew on a comprehensive literature review to identify potential advancements in rainwater treatment methods, highlighting key insights derived from expert perspectives.

Last, Objective 4 involved the development of a proposal outlining a nanotechnology-driven process to enhance HRW quality in rural Umkomaas. This proposal integrated findings from both qualitative and quantitative research, as well as insights from the literature review and best practices benchmarking.

5.3 Summary of Key Findings

It was established from the empirical results that roof harvesting techniques are widely adopted in the rural Umkomaas community due to their familiarity, ease of implementation, and the availability of materials, with metal roofing materials favoured for perceived cleanliness. Plastic tanks are commonly used for rainwater storage, with cleaning intervals varying among users, highlighting diverse maintenance practices. Storage conditions were identified as crucial for safeguarding water quality, with challenges such as algae growth and sediment accumulation pointed out. Concerns regarding the shelf life of HRW underlined the necessity for improved storage practices. Rainwater serves various household needs, including cleaning, cooking, and drinking, although some households expressed hesitancy, due to perceived water quality issues.

The high frequency of reported illnesses, such as abdominal pains and diarrhoea, is linked to suspected water quality issues, emphasising the health risks associated with untreated rainwater consumption. The community consensus stressed the urgency of improving water treatment strategies due to concerns over potential health impacts linked to consuming untreated rainwater. The quantitative and qualitative results were triangulated across five key areas: type of roofing material, frequency of cleaning storage containers, type of storage containers, and frequency of illness, as well as illnesses associated with drinking untreated HRW. These findings, identified as the primary challenges with RWH, were corroborated by the literature review (Matimolane *et al*. 2023: 277; Mbua *et al*. 2024: 32). They highlight the critical need for a comprehensive understanding of RWH practices, household dynamics, and health implications to promote sustainable water management in rural communities. Efforts to enhance public health education and explore alternative water treatment methods are essential to address these challenges effectively.

The findings from the literature review established that nanotechnology possesses excellent adsorption properties, enhanced photocatalysis, and high reactivity, making it highly effective for wastewater treatment. These properties have enabled organisations to achieve a sustainable level of water quality, contributing significantly to environmental protection and economic development. Various nanotechnological techniques for wastewater treatment include adsorption, membrane separation processes, application of nanomaterials, and photocatalysis, often used in combination for optimal purification (Yaqoob *et al*. 2020: 495). For this study, the membrane separation technique, specifically nanofiltration, is considered, due to its suitability for both domestic and industrial water treatment needs. Nanofiltration involves passing a fluid through a membrane that acts as a sieve to separate impurities (Carbotecnia 2022: 3).

The benefits of nanofiltration include its high effectiveness in removing bacteria and viruses, low operating pressure, energy, and cost requirements, as well as the absence of salts or chemicals for optimal operation, and its ability to reduce heavy metals, sulfates, nitrates, and other contaminants (Schweitzer and Noblet 2018: 261). Additionally, nanofiltration can soften hard water with specific softening membranes, in addition to reducing color, turbidity, and tannins in water. However, the limitations of nanofiltration include its high cost and susceptibility to fouling, which can impede performance and increase maintenance requirements. The systematic review confirms, with proper management strategies, rainwater can be effectively harvested and stored without compromising its quality. In cases where HRW quality is compromised, scientific and technological treatments such as nanotechnology can significantly enhance its purification for safe consumption.

5.4 Recommendations

Based on the empirical findings and literature review, the following recommendations are proposed to enhance RWH practices and improve water quality in the rural Umkomaas community:

- Enhanced storage practices: implementing improved storage practices involves transitioning from traditional methods such as buckets and open containers/tanks, to using large plastic tanks. These tanks should be designed to withstand environmental conditions and minimise contamination risks (Nwachukwu *et al.* 2024: 2). For instance, in rural Umkomaas, where algae growth and sediment accumulation are prevalent due to high temperatures, proper covering and placement in shaded, clean environments are crucial. Education programmes can teach residents about the importance of these practices, demonstrating through workshops and guides how to maintain tanks effectively.
- Timely use and management of HRW: encouraging timely use of HRW is essential to maintain water quality and prevent health risks associated with prolonged storage. Implementing monitoring systems can track water storage durations and conditions. For instance, using standardised protocols by marking all storage containers with the date of water collection and using charts or calendars to help families easily track storage durations. This will ensure water is consumed within safe storage timeframes, reducing the risk of contamination, as highlighted by Chaurasiya *et al.* (2019: 6). Educational campaigns can raise awareness on the importance of rotating stored water regularly.
- Promotion of hygienic practices: educational workshops and materials can effectively highlight the importance of hygienic RWH practices. Ensuring cleanliness during both the collection and storage processes is essential for maintaining high water quality (Zdeb and Papciak 2023: 2). Local health clinics can complement these efforts by providing guidance on waterborne diseases and associated symptoms, thereby reinforcing the significance of safe water practices. Integrating hygiene promotion into existing health programmes and community events can foster sustainable behaviour change among residents.

  Additionally, involving community leaders, such as the Induna (traditional community elder), can amplify these messages and further encourage positive behavioural shifts within the community. Partnerships with local schools or community centres can, furthermore, facilitate educational events, where residents can learn about water treatment methods. This can be done using practical demonstrations and case studies; particularly effective in illustrating the benefits of these practices to the community. Moreover, utilising municipal channels, local publications, and community forums will ensure wide dissemination of this vital information. By empowering the rural Umkomaas community with the necessary knowledge and skills, sustainable water management practices can become integrated into their everyday life.

- Government support and sustainable solutions: collaborating with the Umdoni municipality to incorporate RWH infrastructure into rural development plans is crucial for ensuring long-term sustainability (Umdoni Municipality 2022: 92). To initiate this process, securing government funding for the purchase and distribution of large water storage tanks is essential. This investment will significantly improve RWH efforts in rural Umkomaas. Furthermore, local government support can possibly be extended through subsidies or tax incentives, which will encourage households to upgrade their storage infrastructure. Additionally, municipal sponsorship or financial support mechanisms can lower barriers to accessing advanced water treatment technologies. For example, partnerships with NGOs or the private sector can provide grants or subsidies for purchasing nanotechnology-based water treatment methods, such as nanofiltration equipment. Public-private partnerships (PPPs) can also offer technical expertise and maintenance support to ensure the sustainability of water treatment systems. By making these technologies financially viable and operationally sustainable, communities can benefit from improved water quality and enhanced water security.
- Adoption of nanofiltration technology: introducing nanofiltration technology represents a significant leap forward in enhancing water purification capabilities within rural Umkomaas and neighbouring communities. Nanofiltration systems can remove a wide range of contaminants, such as bacteria, viruses, heavy metals, and nitrates from HRW, thus ensuring it meets safe drinking water standards (Li and Mitch 2018: 1687; Sharma 2021: 2). Since integrating these systems into local water treatment infrastructure would require careful planning and investment in equipment, maintenance, and operator training, partnerships with universities or research institutions can facilitate pilot projects to demonstrate the effectiveness of nanofiltration in local conditions. These initiatives will enhance water safety and build community trust and acceptance of advanced water treatment methods.

5.5 Proposed nanotechnology-based filtration process

Based on the research findings it is evident, while RWH is a crucial practice in rural communities to address water scarcity, a significant gap remains in the adoption of advanced filtration technologies to ensure water quality and safety. This study, therefore, proposes a simple and cost-effective nanotechnology-based filtration system that utilises an effective membrane separation technique for water decontamination. The proposed process, as illustrated in Figure 5.1 (adapted from Yulistyorini *et al*. 2018: 2; Zdeb and Papciak 2023: 2), incorporates nanofiltration membranes at both the inlet and outlet of the rainwater storage tank to ensure comprehensive removal of contaminants.

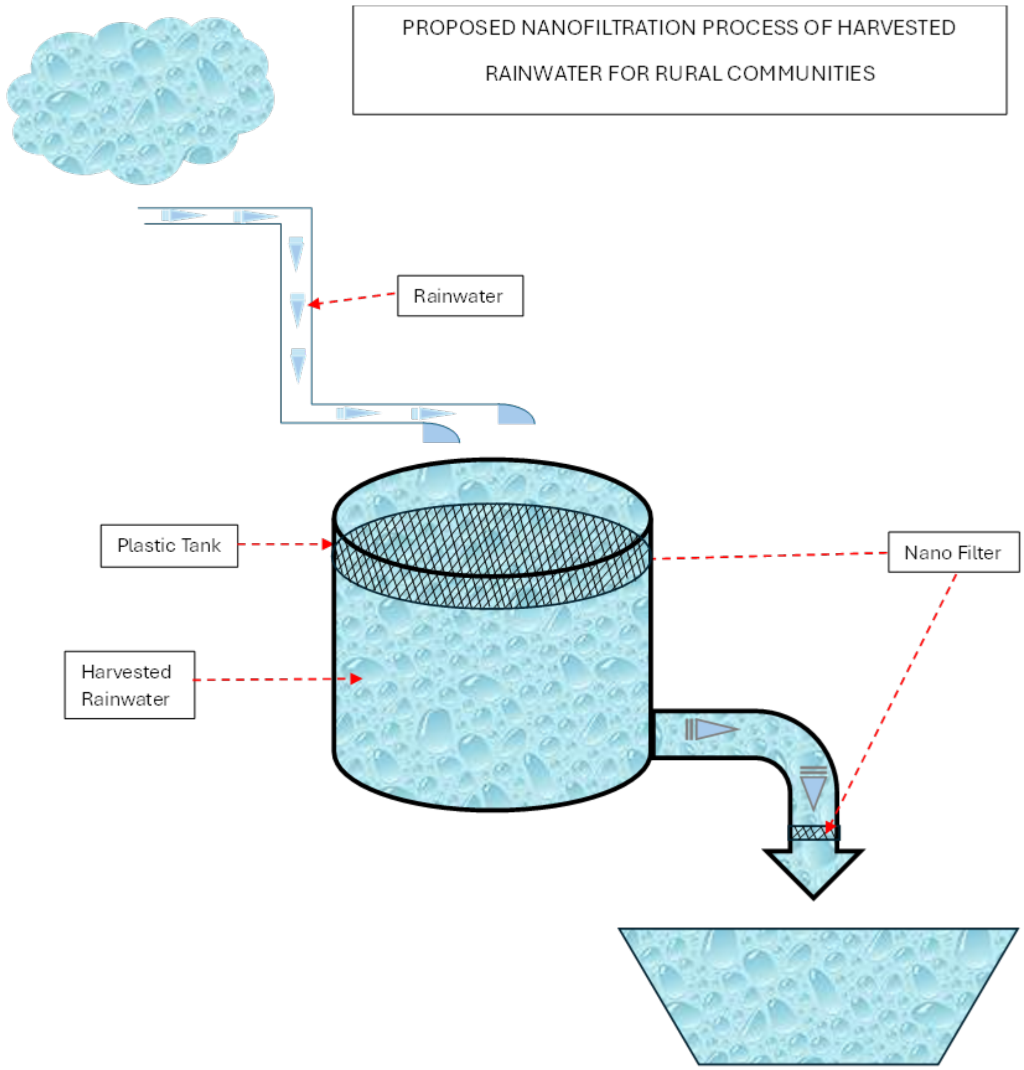

Figure 5.1: Proposed nanofiltration process

Source: Authors own construction

- Filtration process and mechanism - in the proposed system depicted in Figure 5.1, rainwater collected from a catchment area flows through a piping channel into a plastic storage tank. At the tank's inlet, a nanofiltration membrane is installed to capture a wide range of contaminants, including debris, bacteria, pesticides, heavy metals such as copper, and dissolved chemicals such as fluoride (Westerhoff *et al.* 2016: 1241). The pre-filtration process is essential for ensuring these pollutants do not enter the storage tank, where they could degrade the water quality over time. A second nanofiltration membrane is installed at the tank outlet to remove any residual contaminants that may have entered the tank or developed during storage.

The proposed nanofiltration membranes must be installed neatly and securely to the storage tank, as illustrated in Figure 5.1, to ensure optimal performance and effective usage (Samuel and Mathew 2015: 109). By incorporating filters at both the in- and outlet, the system reduces the risk of fouling, a common issue in filtration systems where contaminants accumulate on the membrane surface, leading to clogging and reduced filtration efficiency (Yildirim *et al*. 2022: 2). This dual filtration approach serves as a quality control mechanism to maintain water integrity by addressing two primary concerns: (1) contamination during storage, and (2) microbial growth, which can occur over extended periods. The system thus ensures water drawn from storage remains safe for household use, even after long-term storage.

- Wood-based nanofiltration membrane **-** an important element in this filtration system is the use of wood as the primary material for the nanofiltration membranes. Wood is selected due to its unique material properties, which make it particularly well-suited for use in water filtration applications. According to Zhang *et al*. (2023: 2), wood exhibits high hydrophilicity, meaning it has a strong affinity for water. This characteristic enhances the efficiency of water transport through the membrane, as hydrophilic materials tend to facilitate smoother water flow across their surfaces. These authors further explained wood is composed of numerous hollow cells that are interconnected endwise, forming long channels with low tortuosity (that is, low curvature or winding). The channels provide direct pathways for water flow, allowing for rapid water transport through the membrane. The low-tortuosity channels are particularly advantageous in filtration systems, because they minimise the resistance to water flow, enabling high filtration rates without compromising the removal of contaminants.
- Nanofiltration pore size and contaminant removal - to ensure the filtration system meets the necessary water purification standards, the proposed wooden nanofiltration membranes must be engineered to achieve pore sizes within the 0.001 to 0.01 μm range, as indicated by Pandey and Dahiya (2016: 19-20). This pore size is critical for the effective removal of contaminants at the nanoscale. Membranes with pores in this range can block bacteria, viruses, and various chemical pollutants, while still allowing the passage of clean water.

5.6 Limitations

Some limitations that surfaced through the study include:

- The study was conducted in a selected community, hence there may be traditional practices and preferences observed that may not be applicable to all rural communities.
- The proposed nanotechnology-based filtration process was not tested within this study.
- There was a low level of awareness among rural Umkomaas communities with regard to water treatment processes and technologies.
- The timing of data collection could possibly influence the results, as changes in practices or environmental conditions over time might affect the relevance and applicability of the findings.

5.7 Future Work

Future work can focus on the following areas:

- Conducting similar studies in different rural communities to understand the extent of how RWH is practiced.
- Developing and implementing targeted educational programmes in rural areas to raise awareness on water treatment processes and the potential benefits of nanotechnology.
- Performing practical trials and assessments of affordable nanotechnology-based filtration systems in real-world environments to validate their effectiveness and feasibility.
- Contributing to the formulation of regulatory frameworks and policies that facilitate nanotechnology integration into sustainable water management practices at local and national levels.

5.8 Conclusion

The study has demonstrated the potential of nanotechnology, particularly nanofiltration, to improve the quality of HRW in the rural Umkomaas community. By addressing the challenges associated with current RWH practices and proposing a nanotechnology-based filtration process, this research contributes to sustainable water management solutions in rural areas. Implementing the recommendations outlined in this chapter can enhance water quality, promote public health, and ensure a reliable water supply for the community. Moreover, efforts to secure innovative funding and establish collaborative partnerships will be essential in ensuring the scalability and long-term sustainability of nanotechnology solutions in resource-constrained environments. In conclusion, while this study provides valuable insights into the potential of nanotechnology in enhancing rainwater quality, ongoing efforts are needed to translate research findings into practical solutions that benefit communities and contribute to global water sustainability goals.

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APPENDICES

Appendix A: Ethical Clearance Certificate

TRREE

Zertifikat

Certificado

Certificat

Certificate

Promouvoir les plus hauts standards éthiques dans la protection des participants à la recherche biomédicale
Promoting the highest ethical standards in the protection of biomedical research participants

Clinical Trials Centre
The University of Hong Kong

Certificat de formation - Training Certificate

Ce document atteste que - this document certifies that

Blessing George Akpan

a complété avec succès - has successfully completed

Introduction to Research Ethics

du programme de formation TRREE en évaluation éthique de la recherche
of the TRREE training programme in research ethics evaluation

Release Date: 2021/04/27
CID : Quou0vxEMR

Professeur Dominique Sprumont
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[REV : 20170310]

Appendix B: IREC Approval

Institutional Research Ethics Committee
Research and Postgraduate Support Directorate
2nd Floor, Berwyn Court
Gate 1, Steve Biko Campus
Durban University of Technology

P O Box 1334, Durban, South Africa, 4001

Tel: 031 373 2375
Email: lavishad@dut.ac.za
http://www.dut.ac.za/research/institutional_research_ethics

www.dut.ac.za

27 March 2023

Ms B G Akpan
P.O. Box 2638 Country club
Mount Edgecombe
Durban

Dear Ms Akpan

The application of nanotechnology to improve the quality of harvested rainwater in a selected rural community
Ethical Clearance number IREC 157/21

The DUT-Institutional Research Ethics Committee acknowledges receipt of your notification regarding the piloting of your data collection tool.

Kindly ensure that participants used for the pilot study are not part of the main study.

In addition, the DUT-IREC acknowledges receipt of your gatekeeper permission letter.

Please note that FULL APPROVAL is granted to your research proposal. You may proceed with data collection.

Any adverse events [serious or minor] which occur in connection with this study and/or which may alter its ethical consideration must be reported to the DUT-IREC according to the DUT-IREC SOP's.

Please note that any deviations from the approved proposal require the approval of the DUT-IREC as outlined in the DUT-IREC SOP's.

It is compulsory for a student or researcher to apply for recertification on an annual basis. The failure to do so will result in withdrawal of ethics clearance. It is the responsibility of the researcher and the supervisor to apply for recertification.

Please note that you are required to submit a Notification of Completion of Study form together with an abstract to the DUT-IREC office on completion of your study.

Yours Sincerely

Prof J K Adam
Chairperson: DUT-IREC

ENVISION2030 transparency • honesty • integrity • respect • accountability
fairness • professionalism • commitment • compassion • excellence

Appendix C: Gatekeepers Letter

Appendix B
Gatekeeper's permission

DUT DURBAN UNIVERSITY OF TECHNOLOGY

Date: 2022-01-28

The Nduna,
Umkomaas community

RE: CONSENT TO CONDUCT RESEARCH IN UMKOMAAS, KWAZULU-NATAL

Dear Sir,

I am Blessing Akpan, a master's degree student in Operations and Quality Management department, Durban University of Technology. I am conducting a research for my Masters dissertation and the study is aimed at improving the quality of harvested rainwater in Umkomaas, KwaZulu Natal.

I hereby seek your consent to conduct research using Umkomaas community as case study. It will be a peaceful exercise where the residents will voluntarily answer some questions that are relevant to the study. The input towards the research would add value to this study and the findings might be beneficial to the community in the aspect of treating stored rainwater before use.

Thank you in advance and I look forward to a favorable response from you. Please feel free to contact me or my research supervisor if you require further information.

Researcher
Blessing Akpan
+27 60 373 5168
22063681@dut4life.ac.za

Research Supervisor
Dr R. Rathilall
084 457 7265
raveenrzn@googlemail.com

Approval By the Nduna

I MUZIWAKHE NGIDI... hereby confirm that I understand the contents of this document and the nature of the research project.

I hereby grant consent to Blessing Akpan (Student Number: 22063681) to conduct research in Umkomaas local municipality of KwaZulu-Natal.

SIGNATURE

DATE & STAMP

ZEMBENI TRIBAL AUTHORITY
AMAH[illegible]
INDUNA M.D. NGIDI
CELL: 083 593 0211
17-10-2022

Appendix D: Letter of Information (English)

LETTER OF INFORMATION

Title of the Research Study:

The application of nanotechnology to improve the quality of harvested rainwater in a selected rural community

Principal Investigator/s/researcher:

Blessing George Akpan (BTech)

Co-Investigator/s/supervisor/s:

Dr Raveen Rathilall (DTech)

Purpose of the Study:

Umkomaas is a rural community in KwaZulu Natal with the poor, who don't have full access to pipe borne water provided by the government. They store, use and drink harvested rainwater. This study is aimed at using nanotechnology to improve the quality of harvested rainwater for the residents of Umkomaas.

Taking part in this study involves participating in a survey with the researcher or research assistant. The participants are purposively selected, an average of 25 minutes will be required for the questionnaire. The researcher or a research assistant will be available to explain the questionnaire to you if you are unsure of anything.

There is no financial benefit or remuneration for you, but the benefit is tied to the findings of the study, which is aimed to improve the quality of stored rainwater and make it suitable for human consumption in Umkomaas. For the researcher, the benefit will be the satisfaction derived from solving a problem, an academic qualification and publication.

There is no risk or discomfort to you in this study.

The research is voluntary; you are allowed to withdraw from the study at any time if you feel uncomfortable with the questions during the interview process. There will be no adverse consequences to you should you choose to withdraw.

There will be no monetary reward to you as a result of participating in this research.

There will be no costs to you as a result of taking part in this research study.

The records from this study will be kept as confidential as possible. No individual identities will be used in any reports or publications resulting from this study. All transcripts and summaries will be given codes and stored separately from any names or other direct identification of participants. Research information

will be always kept in locked files. Only research personnel will have access to the files and only those with an essential need to see names will have access to that particular file.

Persons to Contact in the Event of Any Problems or Queries:

Please contact the researcher on 060 373 5168, the supervisor on 084 457 7265 or the Institutional Research Ethics Administrator on 031 373 2375. Complaints can be reported to the Acting Director: Research and Postgraduate Support Prof K Motaung on ttidirector@dut.ac.za

Appendix E: Letter of Consent (English)

DUT DURBAN UNIVERSITY OF TECHNOLOGY | INSTITUTIONAL RESEARCH ETHICS COMMITTEE

CONSENT

Statement of Agreement to Participate in the Research Study:

- I hereby confirm that I have been informed by the researcher, Blessing G. Akpan about the nature, conduct, benefits and risks of this study - Research Ethics Clearance Number: IREC 157/21,
- I have also received, read and understood the above written information (Participant Letter of Information) regarding the study.
- I am aware that the results of the study, including personal details regarding my sex, age, date of birth, initials and diagnosis will be anonymously processed into a study report.
- In view of the requirements of research, I agree that the data collected during this study can be processed in a computerised system by the researcher.
- I may, at any stage, without prejudice, withdraw my consent and participation in the study.
- I have had sufficient opportunity to ask questions and (of my own free will) declare myself prepared to participate in the study.
- I understand that significant new findings developed during the course of this research which may relate to my participation will be made available to me.

______________________ __________ ______ ________________

Full Name of Participant **Date** **Time** **Signature / Right Thumbprint**

I, Blessing G. Akpan herewith confirm that the above participant has been fully informed about the nature, conduct and risks of the above study.

__________________ __________ __________________

Full Name of Researcher **Date** **Signature**

__________________ __________ __________________

Full Name of Witness (If applicable) **Date** **Signature**

__________________ __________ __________________

Full Name of Legal Guardian (If applicable) Date **Signature**

Appendix F: Survey Questionnaire (English)

QUESTIONNAIRE

THE APPLICATION OF NANOTECHNOLOGY TO IMPROVE THE QUALITY OF HARVESTED RAINWATER IN A SELECTED RURAL COMMUNITY

Date: 2020/05/28

Faculty of Management Sciences
Department of Operations and Quality Management

Dear Participant,

I am Blessing Akpan, a Master's degree student in Operations and Quality Management department at Durban University of Technology. I am conducting a research for my dissertation on "The application of nanotechnology to improve the quality of harvested rainwater in a selected rural community''.

In this regard, I am asking for 25 minutes of your time, and effort to answer all the questions in the questionnaire that are important and helpful for the completion of the study. The information provided will be used solely for research purposes and I want you to be rest assured that all data gathered from you will be kept in the highest level of confidentiality.

Your participation in this research is voluntary and there will be no adverse consequences if you choose to withdraw your participation from the study.

Your positive response in this request will be of valuable contribution for the success of the study and will be highly appreciated.

Thank you in advance and I look forward to a favourable response from you. Please feel free to contact me if you require further information.

……………………….

Blessing Akpan
0603735168

Please complete the following as a confirmation of your willingness to participate in the research:

I ……………………………………………, have discussed the study with the researcher and I understand that my participation is voluntary and I may withdraw from the study at any time. I hereby agree to participate in the study by completing the attached questionnaire/interview questions.

………………………………….. ……………………………

SIGNATURE DATE

You can mark the appropriate response with a tick or cross

PART 1 - BIOGRAPHICAL SECTION

1.1 How many people live in your house?

1 - 2 People	
3 - 5 People	
≥ 6	

1.2 Indicate the range of the ages of the people living in this house

	1	2	3	4	5	5+
≤ 12						
13 - 18						
19 - 39						
40 - 59						
≥ 60						

PART 2 - RAINWATER HARVESTING PROCESSES

2.1 Indicate which method is used in your household to harvest rainwater.

Roof harvesting technique	
Deep pit technique	
Non-roof harvesting technique	
Others (Please specify)	

2.2 Indicate which of these roofing materials best describes the one that is used for the roof harvesting technique?

Metal roof	
Thatch	
Tile	
Others (Please specify)	

PART 3 - WATER STORAGE CONDITIONS

3.1 Indicate the type of container that is used to store the harvested rainwater.

Plastic Jojo tank	
Metal Drum	
Plastic container	
Others (Please specify)	

3.2 Indicate how long the harvested rainwater is stored.

≤ 2 weeks	
3 - 4 weeks	
5 - 8 weeks	
≥ 9 weeks	

3.3 Indicate how often the storage container is cleaned.

Weekly	
Monthly	
Quarterly	
Yearly	
Others (Please specify)	

PART 4 - RAINWATER CONSUMPTION

4.1 Indicate what are the main uses of the harvested rainwater.

Farming and irrigation purposes	
Household cleaning and laundry	
Cooking and washing	
Drinking	
Others (Please specify)	

4.2 Indicate what the harvested rainwater is not used for.

Farming and irrigation purposes	
Household cleaning and laundry	
Cooking and washing	
Drinking	
Others (Please specify)	

4.3 Indicate how long the stored harvested rainwater last.

≤ 2 weeks	
3 - 4 weeks	
5 - 8 weeks	
≥ 9 weeks	

PART 5 - HEALTH EFFECT

5.1 Indicate how often you or your family members fall sick.

Monthly	
Quarterly	
Yearly	
Others (Please specify)	

5.2 Indicate what symptoms are commonly associated with the sickness

Diarrhoea	
Vomiting	
Dehydration	
Abdominal pain	
Skin rashes	
Others (Please specify)	

Appendix G: Interview Guide (English)

Interview Schedule

1. Why do you use the specific rainwater harvesting technique as indicated in question 2.1?

2. Describe the condition of the specific storage container as indicated in 3.1 (e.g muddy, greenish etc.)

3. Describe the surrounding area where the specific storage container is stored (e.g. left outside and not covered)

4. What happens when the harvested rainwater finishes and there is no rain for a long period of time?

5. What period of the year are the residents of your household susceptible to sickness?

6. Would you attribute the sickness indicated in 5.2 to be related to the harvested rainwater? Please elaborate.

7. Do you feel comfortable and safe with the quality of the harvested rainwater?
Please elaborate.

Appendix H: Letter of Information (Isizulu)

LETTER OF INFORMATION

Isihloko socwaningo:

The application of nanotechnology to improve the quality of harvested rainwater in a selected rural community

Umcwaningi noma abacwaningi abakhulu:

Blessing George Akpan (BTech)

Abambisene nabo noma abeluleki:

Dr Raveen Rathilall (DTech)

Inhloso yocwaningo:

Mkomazi umphakathi wasemakhaya KwaZulu Natal onabantu abaxakekile, abangenawo amanzi abawahlinzekwe uhulumeni ahamba emapayipini. Bagcina sebesebenzisa futhi bephuza amanzi emvula. Lolucwaningo luhlose ukusebenzisa inanotechnology ukuthuthukisa izinga lamanzi enziwe imvula kubahlali baseMkomazi.

Ukubamaba iqhaza kulolucwaningo kubandakanya ukubamba iqhaza ocwaningweni nomcwaningi noma umsizi kamcwaningi. Abazobamba iqhaza bazokhethwa ngokuhlosiwe, kuzodingeka imizuzu engama-25 ukuqeda uhlu. Umcwaningi noma umsizi kamcwaningi uzokwazi ukukuchazela ngohlu lwemibuzo uma kukhona ongenaso isiqiniseko ngakho.

Awukho umkomelo wemali noma umholo, kodwa umkomelo uhambisana nokutholwa ucwaningo, okuhloswe ngalo ukuthuthukisa izinga lamanzi emvula agciniwe nokuwenza akulungele ukusetshenziswa eMkomazi. Inzuzo kumcwaningi kuzoba ukwaneliseka ngazokuthola ekuxazululeni inkinga, izinqu zemfundo kanye nokushicilelwa.

Abukho ubungozi noma ukungaphatheki kahle kuwena kulolu cwaningo

Ucwaningo lwenziwa ngokuzithandela, uvumelekile ukuhoxa kulolucwaningo noma inini uma ngabe uzizwa ungakhululekile ngemibuzo ngesikhathi senhlolokhono. Angeke kube khona imiphumelela emibi kuwena uma ngabe ukhetha ukuhoxa.

Angeke uthole umvuzo wemali ngokubamba iqhaza kulolucwaningo.

Angeke ube nezindleko ngokubamba iqhaza kulolucwaningo.

Amarekhodi asuka kulolu cwaningo azogcinwa eyimfihlo kakhulu. Ayikho imininingwane yobuwena ezosetshenziswa kunoma yimiphi imibiko noma ukushicilelwa okuvela kulolu cwaningo. Yonke imibhalo izofinyezwa, izonikezwa amakhodi futhi agcinwe ngokungasetshenziswa amagama nanoma yini eqondene nabababambiqhaza. Ulwazi locwaningo luzogcinwa kumafayela akhiyiwe ngaso sonke isikhathi. Izisebenzi zocwaningo kuphela ezizokwazi ukufinyelela kumafayela nalabo abanesidingo esibalulekile sokubona amagama abazokwazi ukufinyelela kulelo fayela.

Abantu oxhumana nabo esimeni sanoma iziphi izinkinga noma imibuzo

Sicela uthinte umcwaningi ku-060 373 5168, umphathi wami ku-084 457 7265 noma Umlawuli wesikhungo semithetho yokwenziwa kocwaningo ku-031 373 2375. Izikhalazo zingabikwa kuMqondisi obhekelele Ezocwaningo nokuSekelwa Kwabafundi uProf. K Motaung noma ku-ttidirector@dut.ac.za

Appendix I: Letter of Consent (Isizulu)

DUT DURBAN UNIVERSITY OF TECHNOLOGY INSTITUTIONAL RESEARCH ETHICS COMMITTEE

IFOMU LOKUNIKA IMVUME

Isitatimende sesivumelwano sokubamba iqhaza ocwaningweni:

- Ngiyaqinisekisa ukuthi uBlessing G Akpan ungichazele mayelana nesimo socwaningo kanye nobungozi balo Ngaphansi wenombolo yemigomo elawula ukwenziwa kocwaningo engu: : _____,
- Ngiphinde ngathola incwadi, ngayifunda futhi ngayiqondisisa yonke imininingwane ebhaliwe (Incwadi yalabo ababambe iqhaza) mayelana nocwaningo.
- Ngiyazi futhi ukuthi imiphumela yocwaningo ebandakanya imininingwane yami yobulili, iminyaka, usuku lokuzalwa, izinhlamvu zokuqala zamagama ami kanye nesifo esingiphethe kuzoba yimfihlo emiphumeleni yocwaningo.
- Ngokwezidingo zocwaningo, ngiyavuma ukuthi imininingwane eqoqiwe kulolucwaningo ingasetshenziswa ngokusebenzisa ubuchwepheshe bekhumpuyutha.
- Ngingahoxa noma inini ngaphandle kokuphoqwa ekubambeni iqhaza.
- Ngibe nethuba elanele lokubuza (ngokuthanda kwami) ngaze ngazizwa ukuthi sengikulungele ukubamba iqhaza ocwaningweni.
- Ngiyaqonda ukuthi okusha okuzotholakala kulolucwaningo okungahlobana nokubamba iqhaza kwami kuzokwenziwa ukuthi nami ngikuthole.

_______________ _______ _____ ___________

Amagama aphelele **Usuku** **Isikhathi** **Sayina Obambe iqha**

Mina, Blessing G. Akpan ngiyaqinisekisa ukuthi umhlanganyeli ongenhla wazisiwe ngokugcwele mayelana nesimo, ukuziphatha kanye nobungozi bocwaningo olungenhla.

Amagama aphelele omcwaningi	**Usuku**	**Sayina**
Amagama aphelele kafakazi (uma ekhona)	**Usuku**	**Sayina**
Amagama aphelele (uma ekhona) kamlondolozi ogunyaziwe	**Usuku**	**Sayina**

Appendix J: Survey Questionnaire (Isizulu)

QUESTIONNAIRE

THE APPLICATION OF NANOTECHNOLOGY TO IMPROVE THE QUALITY OF HARVESTED RAINWATER IN A SELECTED RURAL COMMUNITY

Usuku: 2021/02/28

Faculty of Management Sciences
Department of Operations and Quality Management

Mhlanganyeli othandekayo,

Mina Blessing Akpan, mfundi owenza iziqu zeMaster’s degree emnyangweni waka-Operations and Quality Managament eNyuvesi Yasethekwini Yezobuchwepheshe. Ngenza ucwaningo lwencwadi yami olumayelana ne-“The application of nanotechnology to improve the quality of harvested rainwater in a selected rural community”.

Mayelana nalokhu, ngizocela imizuzu engama-25 yesikhathi sakho, kanye nomzamo wokuphendula yonke imibuzo esohlwini lwemibuzo ebalulekile futhi ewusizo ekuphothulweni kocwaningo. Ulwazi olunikezile luzosetshenziselwa izinjongo zocwaningo kuphela futhi ngifuna ube nesiqinisekiso ukuthi yonke imininingwane eqoqwe kuwe izogcinwa iyimfihlo ephezulu kakhulu. Ukuhlanganyela kwakho kulolu cwaningo kungokuzithandela futhi ngeke kube nemiphumela emibi uma ukhetha ukuhoxisa ukubamba kwakho iqhaza ocwaningweni.

Impendulo yakho enhle kulesi sicelo izoba negalelo elibalulekile ekuphumeleleni kocwaningo futhi izobongwa kakhulu.

Ngibonga kusemanje futhi ngiyibheke ngabomvu impendulo enohlonze evela kuwena. Ngicela ukhululeke ukuxhumana nami uma udinga olunye ulwazi.

……………………….

Blessing Akpan

0603735168

Sicela ugcwalise lokhu okulandelayo njengesiqinisekiso sokuzimisela kwakho ukubamba iqhaza ocwaningweni:

Mina …………………………………………., ngixoxile nomcwaningi ngocwaningo futhi ngiyaqonda ukuthi ukubamba kwami iqhaza kungukuzithandela, futhi ngingahoxa ocwaningweni nganoma yisiphi isikhathi. Ngiyavuma ukubamba iqhaza owaningweni ngokugcwalisa uhlu lwemibuzo/inhlolovo enamathiselwe.

………………………………….. ……………………………

SAYINA USUKU

Ungamaka impendulo ngothikhi noma ngesiphambano

INGXENYE 1 – ISIQEPHU SEBIOGRAPHICAL

1.1 Bangaki abantu endlini kini?

1 - 2 wabantu	
3 - 5 wabantu	
≥ 6	

1.2 Khombisa iminyaka yabantu abahlala kulendlu.

	1	2	3	4	5	5+
≤ 12						
13 - 18						
19 - 39						
40 - 59						
≥ 60						

INGXENYE 2 – IZINDLELA ZOKUVUNA AMANZI EMVULA

2.1 Khombisa ukuthi iyiphi indlela esetshenziswayo kini ukuvula amanzi emvula.

Indlela yokuvuna uphahla	
Umgodi ojulile	
Indlela yokuvuna ungasebenzisi uphahla	
Okunye (Sicela ucacise)	

2.2 Khombisa ukuthi iyiphi kulezizinto zokufulela echaza kangcono le esetshenziselwa indlela yokuvuna?

Uthayela	
Uthango	
Ithayela	
Okunye (Sicela ucacise)	

INGXENYE 3 – IZIMO ZOKUGCINA AMANZI

3.1 Khombisa isiqukathi esitshenziselwa ukugcina amanzi emvula avuniwe.

Ujojo	
Isigubhu sensimbi	
Isitsha sikaplastiki	
Okunye (Sicela ucacise)	

3.2 Khombisa ukuthi amanzi emvula agciniwe ahlala isikhathi esingakanani.

≤ 2 amasonto	
3 - 4 amasonto	
5 - 8 amasonto	
≥ 9 amasonto	

3.3 Khombisa ukuthi isitsha sokugcina amanzi sihlanzwa kaningi kangakanani.

Njalo ngesonto	
Njalo ngenyanga	
Njalo ngekota	
Njalo ngonyaka	
Okunye (Sicela ucacise)	

INGXENYE 4 – UKUSEBENZISA AMANZI EMVULA

4.1 Khombisa ukuthi iziphi izinto amanzi emvula asetshenziselwa zona kakhulu.

Ukunisela nokuwasha	
Ukuhlanza indlu nokuwasha	
Ukupheka nokuwasha	
Ukuphuza	
Okunye (Sicela ucacise)	

4.2 Khombisa ukuthi amanzi emvula agciniwe asetshenziselwa ini.

Ukunisela nokulima	
Ukuhlanza indlu nokuwasha	
Ukupheka nokuwasha	
Ukuphuza	
Okunye (Sicela ucacise)	

4.3 Khombisa ukuthi amanzi emvula agciniwe agcinwa isikhathi esingakanani.

≤ 2 amasonto	
3 - 4 amasonto	
5 - 8 amasonto	
≥ 9 amasonto	

INGXENYE 5 – UMPHUMELA WEZEMPILO

5.1 Khombisa ukuthi wena noma amalungu omndeni wakho avame ukugula kangakanani.

Njalo ngenyanga	
Njalo ngekota	
Njalo ngonyaka	
Okunye (Sicela ucacise)	

5.2 Iziphi izimpawu ezivame ukukhombisa isifo?

Ukuhuda	
Ukuhlanza	
Ukuphelelwa amanzi emzimbeni	
Izinhlungu zasesiswini	
Ukuqubuka	
Okunye (Sicela ucacise)	

Appendix K: Interview Guide (Isizulu)

Uhlelo lwezingxoxo

1. Kungani usebenzisa le indlela ethile yokuvuna amanzi emvula njengoba kukhonjisiwe embuzweni wesi-2.1?

2. Chaza isimo sesitsha sokugcina amanzi njengoba sikhonjiswe ku-3.1 (isb. ezinodaka, eziluhlaza okotshani njll.)

3. Chaza indawo ezungeze lapho kugcinwa khona isiqukathi esithile sokugcina amanzi (isb. sishiywe ngaphandle futhi asimboziwe)

4. Kwenzekani lapho amanzi emvula avuniwe ephela futhi ingabikhona imvula isikhathi eside?

5. Isiphi isikhathi sonyaka lapho abantu bakini besengozini yokugula?

6. Ungasho yini ukuthi ukugula okuveziwe ku-5.2 kuhlobene namanzi emvula avuniwe?

7. Ingabe uzizwa ukhululekile futhi uphephile ngekhwalithi yamanzi emvula avuniwe? Sicela ucacise.

Appendix L: Technical Editor Certificate

Helen Richter
Advanced Editing & Proofreading

editassist2023@gmail.com
+27 729227221

16 October 2024

To whom it may concern

CERTIFICATE OF EDITING & AUTHENTICATION

I have proofread and language edited the Master's dissertation titled:

"THE APPLICATION OF NANOTECHNOLOGY TO IMPROVE THE QUALITY OF HARVESTED RAINWATER IN A SELECTED RURAL COMMUNITY"

by

Blessing George Akpan
22063681

To the best of my knowledge, the work is free of spelling, grammar, structural and stylistic errors and the contents are certified as the author's own work, with adherence to DUT technical parameters.

With thanks.

H. S. Richter

Appendix M: Turnitin Report

THE APPLICATION OF NANOTECHNOLOGY TO IMPROVE THE QUALITY OF HARVESTED RAINWATER IN A SELECTED RURAL COMMUNITY

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