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Assessing Plastic Pollution, Management Practices and Worker Attitudes in Wastewater and Water Treatment Plants: A Case Study of Removal Efficiencies and Environmental Impacts in Vhembe District, South Africa

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A research thesis submitted in fulfilment of the requirements for the Doctor of Philosophy in Science, School of Biology and Environmental Sciences, Faculty of Agriculture and Natural Sciences, University of Mpumalanga

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ABSTRACT

Water and wastewater treatment plants (WWTPs) face significant challenges that hinder their effectiveness, primarily due to inadequate institutional arrangements. The increasing prevalence of plastic pollution worsens these issues, placing additional pressure on treatment plants, particularly wastewater treatment plants, which often struggle to remove plastic contaminants effectively. Human activities, including poor waste management practices, are a major contributor to these environmental problems, raising serious concerns about their impact on aquatic ecosystems. This study involved interviews with 18 workers from water and wastewater treatment plants in two local municipalities, Thulamela and Makhado, located in the Vhembe District. Additionally, 150 community members from the Thulamela Local Municipality participated in the research. A systematic review was conducted to examine the occurrence and removal of microplastics in wastewater treatment plants in other countries. The qualitative data was organized thematically, and Ostrom's Institutional Analysis and Development (IAD) Framework was employed to gain deeper insights into the institutional arrangements and operational challenges faced by treatment plants.

The study revealed several operational challenges faced by water and wastewater treatment plants (WWTPs). Workers generally understood the water treatment process; however, inconsistencies in monitoring water quality and a lack of transparency were identified, with critical parameters from SANS 241 not consistently tested. A significant gap in education and ongoing training among workers contributed to inefficiencies, while institutional and socio-economic factors, coupled with insufficient capacity, load-shedding, limited resources, and inadequate infrastructure, further hindered the plants' performance. Chief process controllers and supervisors had extensive experience, yet the lack of regular training limited their ability to address knowledge gaps and adopt new technologies. Resource disparities, such as access to testing equipment, along with insufficient institutional support, funding, and documentation, were also noted.

Plastic pollution emerged as a significant operational challenge for treatment plants. The study highlighted ineffective methods of plastic removal and inadequate waste collection services, especially in rural areas. Financial and material constraints exacerbated these issues, while inconsistent training and institutional support limited workers' ability to manage plastic pollution effectively. The widespread prevalence of fibres and fragments in influent and effluent streams underscored the difficulty of removing these pollutants, compounded by the diverse sources and variations in colour composition, including black, transparent, blue, and red microplastics.

Public perceptions and awareness about WWTPs and plastic pollution also varied. The study found that 61% of participants were aware of WWTPs, with 48% expressing concerns related to odours, health risks, and property value loss, while others recognized their environmental benefits. Awareness of plastic pollution was high (77%), with 54% of participants having received information on the issue. Participants with higher educational levels showed a greater understanding of WWTP operations and plastic pollution. Many expressed interest in engaging in educational outreach to bridge knowledge gaps. The study highlighted the importance of public education and awareness campaigns to address community concerns, increase environmental awareness, and promote positive perceptions of WWTPs while recommending investments in advanced technologies, standardized procedures, proactive maintenance, and worker training to enhance operational efficiency and reduce plastic pollution.

Keywords: Plastic pollution, Microplastics, Water and wastewater treatment plants, Removal rate, Institutional arrangements, Vhembe district Municipality, Thulamela, Makhado, Public Awareness, Thematic analysis.

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PREFACE

This thesis comprises a general introduction (Chapter 1), literature review (Chapter 2), results (Chapter 3–7) and a general synthesis (Chapter 8) chapter. The combined reference list at the end of the thesis ensures limited repetition. The result sections were organised as scientific papers, which have either been published, or are *in press* or *currently revision submitted* (see below):

Publication list

Mabadahanye, K.; Dalu, M.T.B.; Dalu, T. 2024. Occurrence and removal of microplastics in wastewater treatment plants: perspectives on shape, type, and density. *Water*, 16, 1750.

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Mabadahanye, K.; Dalu, M.T.B.; Munyai, L.F.; Dondofema, F.; Dalu, T. (***In press***) Perceptions and knowledge of water and wastewater treatment plant workers regarding plastic pollution and removal. *Sustainability*

Mabadahanye, K.; Dalu, M.T.B.; Munyai, L.F.; Dondofema, F.; Dalu, T. (***Revision submitted***) Public knowledge and attitudes towards wastewater treatment works and removal of plastic pollution in the Vhembe District, South Africa. *Scientific African*

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DEDICATION

This thesis is dedicated to God almighty, who has given me the strength to carry out this study in good health, my late grandmother Emelina Ntsundeni Maumela Singo, my late uncle Lesley Mbuyiseni Maumela, my mother Wendy Maumela, and my brother Ompfa Mabadahanye.

Without your prayers, this would not have been possible.

Thank you

DECLARATION

I, KHUMBELO MABADAHANYE student number 222574658, hereby declare that the PhD titled "**Assessing plastic pollution, management practices and worker attitudes in wastewater and water treatment plants: A case study of removal efficiencies and environmental impacts in Vhembe District, South Africa. "** has not been submitted by anyone, is my research work and that all sources that I used have been acknowledged by the means of references at the end of this dissertation.

SIGNATURE____ ______

KHUMBELO MABADAHANYE (MS)

DATE…23 March 2025……………………….

LIST OF ACRONYMS

CFCs	Chlorofluorocarbons
DEA	Department of Environmental Affairs
DWS	Department of Water and Sanitation
IAD	Institutional Analysis and Development
mL/day	Megaliters
MLD	Million liters per day
MP	Microplastic
MP/L	Microplastic per litre
Mt	Million tonnes
PA	Polyamide
PE	Polyethylene
PE+PP	Blend of Polyethylene and Polypropene
PES	Polyether Sulfone
PET	Polyethylene terephthalate
PL	Polyester
PP	Polypropylene
PP+PP	Blend of Polypropylene and Polyethylene
PS	Polystyrene
PVC	Polyvinyl chloride
SANS	South African National Standard
SESF	Social-Ecological Systems Framework,
ST	Stakeholder Theory
STPs	Sewage treatment plants

SUPs	Single-use plastics
TPB	Theory of Planned Behaviour
USA	United States of America
VDM	Vhembe district municipality
WTP	Water treatment plant
WWTP	Wastewater treatment plant
WWTWs	Wastewater treatment works

CHAPTER ONE: GENERAL INTRODUCTION

1.1 Background

Plastics provide numerous social and economic benefits, making them an essential material in modern life (Wright & Kelly, 2017). However, their widespread production and disposal have led to severe environmental challenges. Global plastic production exceeds 320 million tonnes (Mt) annually, with 40% of plastics designed for single-use packaging, significantly contributing to plastic waste (Wright & Kelly, 2017; Adam *et al.*, 2020). Items such as plastic bags, straws, cutlery, sachet wrappers, and food containers are discarded after a single use, increasing pollution levels (Adam *et al.*, 2020). Single-use plastics (SUPs) have become a major global concern due to their accumulation in marine environments, where 80% of SUP waste is found along coastlines and ocean floors, posing a serious threat to marine life (Adam *et al.*, 2020). Plastic pollution is defined as the invasion of plastic materials into ecosystems, either through direct introduction or degrading processes, negatively affecting such surroundings (Iroegbu *et al.*, 2021). It threatens both living and nonliving systems on a widespread scale, stressing the environment globally (Bidashimwa *et al.*, 2023).

Plastic pollution moves between different water bodies, disperses through the air, and is transported by human activity, making it a persistent environmental contaminant (Iroegbu *et al.*, 2021; Pandey *et al.*, 2023). Microplastics originate from primary and secondary sources (Xu *et al.*, 2019). Primary microplastics are manufactured for various purposes, such as microbeads in personal care products, while secondary microplastics result from the degradation of larger plastic items through physical, chemical, and microbial processes (Wright & Kelly, 2017; Xu *et al.*, 2019). Wastewater treatment plants (WWTPs) have been identified as significant sources of microplastic release into aquatic ecosystems (Xu *et al.*, 2019). Due to their inefficiencies, these facilities often discharge large quantities of microplastics into receiving water bodies (Dalu *et al.*, 2021). These plastics can then spread into other inland and marine environments after being deposited in riverine systems (Zhang *et al.*, 2018).

Wastewater management infrastructure in developing countries is often underdeveloped, leading to poor wastewater treatment and significant environmental impacts (Dalu *et al.*, 2021). The inability of WWTPs to fully remove microplastics contributes to widespread contamination in aquatic habitats (Murphy *et al.*, 2016). Wastewater treatment involves recycling wastewater to reduce industrial or municipal sewage contamination (Wright *et al.*, 2019). Effective wastewater management supports sustainability by ensuring purified water re-enters the environment, conserving freshwater resources, and reducing pollution (Durán-Sánchez *et al*., 2020). However, many facilities struggle with compliance, particularly in developing regions such as Vhembe district, exacerbating pollution issues (Momba *et al*., 2009; Makungo et al., 2011). Workers' attitudes and perceptions play a critical role in the effectiveness of wastewater management and treatment processes. Employee well-being and perceptions of work conditions significantly impact productivity and adherence to management techniques (Yankelovich, 1983; Harter *et al*., 2010). According to Harter *et al*. (2010), Managerial practices that influence employee perceptions can improve key organizational outcomes, enhancing the efficiency of wastewater treatment facilities. This study addresses knowledge gaps in wastewater management and water treatment in Vhembe District by assessing plastic pollution, evaluating treatment plant removal efficiencies, and examining workers' perceptions and attitudes. Limited research exists on these aspects in the region, making this investigation crucial.

1.2 The problem statement

Wastewater management and treatment play a crucial role in mitigating environmental pollution and ensuring public health. However, in regions like Vhembe District, inadequate wastewater treatment infrastructure and failing systems contribute to water pollution (Mothiba *et al*., 2023). Drinking water treatment facilities and small-scale wastewater treatment plants (WWTPs) in the district have been found to be non-compliant, posing significant health hazards (Momba *et al*., 2009; Makungo *et al*., 2011). Limited funding and a shortage of replacement components prevent proper maintenance and upgrading of wastewater infrastructure, further exacerbating pollution risks (Malima *et al*., 2022). Studies indicate that sewage treatment plants contribute to environmental pollution, with downstream facilities often containing higher concentrations of contaminants such as microplastics (McCormick *et al*., 2014; Estabanati and Fahrenfeld, 2016; Yang, 2019). Despite these challenges, there is limited research on wastewater removal efficiencies and pollution control in the district. Furthermore, workers' attitudes and perceptions towards wastewater management and treatment processes have not been extensively studied, yet they may influence operational effectiveness. Understanding these gaps is essential for improving wastewater management strategies and ensuring better environmental and public health outcomes in the Vhembe District.

1.3 Research aim

The study aims to assess plastic pollution, management practices and worker attitudes in wastewater and water treatment plants within Vhembe District, South Africa.

1.4 Research objectives

(i) To investigate the occurrence and removal of microplastics in wastewater treatment plants, and perspectives on shape, type, and density across different countries.

(ii) To investigate institutional arrangements and roles within water and wastewater treatments.

(iii) To assess perceptions and knowledge of water and wastewater treatment plant workers regarding plastic pollution and removal.

(iv) To assess manager's perceptions towards impacting attitudes and effectiveness towards their work.

(v) To assess public knowledge and attitudes towards WWTPs and removing plastic pollutants in the Vhembe District.

1.5 Hypothesis

- The occurrence and removal efficiency of microplastics in wastewater treatment plants vary significantly based on the shape, type, and density of the microplastics and the technologies employed in different countries.
- Institutional arrangements and clearly defined roles within water and wastewater treatment plants significantly enhance the effectiveness of managing and mitigating plastic pollution in the Vhembe District.
- Workers at water and wastewater treatment plants in the Vhembe District have limited knowledge and varying perceptions about plastic pollution and its removal, which impacts their operational efficiency.
- Managers' perceptions and attitudes toward plastic pollution directly influence their decision-making and the overall effectiveness of operations in water and wastewater treatment plants.
- Public knowledge and attitudes toward wastewater treatment plants and plastic pollution removal in the Vhembe District are insufficient, affecting community support for mitigation strategies.

1.6 Justification of the study

Plastic pollution is a growing environmental challenge in South Africa, particularly in freshwater and marine ecosystems, where it threatens biodiversity, public health, and economic sustainability (De Kock *et al*., 2020). Water and wastewater treatment works play a crucial role in managing water quality; however, there are still knowledge gaps regarding their effectiveness in removing microplastics (Cristaldi *et al*., 2020). While global and national policies have focused on banning primary microplastics, such as microbeads, secondary microplastics from wastewater effluent remain largely overlooked (Contreras-Llin *et al*., 2024). Understanding these perceptions is essential for identifying knowledge gaps, improving operational practices, and strengthening policy implementation (Guvernator & Landaeta, 2020). The study will contribute to the achievement of the goals of Sustainable Development Goal (SDG) 14, which aims to reduce marine pollution, including plastics, by improving waste management and promoting sustainable practices (Kumar *et al*., 2021). Furthermore, it aligns with the South African National Development Plan (NDP) 2030, which emphasises water resource management and environmental sustainability (National Planning Commission, 2012). This study will address a critical knowledge gap by investigating the perceptions, attitudes, and awareness of workers in water and wastewater treatment plants in the Vhembe District, South Africa, while also assessing the capacity of municipal systems to remove microplastics that are continuously discharged into the environment, threatening both aquatic life and human health. The findings will help inform policy recommendations, raise public awareness, and contribute to the development of more effective waste management strategies.

1.7 Outline of the thesis

Chapter 1 will deal with the general background of plastic pollution, wastewater treatment works, and microplastics. The problem statement, aims, objectives, hypothesis and justification of the study will be given.

Chapter 2 will concentrate on the literature review of plastic pollution, the global challenges of plastic pollution in the environment, the effects of microplastics in water bodies, water treatment plants and the challenges of removing microplastics in wastewater treatment work.

Chapter 3 will focus on the occurrence and removal of microplastics in wastewater treatment plants, and perspectives on shape, type, and density across different countries.

Chapter 4 will deal with understanding the institutional arrangements and roles of water and wastewater treatment within the district and South Africa.

Chapter 5 will deal with perceptions of the water and wastewater treatment plant workers about plastic pollution and removal.

Chapter 6 will deal with manager's perceptions and their influence on attitudes and effectiveness towards their work.

Chapter 7 will deal with public knowledge and attitudes towards WWTPs and removing plastic pollutants in the Vhembe District.

Chapter 8 will give a summary and conclusion of the study. Some recommendations for future work will be suggested. The references used in the study will be listed in each chapter.

CHAPTER TWO: LITERATURE REVIEW

2.1 Chapter overview

This chapter explores the social aspects of water and wastewater treatment plant operations using relevant theoretical frameworks, including Ostrom's Institutional Analysis and Development (IAD) Framework, Social-Ecological Systems (SES) Framework, Stakeholder Theory, and the Theory of Planned Behaviour (TPB). This chapter also focuses on the importance of public education, community engagement, and collaboration between stakeholders in improving WWTP efficiency and addressing plastic pollution.

2.2 Institutional Analysis and Development (IAD) Framework

The study program on community-based management of natural resources was developed by Elinor Ostrom using the analytical framework of the Institutional Analysis and Development (IAD) (McGinnis, 2019). Informally, resources that are shared by members of a group are referred to as commons (McGinnis, 2019). People, resources, and rules are all situated within larger social-cultural, political-legal, and biophysical settings. This is where the IAD framework comes in, which was created to work in a variety of policy contexts (Ostrom 1986, 2005, 2010, 2011). The Institutional Analysis and Development (IAD) framework serves as a systematic approach to organizing policy analysis activities. Rather than replacing other analytical methods from the social and physical sciences, it complements them by offering a structured way to integrate diverse perspectives and efforts (Polski & Ostrom 1999). This includes contributions from various stakeholders, particularly those directly involved in or affected by the policy outcomes. By breaking down complex social situations into manageable and actionable components, the IAD framework helps analysts gain a clearer understanding and develop more effective solutions (Polski & Ostrom 1999).

The Institutional Analysis and Development (IAD) framework identifies three variables that influence actions and interactions within an action arena which are biophysical conditions, attributes of the community and rules-in-use (Schlager & Villamayor-Tomas, 2023; Whaley *et al*., 2024). Action arena refers to the social area where people interact, trade products and services, resolve conflicts or control one another (Albagli *et al*., 2018). Biophysical conditions include the environment and material resources in which events take place (Ran *et al*., 2020).

Community attributes encompass cultural and social factors such as reciprocity, trust, mutual understanding, social capital, and shared social practices. Rules-in-use refers to property rights, formal regulations, and informal norms (Ran *et al*., 2020). According to Hess & Ostrom (2004), understanding rules is both a significant and challenging task. If the regulations in place fail to keep pace with the rapid advancements in technology, the laws or policies may be developed based on limited knowledge or a lack of awareness of the true nature of the problems they aim to address (Hess & Ostrom, 2004). This challenge is particularly relevant to water and wastewater treatment regulations and plastic pollution, where outdated policies may fail to address emerging environmental threats. As a result, inadequate regulatory frameworks could hinder effective management and mitigation strategies, emphasising the need for updated policies.

2.3 Social-Ecological Systems Framework (SESF)

The social-ecological systems framework (SESF) is a conceptual framework designed to identify and evaluate variables influencing outcomes in social-ecological systems (SES) through their interactions (Ostrom 2007, 2009; Poteete et al. 2010). It has evolved, and supported by a rich history of empirical studies on the commons, institutions, and collective action (Ostrom 1990; Wollenberg *et al*. 2007; Poteete *et al*. 2010). Initially developed to advance collective action theory, the SESF is now widely used as a general tool to assess the sustainability of social-ecological systems (Ostrom 2009). Social-ecological systems (SES) are dynamic and constantly evolving systems (Schlüter *et al*., 2014). They coevolve through interactions between people, institutions, and resources, which are constrained and shaped by a specific social-ecological context (Holling & Gunderson, 2002). To address collective action issues and conduct institutional evaluations of natural resource systems, the SESF was specifically developed (Nagel & Partelow, 2022). According to Berkes and Folke (1998), Liu *et al*. (2007), and Fischer *et al*. (2015), the SES concept has become a mainstream area of study that focuses on the interdependent relationships between social and environmental change and how those relationships affect the success of sustainability goals across various systems, levels, and scales. In the context of this study, understanding SESF is crucial for assessing how policy implementation and water management interact with environmental factors to influence pollution levels, particularly plastic pollution.

2.4 Stakeholder theory

Stakeholder theory (ST) is a theory of organisational management and business ethics (Kaler, 2006; Schaltegger *et al*., 2019). According to ST, organisations seek to provide a variety of advantages for various stakeholders, groups and persons that have the potential to influence or be influenced by the organisation, including communities, civil societies, governments, shareholders, suppliers, and employees (Mahajan *et al*., 2023). According to Mahajan *et al*. (2023), ST can be characterised as a theory that:

(i) encourages organizations to recognize and take into account their stakeholders, whether they are internal or external to the organization.
(ii) encourages managing and understanding stakeholder needs, wants, and demands
(iii) represents a responsible and holistic framework that extends beyond the focus of shareholders in decision-making processes.
(iv) enables organizations to be strategic, maximize their value creation, and safeguard their long-term success and sustainability.

In the context of this study, ST provides a relevant framework for understanding how different stakeholders such as policymakers, regulatory bodies, local communities, and WWTP operators interact in managing wastewater pollution and mitigating plastic pollution. The theory emphasises the importance of stakeholder engagement in decision-making processes, the need for inclusive governance and collaboration to ensure effective wastewater management strategies.

2.5 Theory of Planned Behaviour (TPB)

The Theory of Planned Behaviour (TPB) states that perceived behavioural control and intentions to engage in eco-friendly behaviours are the direct causes of Pro-Environmental Behaviour (PEB) (De Leeuw *et al*., 2015). Pro-environmental behaviour is defined as actions that either help the environment or cause as little harm as possible (Gifford & Nilsson, 2014). According to the TPB, pro-environmental behaviour is more likely to occur when individuals feel capable of adopting the behaviour (perceived behavioural control), have a positive attitude toward it, and believe that significant others either already engage in it (perceived descriptive social norm) or think it should be done (perceived injunctive social norm) (Gatersleben *et al*., 2014).

Behavioural beliefs are an individual's perceptions about the probable outcomes of engaging in action that form the basis of attitudes toward that behaviour (Ajzen, 2005). The TPB also suggests that a wide range of background variables, including age, sex, race, financial status, education, personality, and prior experiences, may influence an individual's beliefs (Fishbein & Ajzen, 2010).

In modern societies, economic prosperity is highly valued. Cultural norms that encourage acquiring wealth and material possessions are consistently emphasized (Gatersleben *et al*., 2014). However, there is growing concern about the environmental damage caused by current levels of consumption (Jackson, 2009). Therefore, promoting pro-environmental behaviour such as reduced plastic consumption, support for sustainable wastewater management, and responsible waste disposal is essential for mitigating pollution, including microplastic contamination in water bodies (Gatersleben *et al*., 2014). This study applies the TPB framework to understand how public awareness, attitudes, and perceived control influence behaviours related to wastewater treatment and pollution prevention.

The integration of IAD, SESF, Stakeholder Theory, and the TPB provides a comprehensive approach to managing natural and aquatic systems (Figure 2.1). The IAD offers a structured method for analyzing institutions governing resource management, while SESF contextualizes these institutions within broader socio-ecological dynamics (Polski & Ostrom, 1999; Ostrom, 2005; Nagel & Partelow, 2022). Stakeholder Theory ensures inclusive decision-making by emphasizing the roles and interests of diverse actors involved in resource governance (Mahajan *et al*., 2023). The theory of planned behaviour contributes by explaining behavioural intentions and how social and psychological factors drive sustainable management actions (Ajzen, 2005; Fishbein & Ajzen, 2010). The overlap of these frameworks enables a holistic understanding of governance, institutional dynamics, and stakeholder engagement in promoting effective and sustainable management of natural and aquatic systems.

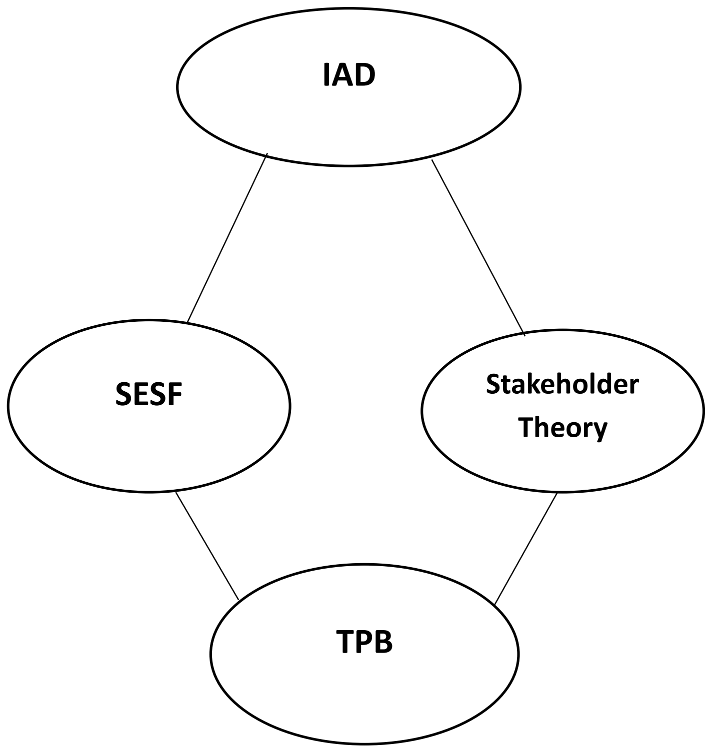

Figure 2.1: Interconnection of IAD, SESF, Stakeholder Theory, and TPB in managing natural and aquatic Systems

2.6 Accumulation of plastic in the environment

Plastic waste has become one of the most pressing global environmental challenges. In 2018, it was estimated that the world produced approximately 6 billion tonnes of plastic waste between 1950 and 2018, with the majority of this waste coming from packaging, followed by products like bottles, containers, and bags (Ayeleru *et al*., 2020). Of the plastic waste generated globally, a significant portion nearly 80% is discarded in landfills or the natural environment, with less than 10% being recycled and 15% incinerated (Ayeleru *et al*., 2020). The bulk of this waste ends up in landfills, which are already facing capacity issues in many low-income countries (Ayeleru, 2016). On a local level, plastic bottles and containers are often discarded carelessly, thrown on the ground, or blown by the wind, further littering the surroundings and contaminating ecosystems (Kehinde *et al*., 2020).

The Journal of Science released the first scientific findings on marine plastic litter in 1972, detailing the discovery of tiny plastic particles in the Sargasso Sea (Rochman, 2020). The initial long-term data set on plastic debris was created in 1986 when undergraduate students on a large ship started counting tiny pieces of plastic litter in surface trawls taken across the North Atlantic Ocean. This was more than ten years later (Rochman, 2020). The "Great Pacific Garbage Patch" was then founded by Captain Charles Moore in 1996, and he also wrote the first report of significant plastic waste accumulations in the center of the North Pacific Subtropical Gyre (Rochman, 2020). Furthermore, the word "microplastic" was first used by Richard Thompson in 2004 to describe the persistent tiny plastic particles (less than 5 mm) that are present in surface waters and ocean sediments (Rochman, 2020).

Irrational manufacturing, improper landfill disposal, and insufficient recycling management are the reasons why plastics end up as waste (Kumar *et al*., 2021). Once plastic wastes are released into the environment, physical, chemical, and biological activities can cause them to gradually decompose and produce many smaller plastic debris (Zhang *et al*., 2021). The most prevalent type of plastic in the ocean is microplastic, and since 8 trillion microbeads are discharged into wastewater every day, it is challenging to remove them from aquatic settings (Schnurr et al., 2018). Microplastics have been discovered in isolated aquatic and marine settings, and they have been observed to collect in ocean gyres (Baldwin *et al*., 2016; Hurley *et al*., 2018). Because marine creatures like filter-feeding bivalves ingest microplastics, Rochman et al. (2015a) claimed that microplastics are more dangerous than macroplastics (Mathalon and Hill, 2014).

The unprecedented rate of plastic litter leakage into the environment, especially land and aquatic ecosystems, presents serious obstacles to waste management for expanding populations, mostly in developing countries (UNEP, 2018; Godfrey, 2019). According to Geyer et al. (2017), if existing waste management practices continue as they are and no specific advancements in the form of technical innovations and other interventions are implemented, the amount of plastic litter that ends up in landfills and natural ecosystems by the year 2050 is expected to exceed 12 billion tons.

2.7 Characteristics of microplastics

It could be challenging to identify the origin of microplastics since they are tiny and frequently deteriorated remains of their original product. However, tracing microplastics back to their original products by an analysis of their shape, color, size, and polymer type is a useful way to try and source-apportion them. (Figure 2.2). When identifying the product from which microplastics originated, these characteristics can be used as hints (Helm, 2017; Rochman *et al*., 2019).

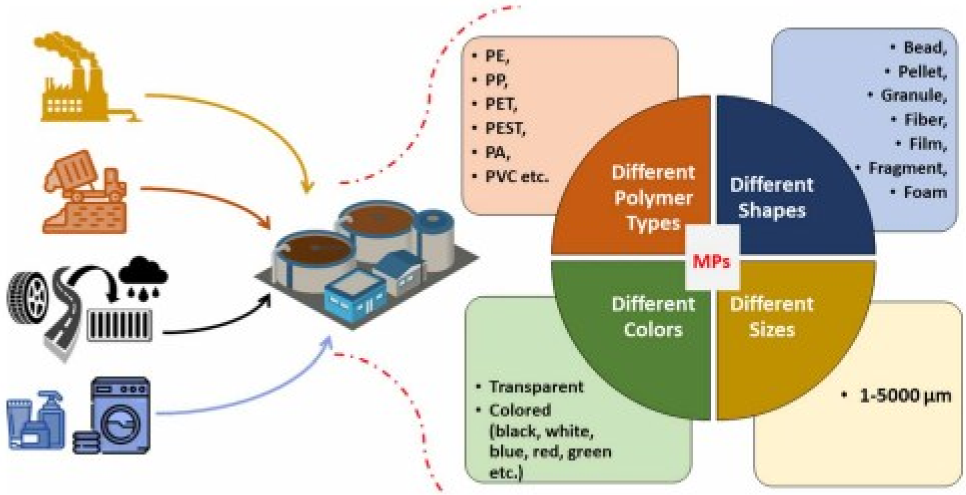

Figure 2.2: Properties of microplastics (Acarer *et al*., 2023)

Size is the characteristic of microplastics that varies the most. The size range of microplastic particles spans more than six orders of magnitude, from nanometers to millimeters. The distribution of microplastic particles size has frequently been observed to follow a power law with a negative exponent. The size of this power law is determined by the mechanisms that either generate the particles by fragmentation or remove them by settling, size-selective transport or erosion from environmental systems, including air (Koelmans *et al*., 2022). According to this, number concentrations rise sharply as size decreases, which could have detrimental effects on the quantity of plastic particles that are currently invisible at the nanoscale (Mohamed *et al*., 2021).

Microplastics have a diverse range of shapes. A microplastic's shape is frequently utilized to classify it into a shared category, which helps identify the source (Helm, 2017). Typically, researchers employ four to seven distinct categories based on shape or morphology. These categories include pellet, film, foam, spherical (or bead), fibre, fibre bundle, and fragment (Rochman *et al*., 2019). The three most observed microplastic shape groups are films, fibres, and fragments. These shapes appear partly because of product or material categories including films, fibres, and beads (Hartmann *et al*., 2019; Kooi and Koelmans, 2019; Rochman *et al*., 2019). We are aware that different products tend to shed certain forms, which can aid in source allocation. For instance, spheres can be microbeads from industrial scrubbers or personal care products; pellets are typically associated with industrial feedstock; fibers and fiber bundles tend to shed from clothing, upholstery, or carpet; and foam is frequently derived from expanded polystyrene foam products like food packaging or insulation (Rochman *et al*., 2019).

Plastic manufacturing industries utilize pigments and dyes to create colorful macro-plastics and microplastics (Upadhyay and Bajpai, 2021). Researchers studying microplastic pollution continue to agree that microplastics should be reported according to color, with most studies providing quantitative information on the various colors of microplastics in the environment (Upadhyay and Bajpai, 2021). However, no study on landfills has included any data regarding microplastic color. A range of microplastics, such as orange, red, blue, brown, off-white, yellow, white, tan, green, grey, etc., have been documented (Upadhyay and Bajpai, 2021). Transparent microplastics are derived from single-use plastics like plastic bags, cups, and plates as well as from industries that use them as raw materials (Upadhyay and Bajpai, 2021). The majority of colored microplastics are secondary microplastics resulted from fragmentation of colored macro-plastics. Nonetheless, it is difficult to determine the kind or origin from the color of the plastic particle. Crucially, because brighter colors are easier to see when inspected visually, color information can be biased (Upadhyay and Bajpai, 2021).

A wide variety of polymer types make up microplastics. The fundamental building blocks of all polymeric polymers are repeating monomers (Rochman *et al*., 2019). Plastics differ fundamentally from one another in their backbone structures, which determine their physical and chemical characteristics (Rochman *et al*., 2019). The most common forms of polymers that are made and used are polypropylene, polyvinyl chloride (PVC), polyethylene terephthalate (PET; also called polyester), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polystyrene (Rochman *et al*., 2019). To meet the needs of the numerous uses for plastics, this variety of polymers is essential. PET is utilized in water bottles, for instance, because LDPE is too delicate for such application. Moreover, LDPE is frequently utilized in film, food packaging, and single-use shopping bags. PET is made into fibres as well as bottles, which are used to create synthetic apparel (Rochman *et al*., 2019). Polyethylene (PE), Polyethylene Terephthalate (PET), Polyamide (PA), Polypropylene (PP), Polystyrene (PS), Polyvinyl Alcohol (PVA), and Polyvinyl Chloride (PVC) are the most common polymers found in microplastic (Koelmans *et al*., 2022).

2.8 Impacts of plastic pollution

According to Jambeck *et al*. (2015), 5 trillion plastics are estimated to be floating in the water, while an average of 8 million tonnes of plastics are introduced into the ocean each year. Plastic in the water usually begins to break down in a year, but not entirely. Water pollution can result from the release of harmful compounds like Bisphenol A (BPA) and polystyrene into the water during plastic degradation process (Alabi *et al*., 2019). Approximately 80% of the waste discovered in the oceans is composed of plastics. Because plastic waste remains on the ocean's surface for extended periods of time, it can be quickly colonized by marine life, which could facilitate the influx of "alien" or non-native species (Alabi *et al*., 2019). The ocean is suffering from plastic pollution and littering, which has a negative impact on it (Obebe and Adamu, 2020). Many marine species have suffered greatly as a result, which has negative implications on people who depend on fish and other marine animals for their nutrients (Obebe and Adamu, 2020).

Surface water systems and the Earth's crust are interconnected through groundwater, which serves as a vital link in the hydrological cycle. Groundwater refers to water stored in rocks or loose materials beneath the Earth's surface (Obebe and Adamu, 2020). In its natural state, groundwater is generally free from contaminants in most regions (Obebe and Adamu, 2020). However, as a primary source of drinking water, groundwater contamination poses significant risks. Rainfall can transport pollutants from plastic waste, landfills, and trash dumps, allowing harmful substances to seep into groundwater supplies, which serve as a crucial source of potable water (Obebe and Adamu, 2020). Contaminants may infiltrate reservoirs and aquifers through leakage, leading to degraded water quality and potential health hazards (Obebe and Adamu, 2020).

When plastic debris that was landfilled eventually breaks down, carbon dioxide and methane are released into the atmosphere (Chandegara *et al*., 2015; Alabi *et al*., 2019). In 2008, an estimated 20 million tonnes of CO_2 equivalent (CO_2e) were released into the atmosphere during the decomposition of solid waste in landfills. Burning plastics and plastic-related items releases CO_2 into the atmosphere, which can retain radiant heat and prevent it from fleeing the planet, leading to global warming (Chandegara *et al*., 2015; Alabi *et al*., 2019). Over 6 million deaths linked to environmental pollution are attributable to air pollution, making it one of the main environmental hazards to public health (Alabi *et al.*, 2019). Inhaling contaminants such as dioxins, heavy metals, furans, and PCBs can lead to health hazards, particularly respiratory diseases, when plastics and plastic goods are burned openly. Plastic pollution poses a serious threat to future generations and is a major contributing factor to air pollution in emerging developing countries across the globe (Hamlet *et al*., 2018).

Plastic items are prevalent in both residential and work environments in significant quantities. Pollution of plastics and plastic-related products have the potential to harm and contaminate the terrestrial ecosystem, which can then spread to the aquatic environment. Although nearly 80% of the plastic waste found at sea comes from land-related sources, there is a lack of data on the volume of plastic waste on land compared to the vast amount of data on plastic debris in marine habitats (Alabi *et al*., 2019). When plastics are dumped on land or disposed of in a landfill, they degrade both biologically and abiotically. As a result, plastic additives such as stabilizers, hazardous colourants, plasticizers, and heavy metals leach and eventually seep into the environment, contaminating the land and water. Five years after being added to sewage sludge and soils, reports have indicated that microplastics (Dubaish and Liebezeit, 2013) and synthetic polymer fibres can still be found (Alabi *et al*., 2019).

According to several studies, MPs have a negative effect on soil biota (de Souza Machado *et al.*, 2018) and soil characteristics (Ren *et al*., 2021). Although crops use the nutrients from the biosolids (dry sludge), MPs are retained in the soil and are transported by physical, chemical, and biological processes all the way through the soil system (Wong *et al*., 2020). Additionally, by modifying the soil's porosity and moisture content, MPs may alter the relative distribution of aerobic and anaerobic microbes, hence altering the oxygen flow in the soil (Yaseen *et al*., 2022). The extinction of native microorganisms and the loss of microhabitat are possible outcomes of MP alteration in pore spaces (Veresoglou *et al*., 2015).

Marine life is heavily exposed to plastics that have different sizes and chemical compositions. When marine animals such as duck, dolphins, fish, fowl, turkey, tortoises etc. come into contact with large plastic particles, they become entangled and trapped, which increases the likelihood that they may suffer injuries or premature death (Obebe and Adamu, 2020; Yong *et al*., 2020). Furthermore, when marine animals swallow plastics, their digestive systems are blocked and their ability to properly consume food is hampered, leading to asphyxia and starvation (Yong *et al*., 2020). Sea turtles and other species that mostly eat jellyfish are primarily impacted by marine pollution caused by plastic wastes because they frequently mistake discarded plastic bags for jellyfish. Similar situations frequently occur with seabirds, who misidentify plastic garbage for their natural prey or mistake microplastics for cuttlefish or fishes (Alabi *et al*., 2019). There is little evidence to suggest that terrestrial animals are immune to the chemical toxicity of plastics and may even have systemic effects. Furthermore, although the consequences of these systems are still unknown, animals that eat plastic may pass it on to other creatures through reproduction and the food chain (Bucci *et al*., 2020; Hu *et al*., 2022).

Plastics can pose a risk to human health because of their additives such as plasticizers or monomeric building blocks like bisphenol A, or antimicrobial polycarbonate (Proshad *et al*., 2018). Plastics release several hazardous materials into the environment. We focus on those that are of primary concern when it comes to plastics, like phthalates and bisphenol A (Proshad *et al*., 2018). Most people are familiar with bisphenol A (BPA) as the monomeric component of polycarbonate plastics (Proshad *et al*., 2018).

There are three basic ways that plastics are introduced to humans: through ingestion, inhalation, and skin contact (Bidashimwa et al., 2023). These sources include food, water, and consumer products. Humans are known to ingest 0.1–5 g (or 0.004–0.18 ounces) of micro- and nanoplastics (smaller than 100 nm) on average per week, according to recent research, although the exposure–outcome relationship has not yet been thoroughly studied (Bidashimwa et al., 2023). The fact that plastic pollution contributes to the spread of infectious diseases carried by vectors is among the most compelling evidence of the negative impacts of plastic pollution on human health. An increasing amount of data indicates that diseases and vectors thrive in places with high population densities and inadequate sanitation because of the presence of macro- and microplastic trash (McCormick *et al*., 2014).

Both on land and in water, pathogenic species carried by plastic include germs that are harmful to humans, mosquitoes that spread dengue and Zika, and snails that carry schistosomes (Bidashimwa *et al*., 2023). The effect of plastics on the availability and safety of seafood represents another real hazard to human health. Plastics have an effect on marine life at all food chain levels, which results in a growing concentration of substances in organisms' tissues at successively higher levels in the food chain (Awuchi and Awuchi, 2019; Beaumont *et al*., 2019). Consuming seafood may therefore expose them to more toxins and plastic particles. Because high-income countries are the primary manufacturers of plastic while low- and middle-income nations bear the brunt of the pollution's effects, plastic pollution is also a social justice issue (Bidashimwa *et al*., 2023).

2.9 Sources of and types of microplastics

There are two types of microplastic (MPs) sources which are primary and secondary. Primary MPs come from recycling and micro-cleaning particles in personal care products, as well as spills that occur during the plastic manufacturing process (Anderson *et al*., 2017). Certain products, such as face scrubs, have been noted as possibly significant initial sources of microplastics (MPs) in the environment, particularly in marine environments (Conkle *et al*., 2018). Secondary microplastics are created from broken fragments of bigger plastic items that come from a variety of sources, including synthetic fibres produced during laundry, marine litter, landfill waste, and agricultural or industrial processes. According to Zhao *et al*. (2015), thermo-degradation, thermo-oxidation mechanical forces, biodegradation and photolysis processes cause the bigger plastic waste to break down into smaller plastic particles. Because there are so many different sources and pathways involved, it can be difficult to determine the origins of secondary MPs (Figure 2.3) (Stolte *et al*. 2015).

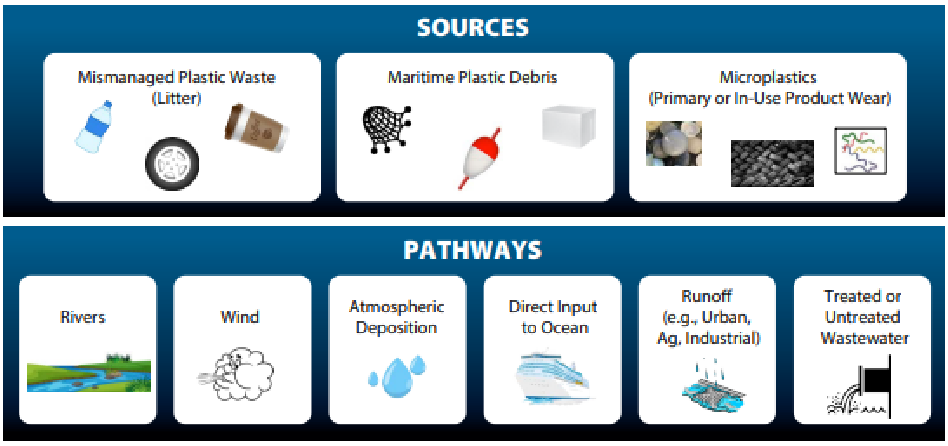

Figure 2.3: Sources of microplastics and pathways to aquatic environment (Rochman, 2020)

2.10 Distribution of microplastic in drinking water treatment plants (DWTPs)

Microplastics in DWTPs have drawn more attention than those in DWTPs (Eerkes-Medrano et al., 2019; Novotna et al., 2019). But since MPs in drinking water may be harmful to human health, this is a problem that is gaining more attention (Eerkes-Medrano et al., 2019; Shen et al., 2020; Vethaak and Legler, 2021). It is noteworthy that, in most situations, the amount of microfibres found in DWTP influents is significantly less than that found in WWTP influents. This is most likely because of the water's source; in DWTPs, influent is drawn from a variety of water sources (reservoirs, aquifers, etc.), but in WWTPs, influent is primarily wastewater from urban areas that enters the sewage system.

2.11 Microplastics removal treatment units in drinking water treatment plants

Drinking water treatment is comparable to wastewater treatment, with the exception that there is no additional treatment to remove organic materials. The rationale is that, in comparison to municipal and industrial wastewater, raw water used to feed DWTPs typically has a much lower organic load and is of higher quality (Tang and Hadibarata, 2021). Similar to wastewater treatment, the process of treating drinking water begins with grit and screening. Alum is then added to the raw water to cause flocculation and coagulation (Tang and Hadibarata, 2021). After that, the mixture goes into the sedimentation tanks, where much like in wastewater treatment, the heavier floc particles sink to the bottom (tang and Hadibarata, 2021). The water is filtered rather than subjected to secondary treatment in wastewater treatment. Coagulation-Flocculation involves addition of chemicals that encourage particle aggregation, which leads to subsequent particle settlement in a clarifier (sedimentation process) (Shen *et al.,* 2020; Sol *et al*., 2020). A filtration procedure is used to further purify the water. Depending on the treatment method, pore size and filter material (gravel, sand, activated carbon) change. The filtration process reduces turbidity and removes microorganisms (Rahman *et al*., 2014; Shen *et al*., 2020; Tang and Hadibarata, 2021). The final step in ensuring that there are no pathogenic agents in the drinking water is to disinfect it. The disinfection methods that are most commonly used are ultraviolet irradiation, ozonation, and chlorination (Figure 2.4) (Eerkes-Medrano *et al*., 2019; Novorta *et al*., 2019).

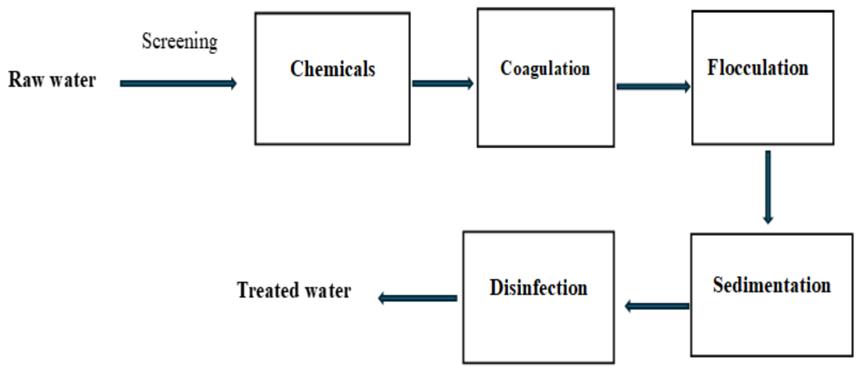

Figure 2.4: Drinking water treatment units.

2.12 Distribution of microplastics in wastewater treatment plants (WWTPs)

The fate of microplastics during wastewater treatment has received less attention from scientists than the presence of wastewater-based microplastics in the aquatic environment, which has recently caught their attention (Ziajahromi *et al*., 2016). Microplastics are introduced into wastewater treatment plants in various forms, including films, fiberes, granules, pellets and foams in which fiberes and fragments account 57 % and 34 %. Fiberes with high length to width ratio and other physical characteristics make it challenging to remove them from wastewater treatment facilities (Ngo *et al.,* 2019). In WWTPs, more than 30 distinct polymeric polymers with various chemical compositions have been found. The type of polymer that is abundant depends on whether it comes from an industrial, agricultural, or urban source and transports household wastewater from the adjacent city into the wastewater treatment facility (Ngo *et al*., 2019; Sun *et al*.,2019). In the primary and secondary settling processes, larger, highly dense MPs settle down with sludge, whereas smaller, less dense MP stay suspended in water and are more likely to pass with the final influent into the receiving water body (Rolsky *et al*., 2020).

2.13 Microplastics removal treatment units in WWTPs

Wastewater treatment plants consist of pretreatment, primary treatment, secondary treatment, and tertiary treatment units. Microplastics removal efficiency has not taken into account while developing WWTPs (Figure 2.5) (Acarer, 2023). Microplastics originates from commonly used personal care products, washing machine wastewater, and leachate from solid waste landfills and ends up in WWTPs in a variety of polymeric structures, morphologies, sizes, and colors (Acarer, 2023). Given the treatment capacity of the WWTPs, even in cases where the MP concentration in the effluent is low and/or the MP removal efficiency is good, very large quantities of water containing MPs are discharged into the aquatic environment, where MPs accumulate (Acarer, 2023).

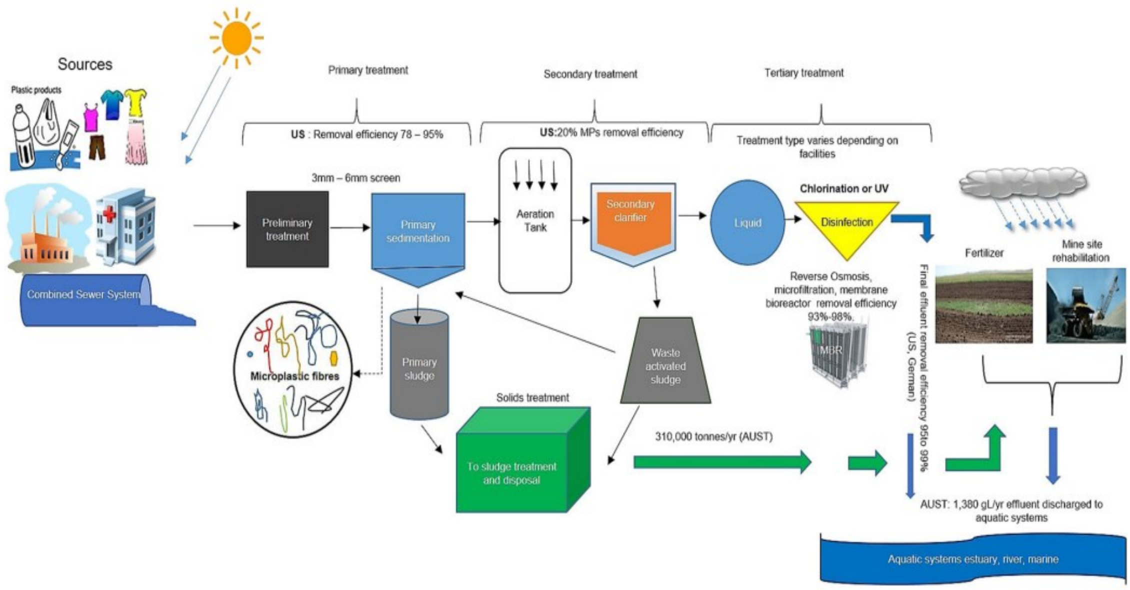

Figure 2.5: WWTPs units (Raju *et al*., 2018).

2.13.1 Flotation and primary settlement

In wastewater treatment, primary settling tanks are used to remove high-efficiency suspended solids using gravity before biological treatment (Acarer, 2023). Flotation, as opposed to sedimentation, is a process that uses gas bubbles to propel materials with a lower density than water against gravity to the water's surface. These materials can be skimmed off the water's surface (Acarer, 2023). High-density MPs have a tendency to settle in water, whereas low-density MPs typically float. For this reason, it is sense to use precipitation to separate MPs like PET that have a higher density from the wastewater. Furthermore, low-density or medium-density MPs that are not precipitable may be removed using the flotation approach. According to Talvitie *et al*. (2017), dissolved air flotation (DAF) was able to remove 95 % of the MPs in wastewater, reducing the amount from 2 MP/L to 0.1 MP/L. Long *et al*. (2019), found that removal efficiencies of 92, 87.8, 94.8, and 96.4 % were attained for PP, PE, PS, and PET type MPs, respectively. They also observed that the removal rate of these MPs rose in the WWTP with increasing density.

2.13.2 Biological treatment and secondary settling

Biological treatment is a step in the secondary treatment stage that guarantees the removal of organic contaminants from wastewater by microorganisms in a controlled environment (Acarer, 2023). Microorganisms facilitate the removal of organic debris and nutrients in anaerobic, anoxic, and aerobic processes. Microorganisms' activities also eliminate MPs when dissolved organic debris is eliminated (Kwon *et al*., 2022). The removal of MPs from aeration tanks can be attributed to their hydrophobic structure, which allows them to cling to microbes and sludge (Hongprasith *et al*., 2020). According to Liu *et al*. (2019), anaerobic, anoxic, and aerobic processes were found to reach 16% MP removal efficiency, however Yang *et al*. (2019) claimed that anaerobic, anoxic, and aerobic processes were responsible for 54.47% of MP removal. Similarly, it was reported that the secondary settling tank came after the activated sludge tank to reach 60.0% (Pittura *et al*., 2021) and 74.8% (Bretas Alvim *et al*., 2020) MP removal efficiency. Thus, variations in removal efficiencies may result from the features of MPs and WWTP operation, even when the same biological treatment technique is used.

2.13.3 Filtration

A popular technique for treating wastewater and drinking water is membrane filtration. Because of their superior qualities, affordability, and ease of production, membranes made of various polymers, including polyethersulfone (PES), polyvinylidene fluoride (PVDF), polycarbonate (PC), and PE, PP, and PA, are frequently used in the treatment of drinking water and wastewater (Himma *et al*. 2016; Acarer *et al*. 2021; Li *et al*. 2021; Pizzichetti *et al*. 2021;). Reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) are the pressure-driven membranes that are classified in decreasing order of pore size. With the MF membrane having the largest hole size among all four pressure-driven membranes, ranging from around 100 nm to 10 µm, it is expected that it can hold MPs of less than 5 mm. According to Pizzichetti *et al*. (2021), a membrane consisting of three distinct polymers and having a pore size of 5 µm may hold on to 99.6–99.8% of PA MPs and 94.3–96.8% of PS MPs. Although these polymeric barriers keep MPs away from water because they are composed of polymers, they may also fracture or rupture, allowing MPs to migrate toward the water (Tang and Hadibarata, 2021).

2.13.4 Membrane bioreactors (MBRs)

Membrane bioreactors (MBRs) are systems that integrate membrane filtration (often MF and UF) with biological treatment (Mabrouki *et al*. 2020). When compared to other treatment techniques utilized in the treatment of water and wastewater, MBRs have a superior MP removal efficacy of over 99% (Talvitie *et al*. 2017; Lares *et al*. 2018). However, according to Bayo *et al*. (2020), MP removal efficiency with MBR is 79.01%. The MP removal efficiency of the membrane is affected by several factors, including the MP that has been removed, its morphological characteristics, the membrane's material, its properties, the interaction between the membrane and MP, the presence of other pollutants in the wastewater, and membrane contamination (Dey *et al*. 2021).

2.13.5 Reverse osmosis

The pollutants in wastewater that MF, UF, and NF membranes are unable to separate because of their smaller pore diameters (< 1 nm) and lower molecular weight separation limits (MWCO) (less < 200 Da) are removed by reverse osmosis membranes. Nevertheless, recent research has shown that wastewater may still contain sizable concentrations of MPs even after it has been treated tertiary by RO membranes (Ziajahromi *et al*. 2017; Sun *et al.* 2021; Cai *et* *al*. 2022). According to Cai et al. (2022), MPs in a WWTP's influent achieved 93.2 and 98.0 % MP removal efficiency after MBR and RO, respectively, after primary sedimentation, biological treatment, MBR, and RO procedures were implemented.

2.13.6 Coagulation

The process of coagulating water involves introducing chemicals to balance the charge of colloidal particles that float on the surface and prevent precipitation. Studies on the removal of MPs from water by coagulation have typically been conducted in surface water such as river and lake water (Lapointe *et al*. 2020; Na *et al*. 2021; Xue *et al*. 2021) and deionized water (Na *et al*. 2021). This is because coagulation is a process that is specifically used in drinking water treatment. In WWTPs, coagulation can be employed as a tertiary treatment to eliminate total phosphorus that cannot be eliminated entirely. Nonetheless, there are still surprisingly few studies on MP removal in WWTPs using jar tests and the coagulation process. According to Kwon *et al*. (2022), the overall MP removal efficiency in wastewater treated up to secondary treatment was 91.63 and 97.74% for domestic industrial and domestic wastewater, respectively. Following coagulation, these removal efficiencies increased to 96.33 and 98.1%.

2.14 Human perceptions towards plastic pollution

Understanding attitudes, behaviours, and perceptions of plastics is crucial, as human actions significantly contribute to environmental challenges like marine litter (Henderson and Green, 2020). Plastic products are deeply integrated into daily life, making it difficult for individuals to reduce or avoid their use, which can discourage efforts to address plastic pollution (Tang, 2023). Individual behaviour is shaped by awareness, perceptions, attitudes, and concerns about plastic pollution, as well as motivations to participate in solutions. At the societal level, laws and policies regulating consumption and waste management play a pivotal role in shaping behaviour (Devi *et al*., 2017). Recognizing these influences is vital for developing practical strategies to reduce plastic pollution in the environment (Pahl and Wyles, 2016; Hartley *et al*., 2018). Furthermore, understanding public perceptions is essential for predicting responses to initiatives and promoting collective efforts to address this pressing issue (Tang, 2023).

Education is a key component of the strategy for raising awareness and promoting behavioural and attitude change. To stop plastic pollution, people must be directed and counselled on how to dispose of plastic. It is necessary to discuss the alternatives that local restaurant and company owners can use for stocking and packing goods with them (Obebe and Adamu, 2020). Public awareness of the possible harm that plastic trash pollution may do to the environment and public health must be raised. This will go a long way to minimize the pollution rate and preserve the quality of the environment. People must be informed about the chemicals found in plastic products and how they may affect their health. Information resources about waste management systems and strategies to reduce plastic pollution must be included in educational curricula at all educational levels (Alabi *et al*., 2019).

2.14 Waste management in South Africa

Waste management is a pressing issue in South Africa, as in many other developing countries. Many municipalities face challenges in providing effective waste management services, with approximately 32% of South African households lacking access to basic refuse collection (Strydom, 2018; Rodseth *et al*., 2020). Landfilling remains the dominant waste disposal method, with about 90% of all waste generated being landfilled (Department of Environmental Affairs, 2012). However, this is not always done per regulated standards, leading to approximately 50% of formally disposed waste ending up in deficient landfills (Goga *et al*., 2022). Unlike some other nations, South Africa does not implement commercial-scale waste incineration (Goga *et al*., 2022). The South African plastics industry converts over 1.8 million tons of locally produced and imported polymer annually, along with recyclates (South African Department of Trade and Industry, 2020). Recycling has been practiced for many years, initially driven by social needs and resource requirements (Nampak, 2002). Programs like Collect-a-Can, established in 1976 by Metal Box and Crown Cork (now Nampak and ArcelorMittal), have long encouraged the recycling of beverage cans. However, household recycling participation remains voluntary (Collect-a-Can, 2011).

In 2010, only 4.0% of urban South Africans regularly recycled their paper and packaging, and by 2015, this increased to 7.2% of households routinely recycling more than half of their recyclable materials (Strydom and Godfrey, 2016). Despite this progress, the country continues to delay in recycling efforts compared to developed countries. The evolution of South Africa's waste management policies has played a critical role in shaping the sector. The Environmental Conservation Act (Act 73 of 1989) marked the start of formal waste regulation, introducing guidelines for waste management and providing the first official definition of waste (Government Gazette, 1989). Its focus, however, was primarily on managing and controlling waste disposal sites, aiming to mitigate the environmental impact of poorly managed landfills (Godfrey and Oelofse, 2017). Between 1989 and 2007, there were limited policy developments. Key milestones included the release of the White Paper on Integrated Pollution and Waste Management (Department of Environmental Affairs and Tourism (DEAT), 2000) and the First National Waste Management Strategy (NWMS) (DEAT, 1999). The NWMS of 2011 aimed to divert 25% of recyclables from landfills by 2016 (Department of Environmental Affairs, 2011). However, achieving this target was hindered by a lack of reliable waste data (Strydom, 2018). A DEA assessment conducted between 2007 and 2009 revealed that 431 of South Africa's 581 waste disposal sites (74%) were unlicensed, highlighting significant gaps in infrastructure and compliance (Pienaar *et al*., 2014).

Policies remain critical in addressing waste challenges, especially in transitioning toward sustainable plastic use and a circular economy. These include regulatory approaches (such as bans and limitations), economic instruments (like taxes and subsidies), and educational initiatives to raise public awareness (Jambeck *et al*., 2015). Despite these efforts, South Africa continues to rely heavily on landfilling, with insufficient progress toward widespread recycling or alternative disposal methods (SAPRO, 2020). In reviewing policy evolution, Godfrey and Oelofse (2017) noted a gradual increase in waste policy initiatives since the 1989 Environmental Conservation Act. However, the country still falls behind developed nations in reducing reliance on landfills and promoting recycling. While South Africa has made strides in recognizing the importance of waste management, there remains a critical need for effective implementation and enforcement to address the ongoing challenges.

2.15 Municipal Wastewater Management and Regulation Framework in South Africa

The deteriorating state of municipal wastewater and sewage treatment infrastructure in South Africa is a significant contributor to widespread pollution and public health crises, particularly in impoverished communities. Recent cholera outbreaks illustrate the severe consequences of inadequate wastewater management (Mema, 2010). Effluents from industrial and domestic sources are the second-largest contributors to water pollution, introducing both chemical and microbial contaminants into South Africa's water bodies (Sibanda *et al*., 2015; Chetty & Pillay, 2019). Researches indicate that many municipal wastewater treatment plants (WWTPs) in South Africa fail to treat wastewater to acceptable standards (Morrison *et al*., 2001; Momba *et al*., 2006; Edokpayi *et al*., 2017). Some plants even discharge industrial effluents directly into surface water sources without adequate treatment (Ntuli, 2012), further exacerbating pollution. Additionally, many WWTPs lack the capacity to effectively remove non-biodegradable waste and recalcitrant heavy metals, leading to their accumulation in surface water bodies (Mema, 2010). To regulate wastewater discharge, the South African National Standard (SANS 241) and the National Water Act (NWA) No. 36 establish guidelines enforced by the Department of Water and Sanitation (DWS) (Negwamba & Dinka, 2019). The Green Drop system serves as a performance assessment tool for wastewater treatment facilities, evaluating Water Service Authorities (WSAs) and their providers. This system incentivizes compliance by rewarding municipalities that meet the required standards and penalizing those that fail to do so (Khuzwayo & Chirwa, 2020).

CHAPTER THREE: OCCURRENCE AND REMOVAL OF MICROPLASTICS IN WASTEWATER TREATMENT PLANTS: PERSPECTIVES ON SHAPES, TYPES AND DENSITY

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Conference attended

Mabadahanye, K.; Dalu, M.T.B.; Dalu, T. 2024. Occurrence and removal of microplastics in wastewater treatment plants: perspectives on shape, type, and density. NRF Next Generation and Emerging Researcher Symposium. 23-25 October 2024. Boksburg, South Africa.

3.1 Introduction

Every day, there is a greater risk of plastic pollution harming the environment (Acarer, 2023). Plastic products and materials are widely employed in both industry and daily life. China (30.0%), Europe (17.0%), and North America (18.0%) produced most of the raw materials used to make the nearly 360 million tons of plastic produced globally in 2018 (Li *et al*., 2021). Plastic output is anticipated to double by 2025 and quadruple by 2050 due to population growth, current global plastic consumption, and waste (Freeman *et al*., 2020). According to Eerkes–Medrano *et al*. (2015), plastic litter pollution is one of the most serious man-made hazards to the natural environment and is, therefore, a subject of growing concern. Due to their greater quantities and smaller sizes, microplastics are thought to be more common in the environment than macro- or mesoplastics (Karbalaei *et al*., 2018). Richard Thompson used the term "microplastics" in 2004 to refer to the very small plastic particles (less than 5 mm in size) that are found in surface waters and ocean sediment (Thompson et al., 2004). According to Estahbanati and Fahrenfeld (2016), microplastics can either be produced accidentally by the breakdown of macroplastics (secondary MPs) or purposefully produced. Microplastics are a significant component of plastic pollution, which persists in the environment due to the extensive use of polymers, low recycling rates, and resistance to decomposition (Dalu *et al*., 2021; Liu *et al*., 2021; Acarer, 2023).

Microplastics are categorized into primary and secondary types. Primary MPs are directly manufactured for various industrial and consumer applications, including packaging, vehicle construction, office equipment, personal care products, and air-blasting granules and pellets (Mani *et al*., 2015). Secondary MPs result from the degradation of larger plastic items through biotic processes such as hydrolytic degradation, photolysis, weathering, UV radiation, and abrasion (Ziajahromi *et al*., 2017; Arhant *et al*., 2019). These MPs are predominantly composed of widely used plastic types such as polyethylene (PE), polypropylene (PP), polyester (PL), polyamide (PA), polystyrene (PS), and polyethylene terephthalate (PET), and have a high specific surface area that enhances their ability to adsorb contaminants (Liu *et al*., 2021; Acarer, 2023). They enter sewage systems primarily when plastic particles are discharged from garments during household washing and laundry due to synthetic fabric abrasion, and from personal care products (Iroegbu *et al*., 2020; Acarer, 2023). Consequently, MPs are found in WWTPs and eventually in natural water bodies, posing risks to the environment and human health. Aquatic animals that consume microplastics may suffer from physical injuries including digestive tract obstructions and may be exposed to harmful compounds that are adsorbed on the MPs' surface. Heavy metals, persistent organic pollutants, and other dangerous chemicals are some of these substances (Rochman *et al*., 2013). Additionally, MPs can act as vectors for pathogens, further threatening aquatic life and potentially entering the human food chain through seafood consumption (Setälä *et al*., 2014).

Wastewater treatment plants (WWTPs) play a crucial role in managing MP pollution. However, despite their significant capabilities, they still release a substantial number of MPs into the environment (Turan *et al*., 2021; Dalu et al., 2023a,b). The MPs that enter WWTPs vary in polymer types, shapes, sizes, and colors (Acarer, 2023). Extensive research has been conducted on the detection and quantification of MPs in WWTP effluents and the removal efficiencies of these plants (Dyachenko *et al*., 2017; Xu *et al*., 2019; Turan *et al*., 2021). Although current technologies can remove large plastics from wastewater, they are not specifically designed to retain small MPs effectively (Mintenig *et al*., 2017). Conventional WWTPs can achieve removal efficiencies of 64–99%, but this is insufficient given the volume of MPs discharged daily (Franco *et al*., 2021).

The purpose of this review is to thoroughly evaluate the prevalence, origins, disposition, and removal methods of MPs in wastewater treatment plants (WWTPs) in various global regions. This study aims to advance awareness of the difficulties and opportunities involved in managing microplastic pollution in WWTPs by synthesizing existing research and identifying knowledge gaps. Previous studies have focused on various aspects of microplastic removal in WWTPs, such as the efficiency of different treatment processes (primary, secondary, and tertiary treatments), the impact of operational parameters, and the fate of microplastics in sludge. However, significant gaps remain, particularly in understanding the long-term effectiveness of different removal technologies, the behavior of microplastics under different conditions, and the development of standardized methods for microplastic quantification and characterization in WWTPs.

3.2 Materials and methods

The methodology used for this review, which examined the levels of microplastics in WWTPs, was produced to give a systematic and in-depth analysis of previous work. An internet search of mostly journal databases such as Google Scholar, Springer, ScienceDirect, Frontiers, and important institutional websites was used to compile the data (Tang, 2021). A variety of keywords, including “microplastics”, “WWTPs”, and “prevalences and abundances”, were used in the initial searches. A search was restricted to peer-reviewed articles from research written in English and published between 2015 and 2023. A total of 132 articles were screened based on relevance to the study’s focus on wastewater treatment and microplastic pollution and the alignment with the research objectives. Out of these, 41 articles were selected . Information about MP pollution, WWTPs, microplastic concentrations, microplastic per liter (MP/L), removal rates, types of microplastics, polymer types, and colors in the influents and effluents of WWTPs was extracted.

3.3 Results

3.3.1. Abundances of microplastics and removal rates

The study found that Spain and Lithuania had high concentrations of MPs in the influent, with values of 796.05 MP/L and 2473 MP/L, respectively. In the effluent, the concentrations of MPs decreased to 994 MP/L and 38.55 MP/L. However, Iran was found to have low concentrations of MPs in the effluent, with 5.3 MP/L compared to Spain, while Thailand had low concentrations of MPs in both the influent and effluent with values of 0.4 MP/L and 0.05 MP/L (Table 6.1). Our analysis showed that the water treatment plants in Iran had high MP removal rates, with 99.1% of the MPs being removed from the influent. Treatment plants in Turkey only had a 48% MP removal rate, which suggests improvement is needed. The removal rate was unusually low in Lithuania, with high MP abundance, which was an interesting phenomenon given the country's significant microplastic contamination. The data show that MPs have been significantly removed in Morocco. In the first plant, influent concentration dropped from 188 MP/L to 50 MP/L, indicating a 74% removal rate. The second plant showed better performance, attaining an 87% removal rate where influent concentrations decreased from 519 MP/L to 86 MP/L (see Table 3.1).

Table 3.1. The abundance of microplastics in the influent and effluent and the removal rate of WWTPs in different countries in microplastic per liter (MP/L).

Location	WWTPs Unit	Influent (MP/L)	Effluent (MP/L)	Removal Rates (%)	References
China	Primary sedimentation, secondary sedimentation, filtration pool, dewatering	16.0	2.9	81.9	Ren *et al*., 2020
Finland	Screening, grit separation, primary clarification, biological treatment with activated sludge, final sedimentation, and disinfection	57.6	1.0	98.3	Lares *et al*., 2018
Iran	Inlet, outlet, and anaerobic digested sludge	180.0	5.3	99.06	Oveisy *et al*., 2022
Iran	Secondary settling tank	206.0	94.0	54.4	Yahynezhad *et al*., 2021
Kuwait	Reverse osmosis and ultrafiltration membranes, aeration tanks	120	1.5	98.8	Uddin *et al*., 2022
Kuwait	Oxidation ditch system, sand filtration, UV treatment, chlorination	226.5	11.5	94.9	Uddin *et al*., 2022
Kuwait	Vertically activated sludge process for biological treatment,	132.0	5.0	96.2	Uddin *et al*., 2022

	Distributed Control system technology				
Lithuania	Screening, grit chambers, sedimentation tanks, aeration tanks, sludge dewatering system, nitrogen and phosphorus removal	2473 MP/L	994.0 MP/L	57.0	Uoginte *et al*., 2022
Morocco	Sedimentation, infiltration percolation, UV disinfection	188.0	50.0	74.0	Hajji *et al*., 2023
Morocco	Activated sludge treatment, aeration tanks, clarification tanks, mechanical filtration	519.0	86.0	87.0	Hajji *et al*., 2023
Spain	Pretreatment (grease trap, grit chamber, several screens), primary clarifiers, simultaneous nitrification and denitrification in a bioreactor, secondary clarifiers, anoxic tank, anaerobic digestion to treat solid fraction	796.1 MP/L	38.6 MP/L	84.0	Franco *et al*., 2023
Thailand	Equalization tank, grit chamber, aeration tanks, sedimentation tanks, sludge dewatering	0.4 MP/L	0.1 MP/L	86.5	Maw *et al*., 2022
Turkey	Screening, ventilated sand and an oil chamber, preliminary sediment tank biological and chemical phosphorus removal units, aeration tanks, and final sediment tank	3.1 MP/L	1.6 MP/L	48.0	Akarsu *et al*., 2020
Turkey	Screening, preliminary sediment, aeration tanks, and final sediment tanks	2.6 MP/L 1.5 MP/L	0.7 MP/L 0.6 MP/L	78.0 60.0	Akarsu *et al*., 2020

United Kingdom	Primary settlement, activated biological anoxic treatment, activated biological aerobic treatment	–	1.5 MP/L	–	Tagg *et al*., 2020
USA	Primary screening, primary clarifiers, activated sludge, secondary clarifiers, sludge handling, dewatering (rotary press), disinfection	2.5 MP/L	15.5 MP/L	97.6, 85.2, 85.5	Conley *et al*., 2019

3.3.2. Microplastic types

Fibers and fragments were the most prevalent types of plastic pollution observed in influents and effluents in various global regions. For instance, plastic fibers make up over 70.0% of the influent and 68.0% of the effluent in Jakarta, Indonesia, while fragments make up ~24% of the influent and 26.0% of the effluent. Location affects how plastic contaminants in the influent are composed. Granules make up roughly 49.8% of the influent and 36.0% of the effluent in Xiamen, China, while microbeads make up roughly 1.0% of the influent and 2.0% of the effluent in Jakarta, Indonesia. Local elements and the sources of plastic waste in these areas, along with microplastics originating from remote areas through atmospheric deposition, are the main sources for these variations (Xiao *et al*., 2023). Large plastic objects like granules, pellets, and films are frequently reduced in quantity by wastewater treatment procedures. For instance, in Turkey, there is a little decrease in the percentage of plastic fibers from 87.7% in the influent to 86.5% in the effluent. The amount of small plastic fibers and fragments in the effluent after treatment usually remains constant or may even increase. For instance, in Korea, the fragment content significantly increased from 68.2% in the influent to 82.3% in the effluent. In South Tehran, Iran, plastic fragments increased slightly from 0.19% in the influent to 0.7% in the effluent, whereas in Korea, the fragments increased significantly from 68.2% in the influent to 82.3% in the effluent (Table 3.2).

Table 3.2. Types of microplastic found in the influent and effluent of WWTPs in different countries.

Location	Influent	Effluent	References
China, Xiamen	Pellet (2.5%), Fibers (17.7%), Fragments (30.0%), Granules (49.8%)	Pellet (5.6%), Fibers (30.4%), Fragments (28.0%), Granules (36.0%)	Long *et al*., 2019
Indonesia, Jakarta	Fibers (70.0%), Fragments (24.0%), Microbeads (1.0%), Film (3.0%), Foam (2%)	Fibers (68%), Fragments (26.0%), Microbeads (2.0%), Film (1.0%), Foam (3.0%)	Setiadewi *et al*., 2022
Iran, South of Tehran	Fibers (99.4%), Fragments (0.2%), Film (0.4 %)	Fibers (98.95%), Fragments (0.7%), Film (0.3%)	Oveisy *et al*., 2022
Korea	Fragments (68.2%), Fibers (31.8%)	Fragments (82.3%), Fibers (17.7%)	Park *et al*., 2020
Iran, Sari City	Fibers (35.0%), Pellets (39.0%), Fragments (22.0%)	Fibers (34.0%), Pellets (22.0%), Fragments (38.0%)	Yahyanezhad *et al*., 2021
Turkey	Fibers (54.8%), Film (18.5%), Fragments (26.8%)	Fibers (44.4%), Film (30.2%), Fragments (25.4%)	Gundogdu *et al*., 2018.
Turkey	Fibers (87.7%), Film (2.4%), Fragments (10.0 %)	Fibers (86.5%), Film (2.5%), Fragments (10.8%)	Gundogdu *et al*., 2018
United States	–	Fibers (59.0%), Fragments (33.0%), Films (5.0%), Forms (2.0%), Pellets (1.0%)	Mason *et al*., 2016

3.3.3. Polymer types

Region-specific variations in plastic waste composition and treatment effectiveness are highlighted by the many major polymer types that are present in different countries (Table 3.3). In several places, including Changzhou, China, and Turkey, polyethylene terephthalate (PET) is a predominant polymer type in both the influent and effluent. When compared to the influent, polypropylene (PP) dominates the effluent in Korea (63.3%), while the influent PP was 39.6%. Another important kind of polymer to consider is polyethylene (PE), which is present in both the influent and effluent in different countries. PE is persistent in the environment, as evidenced by its presence in the influent and effluent from different regions. Although PE is constantly present, the amount of it might fluctuate depending on the area and how well wastewater treatment systems remove it. The overall microplastic pollution in sewage systems is mostly caused by PE, along with other important polymers including PET and PP.

Table 3.3. Distribution of polymer types in the influent and effluent of WWTPs in different countries by percentages. Abbreviations: PE—polyethylene, PET—polyethylene terephthalate, PP—polypropylene, PS—polystyrene, PA—polyamide.

Location	Influent	Effluent	References
China, Changzhou	Rayon (41.8%), PET (27.6%), PP (15.52%), PE (6.1%), PS (3.4%), PE–PP (2.1%)	Rayon (43.5%), PET (29.2%), PP (14.5%), PE (6.28%), PS (2.12%), PE–PP (1.51%)	Xu *et al.*, 2019
China, Xiamen	PE (26.9%), PP (30.2%), PS (10.3%), PE + PP (6.3%), PP + PE (5.1%), PES (3.3%), PET (7.5%), PA (9.9%)	PE (17.9 %), PP (34.8 %), PS (9.6%), PE + PP (4.7%), PP + PE (13.9%), PES (1.1%), PET (7.5%), PA (10.1%)	Long *et al.*, 2019
Korea	PP (39.6%), PE (25.6%), PET (21.3%)	PP (63.3%), PE (13.8%), PET (13.3%)	Park *et al.*, 2020
South Africa, Gauteng	–	PVC (47.8%), PET (17.4%), PA (13.1%), PE (4.3%)	Vilakati *et al.*, 2021
Turkey	PE (29.2%), PET (50.8%), PP (13.8%)	PE (31.3%), Nylon–6 (6.3%), PET (43.8%), PP (18.8%)	Gundogdu *et al.*, 2018
Turkey	PE (23.8%), PET (61.9%), PP (11.9%)	PE (18.8%), PET (68.8%), PP (12.5%)	Gundogdu *et al.*, 2018

Notes: Abbreviations: Polypropylene (PP), Blend of Polyethylene and Polypropylene (PE + PP), Polyethylene Terephthalate (PET), Blend of Polypropylene and Polyethylene (PP + PP), Polyether Sulfone (PES), Polyamide (PA), Polyvinyl Chloride (PVC).

3.3.4. Microplastic colours

Microplastics exhibit a wide range of colors influenced by environmental factors such as consumer habits, industrial activities, waste disposal methods, and local environmental conditions. Black and transparent MPs appear to be predominant in the influent and effluent across several studied locations, including China, Indonesia, and Iran. According to the collected data, black and transparent plastics are extensively used in various products and contribute significantly to microplastic pollution in these countries. White MPs dominate in Xiamen, China, and Thailand, comprising a substantial portion of MP composition in these regions. Additionally, red and blue MPs are notable in several areas, such as Indonesia, Iran, China, and Thailand, serving as potential indicators of MP sources (Table 3.4).

Table 3.4. Distribution of microplastic colors in the influent and effluent of WWTPs in different countries by percentages.

Location	Influent	Effluent	References
China	–	Black (36.6%), Transparent (33.8%), Blue (11.9%)	Yang *et al*.,2019
China	Black (5.8%), Yellow (8.1%), Red (9.8%), Blue (9.1%), Green (12.1%), White (35.5%), Clear (19.6%)	Black (9.3%), Yellow (5.1%), Red (10.1%), Blue (8.0%), Green (17.2%), White (30.4%), Clear (19.9%)	Long *et al*., 2019
Indonesia	Transparent (36.0%), Blue (10.0%), Red (22.0%), Brown (3.0%), Green (1.0%), Yellow (2.0%), Black (26.0%)	Transparent (35.0%), Blue (13.0%), Red (21.0%), Brown (6.0%), Green (3.0%), Yellow (5.0%), Black (17.0%)	Setiadewi *et al.,* 2022
Iran	Transparent (69.8%), Red (5.3%), Blue (9.2%), Brown (0.3%), Gray (0.1%), Orange (0.4%), Yellow (0.3%), Green (1.1%), Black (13.3%)	Transparent (67.5%), Red (6%), Blue (6.574%), Black (17.6%), Green (1.3%), Brown (0.2%), Gray (0.2%), Orange (0.5%), Yellow (0.4%)	Oveisy *et al*., 2022
Thailand	–	White (57.0%), Blue (17.0%), Red (13.0%), Brown (8.0%), Black (5.0%)	Maw *et al*., 2022

3.4. Discussion

The investigation of MPs in wastewater treatment plants (WWTPs) reveals that their presence in influent and effluent streams is influenced by various factors including the type and origin of microplastics, treatment processes used, the effectiveness of the removal technologies used in the WWTPs, and environmental conditions. Our analysis indicates significant microplastic contamination in influent waters, with varying levels of abundance observed across different geographical areas and WWTP types. Wastewater treatment plants in urban areas tend to have higher concentrations of MPs compared to those in rural areas, likely due to higher population density and greater industrial activities. This results in increased MP inputs from household wastewater, runoff, and industries (Akarsu *et al*., 2020). The analysis further revealed that the success rate of WWTPs in reducing MP pollution varies significantly depending on the treatment methods employed. For instance, WWTPs in Finland, Iran, and Spain which use comprehensive treatment units, including grit separation, screening, biological treatment, sedimentation, and disinfection, exhibited removal rates ranging from 84.0% to 98.3%. This contrasts with WWTPs in Turkey, where simpler treatment designs showed lower removal rates between 48.0 and 78.0%. These findings show the importance of advanced and multi-stage treatment processes in enhancing the removal efficiency of MPs. Based on our analysis, a considerable number of MPs still persist in the effluent although the total concentration of MPs can be greatly decreased by WWTPs. Despite mechanical, chemical, and biological treatments achieving up to 99.0% MP removal, the remaining MPs in the effluent still pose environmental risks (Talvitie *et al*., 2015; Carr *et al*., 2016).

Primary and secondary treatment stages are crucial in the elimination of MPs. Murphy *et al*. (2016) and Nafea *et al*. (2024) found that 80.0–90.0% of MPs are removed during these stages. Heavier MPs are eliminated by sedimentation during primary treatment, while lighter MPs are skimmed off with fats, oils, and grease. Screening techniques are effective in removing solid particles, anticipating a removal of 50.0–70.0% of total suspended solids (Westphalen *et al*., 2018). During secondary treatment, MPs may be biodegraded by bacteria and microorganisms. However, some studies report less than 90.0% removal efficiency (Dris *et al*., 2015; Talvitie *et al*., 2017; Ziajahromi *et al*., 2017). Tertiary treatment technologies, such as biological aerated filters and gravity sand filtration, have shown varying levels of effectiveness in removing MPs (Carr *et al*., 2016; Mintenig *et al*., 2016).

Our analysis also noted the prevalence of fibers and fragments as the dominant types of MPs in both influent and effluent streams. The high presence of synthetic fibers, particularly polyester microfibers, is attributed to their extensive use in textiles and household products. These fibers are challenging to remove due to their flat surfaces and large length-to-width ratios, which make them difficult to capture during treatment processes Talvitie *et al*. (2017). As people wear more clothing in the winter than in the summer, Browne *et al*. (2011) predicted that more microfibers would enter WWTPs during the winter.

The analysis of polymer types revealed that PP, PE, and PET are the most common in both influent and effluent streams. The widespread use of these polymers in household and industrial products explains their prevalence. For example, PET is commonly found in water bottles, food packaging, and synthetic clothing, contributing to its high presence in wastewater (Ngo *et al*., 2019). The color analysis of MPs provided insights into their potential sources. Transparent, white, black, red, and blue MPs were dominant, reflecting their diverse origins from industrial raw materials, personal care items, and household products (Zahra *et al*., 2022). Understanding the sources and behavior of these MPs is crucial for improving treatment designs and enhancing removal efficiency.

3.5. Conclusions

The data gathered from various regions about MPs in WWTPs show a diverse and varied situation. Various WWTPs use different treatment methods, exhibiting a broad variety of removal rates and efficiencies. Certain WWTPs, such as those in Finland, Iran, and Spain, demonstrate remarkable removal rates surpassing 98%, but other WWTPs such as one in Turkey struggle to efficiently reduce microplastic concentrations. In Iran and Spain, effective removal is attributed to comprehensive inlet and outlet treatments along with anaerobic digested sludge, resulting in rates of 99% and 84%, respectively. These methods likely succeed due to their integrated approach combining physical, biological, and chemical processes adapted to local environmental conditions, contributing significantly to reducing microplastic pollution. Different MP types such as fibers, pieces, films, and pellets are found in different regions, which reflect regional differences in industrial activities and consumption patterns. Additional complexity is added by the existence of various polymers, including PS, PP, PE, and PET. The observed geographic variability highlights the impact of regional influences on the profiles of MPs. The environmental damage is further compounded by the colors of MPs, which range from translucent to blue and white to black. To further reduce the amount of microplastics in WWTP effluents, our review emphasizes the need for ongoing research into the efficiency of various treatment systems. The data also highlight areas for further investigation, such as missing data on color profiles and removal rates. To tackle the worldwide problem of MP pollution, continuous investigation and the creation of focused reduction plans according to the various obstacles presented by MP compositions in various areas are necessary.

CHAPTER FOUR: INSTITUTIONAL ARRANGEMENTS AND ROLES WITHIN WATER AND WASTEWATER TREATMENTS IN THE VHEMBE DISTRICT, SOUTH AFRICA

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4.1 Introduction

Water shortage is a major concern worldwide (Wilson *et al*., 2019). According to the World Health Organization (WHO), (2017), over 2.1 billion people cannot access clean drinking water globally. Africa is the second driest continent after Australia, possessing only 9% of the world's renewable water resources to support approximately 15% of the global population (Wang *et al*., 2014). According to a report, 411 million people in Africa did not have access to basic services for drinking water in 2020 and 779 million people lack access to sanitation services (UNICEF and WHO, 2022). Water shortage is a result of inadequate and malfunctioning water and wastewater treatment facilities in Africa, particularly given the continent's rapid urbanization and population growth (Omosa *et al*., 2012; Wang *et al*., 2013; Adam *et al*., 2020). Water and wastewater treatment plants are crucial for preserving environmental integrity and protecting public health by cleaning water to acceptable environmental and human health standards (Obaideen *et al*., 2022; Samaila *et al*., 2022). Water treatment plants ensure the availability of safe drinking water by removing harmful contaminants and pathogens, while wastewater treatment plants reduce pollutants before water is released back into the environment (Jasim, 2020; Samaila *et al*., 2022). These treatment facilities contribute to reducing the danger of waterborne illnesses and promoting sustainable water supplies for communities (Obaideen *et al*., 2022; Jasim, 2020; Samaila *et al*., 2022).

More than 3 million people in South Africa still lack access to a basic water supply service, and 14.1 million people are without access to safe sanitation (Koppen *et al*., 2020). The Department of Water and Sanitation (DWS), (2017) reported that South Africa has limited water resources and projections indicate that by 2025, there will be more demand for water than supply due to growing demands from competing users such as agriculture and mining industries. The local and district municipalities in South Africa are responsible for treating wastewater in their respective areas. One example is the Vhembe District Municipality (VDM) in Limpopo, located in the northernmost province. Murei *et al*. (2022) reported that the majority of the water sources in the Vhembe District Municipality are unsafe for human consumption due to persistent faecal pollution, given that many people rely on surface water for drinking and other household purposes. The lack of water treatment infrastructure and poor sanitation practices in rural communities are linked to the spread of cholera epidemics (D'Mello-Guyett *et al*., 2020; Murei *et al*., 2023). The 2023 cholera outbreak in Hammanskraal, Gauteng Province, shows a serious problem of limited access to potable water, with the Rooiwal facility identified as the outbreak centre (Obasa *et al*., 2023).

According to the Constitution of South Africa (1996), access to sufficient and safe water is a fundamental human right, essential for survival. Section 27(1)(b) states that "everyone has a right to have access to sufficient food and water". Since independence in 1994, the South African government has made significant efforts to address rural inequalities and poverty inherited from the apartheid era (Molobela and Sinha, 2011); however, access to water services in most rural communities remains a big challenge. In recent years, the country's drinking water treatment infrastructure has expanded, with more than 1300 drinking water treatment works (WTWs) now in operation (Edokpayi *et al*., 2018; DWS, 2022). However, significant challenges remain, particularly in wastewater management. According to the Green Drop Watch Report 2023, there are 850 wastewater treatment works (WWTWs) across 144 municipalities, with 334 of these plants in a critical state (DWS, 2023). Despite efforts to improve infrastructure, persistent water access issues remain a significant barrier, as reported by Edokpayi *et al*. (2018) and Moropeng *et al*. (2018). These latter studies highlight the failures in achieving sustainable access to clean water in rural areas as a systemic problem, including low investment, inadequate maintenance of existing infrastructure, and a lack of focus on rural community needs. To ensure the sustainability and sufficient availability of water resources, Idoga *et al*. (2019) and Obasa *et al*. (2023) emphasize the need to strengthen institutional functions and adopt innovative approaches that encourage responsible management of water resources.

Institutional arrangements refer to the formal and informal norms and standards that define decision-making authority over shared resources, such as water, and the specific decisions related to its usage, management, enforcement, and monitoring (Hassenforder and Barone, 2018). Ostrom *et al*. (1994) developed the Institutional Analysis and Development (IAD) framework, which identifies key variables that influence the function of institutions in shaping social interactions and decision-making processes (Onate-Valdevieso *et al*., 2021; Sarr *et al*., 2021). According to the IAD framework, three primary variables must be considered: (i) "attributes of the community", (ii) "biophysical conditions", and (iii) "rules-in-use" (Figure 3.1) (Sarr *et al*., 2021). The "attributes of the community" refer to the characteristics of each stakeholder group—such as citizens, government organizations, and industrial producers—that influence their decision-making processes (Sarr *et al*., 2021). The "biophysical conditions" encompass both constructed and natural environmental aspects of the issue at hand (Sarr *et al*., 2021). Lastly, the "rules-in-use" indicate the formal and informal rules and customs that govern the situation (Sarr *et al*., 2021). Ostrom's IAD framework has been effectively applied in various contexts, including assessing the effectiveness and sustainability of soil and water conservation initiatives, analysing community participation in water use governance from alluvial aquifers, and understanding the political–economic dynamics contributing to air pollution while suggesting alternative solutions (Nigussiea *et al*., 2018; Tsuyuguchi *et al*., 2020; Onate-Valdevieso *et al*., 2021; Sarr *et al*., 2021). This study aims to assess the institutional arrangements, operational challenges, and environmental concerns affecting water and wastewater treatment plants in the Vhembe District Municipality. To achieve this, the study examines the governance structures affecting plant operations, assesses the operational challenges such as infrastructure and capacity constraints, and explores the environmental issues impacting plant sustainability such as water quality.

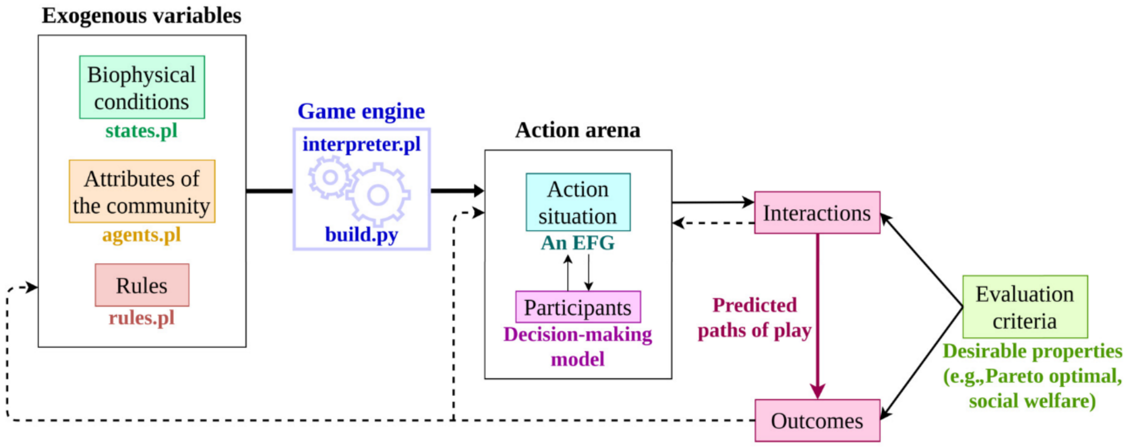

Figure 4.1. Institutional analysis and development framework with thematic analysis. Colored text outside boxes indicate either the scripts that contain information on the boxed component and/or the game-theoretical concepts that represent it. Adapted from Montes *et al*. (2022).

3.2 Methods

3.2.1 Research ethics

Before conducting the study, application documents were submitted to the District Manager of Vhembe District Municipality, seeking permission to conduct a study on water and wastewater treatment works within the district. The study was conducted only with the consent of the participants; no one had to be forced by the researchers to take part. We ensured compliance with informed consent requirements and protected participant's privacy by adhering to two common standards: (1) secrecy and (2) anonymity. Through in-person interviews, managers and process controllers from wastewater and water treatment plants provided qualitative data for the study. Every name was crossed out and replaced with an alphanumeric code in all the notes and transcripts. Access to the consent forms and hard copies of the interview notes was restricted to the researchers, who stored them in a locked box.

3.2.2. Study area

The study was conducted in the Vhembe District Municipality (VDM) (category C, meaning a municipality that has municipal executive and legislative authority in an area that includes more than one municipality—consisting of four category B (a municipality that shares municipal executive and legislative authority in its area with a category C municipality within whose area it falls—local municipalities: Collins Chabane, Thulamela, Makhado, and Musina (Vhembe District municipality, 2020/21).

Vhembe District Municipality is situated in the northern region of the Limpopo province, sharing borders to the east and west with the Capricorn and Mopani District Municipality (Vhembe District Municipality, 2020/21). According to Statistics South Africa's 2022 community survey, VDM covers an area of 27,969,148 km^2, with a population of approximately 1,653,022. The district has 21 water treatment works, and 28 wastewater treatment works recorded, and 13 of them are not owned and operated by the Water Services Authority (Vhembe District Municipality, 2020/21). Two local municipalities were selected in this study, which were Thulamela and Makhado Local Municipalities. Table 4.1 shows the demographics of the two local municipalities.

Table 4.1. Demographics of two selected local municipalities within the Vhembe District Municipality, South Africa. Data source: Statistics SA (2011).

Municipality	**Population**	**Male (%)**	**Female (%)**	**Educational Institution Attendance (%)**	**Working Age (15–64 Years) (%)**	**Young (0–14 Years) (%)**	**Formal Homes (%)**	**Access to Piped Water (%)**	**Access to Flushed Toilets (%)**
Thulamela Local Municipality	575,929	46.6	53.4	83.2	61.7	31.8	96.4	26.0	28.1
Makhado Local Municipality	502,397	47.0	53.0	81.9	61.6	31.3	94.7	26.0	29.7

Six sewage treatment works (STW) were sampled, which consisted of activated sludge ($n = 4$), oxidation package ($n = 1$), and package plants ($n = 1$) (Figure 4.2), with a capacity of 0.25–3.94 million liters per day (MLD). The plants experience sporadic incidents, with the Makhado STW being regular in terms of incidents. The water treatment works (WTWs) fell under the regional bulk WTW class ($n = 4$), with two belonging to the internal bulk WTW class. The capacity a day ranged from 2.85 to 18.9 MLD and the 3 and 3 WTWs experienced periodic and regular incidents, respectively.

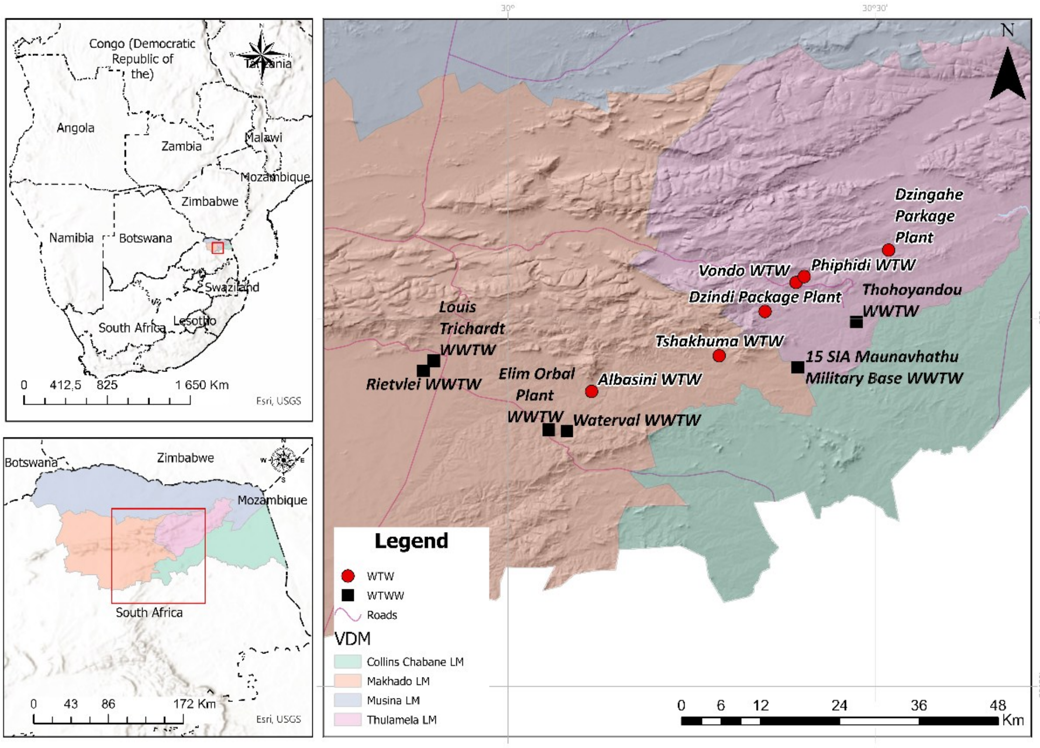

Figure 4.2. Location of the water and wastewater treatment plants that had workers surveyed for the current study within the Vhembe District Municipality, South Africa.

3.2.3. Sampling and data collection

The study employed a qualitative methodology that comprised semi-structured, in-depth interviews (Dalu *et al.*, 2020; Alsaawi, 2024) to evaluate and investigate the viewpoints of workers regarding water and wastewater treatments and their educational backgrounds, as well as the preservation and conservation of water resources. Semi-structured interviews are interview guides that consist of open-ended questions and topics related to the study (Belina, 2023). Interviews were conducted with 18 employees (water treatment works (WTW) $n = 10$; wastewater treatment (WWTW) $n = 8$), including supervisors, chief process controllers, and process controllers. Although the sample size of 18 workers is relatively small, it is appropriate given the qualitative nature of the study, which aims to provide in-depth insights rather than statistical analysis. Participants were selected based on their roles in the treatment plants, which puts them in a unique position to provide valuable information. The plant workers were interviewed for between 30 and 45 min during the day, either in English or TshiVenda. After conducting 18 interviews to fulfil the defined objectives, data saturation was reached because no new or relevant information surfaced (Dalu *et al*., 2020).

4.2.4. Data analysis

4.2.4.1 Thematic analysis

The study used a thematic approach to analyze and interpret the data, which involved identifying themes or patterns in qualitative data. The goal of this approach was to find and apply key themes to understand the study or discuss a subject (Maguire and Delahunt, 2017). Ostrom's Institutional Analysis and Development (IAD) Framework was used in this study to deductively analyze the governance of water resources in water and wastewater treatment plants in the Vhembe District Municipality (2020/21). The IAD framework was used to identify relevant themes for analysis, providing a clear and comprehensive approach to address the study's objectives and discuss the findings in detail (Figure 4.1).

4.3. Results and discussion

The findings of the semi-structured interviews that were done with the supervisors and process controllers from 12 water and wastewater treatment plants in the Vhembe District Municipality were grouped into five key research themes: (1) understanding of water/wastewater treatment system, (2) educational and demographic profile, (3) water quality assessments, (4) operational performance and regulatory compliance, and (5) water volume in waterworks plants. A thorough image of the existing condition of the treatment plants, staff perceptions, and institutional and operational challenges was created by categorizing the responses per these themes. Based on the themes and interview questions, particular codes were assigned to each response as part of the coding process. For instance, theme 1 (knowledge of water/wastewater treatment systems), participant 5, and question 24 are represented by the code T1/P5/Q1 (Table 4.2). This section was divided into five parts to analyze the findings according to the themes.

Table 4.2. Interview questions administered to water and wastewater treatment employees.

Questions	Theme
Do you understand the current water or wastewater treatment system at your workplace?	1
What treatment methods do you use to treat water or wastewater?	1
What is your gender?	2
What is your age?	2
What is your education level?	2
What is your length of time in post (job)?	2
What is your post (job) or level?	2
What is your position within the company?	2
How long have you ever been with the company?	2
Are you satisfied with the standard of treated water at your plant? If no, what do you think needs to be improved?	3
Do you drink the water treated at your plant? Would you consider it to be safe to be released into the environment?	3
What is the quality of surface waters or wastewater that you treat in your organization?	3
Do you regard water quality as a problem?	3
Do have the treated water tested? What tests do you do?	3

Questions	Theme
Where do you get your water from that you treat? Do you think your plant has sufficient capacity to meet every day needs?	4
How much water/wastewater do you treat per day? If so wastewater treatment: how often do you break down? And what do you do to mitigate breakdown and ensure water released into the environment meets standards?	5

Using Ostrom's IAD approach, we can systematically investigate the institutional structures, laws, and community attributes that affect water management efficiency in the Vhembe District's water and wastewater treatment plants (Sarr *et al*., 2021). Several studies on local resource management employed Ostrom's IAD framework (Nigussie *et al*., 2018). "Action arena" is the central component of the framework composed of actors and action situations (Nigussie *et al*., 2018; Sarr *et al*., 2021). In this study, water and wastewater treatment plants serve as the action arena, where various actors engage to manage water resources. Chief process controllers, supervisors, process controllers, and operators are among the key actors that have been identified. The action situation covers tasks including managing plant capacity, sourcing water, and purifying water to meet required standards (Figure 4.1).

4.3.1. Theme 1: Understanding of water/wastewater treatment system

The participants showed a strong understanding of the water and wastewater treatment systems at their workplaces. Several participants, mainly those holding supervisory roles, showed a thorough comprehension of the treatment procedures by naming techniques such as backwashing, activated sludge treatment, and rapid gravity sand filtration. This reflects the "rules-in-use" of Ostrom's framework within their organizational settings, indicating the established protocol and procedures governing treatment processes (Sarr *et al*., 2021). Ostrom's framework has been used in other research to examine different aspects of resource governance. Meinzen-Dick (2007), for instance, employed it to examine water administration in India and showed how regional norms and rules significantly affect the success of water management practices. Cox *et al*. (2010) demonstrated how institutional arrangement affects sustainability outcomes by applying the framework to forest management. Applying these frameworks to waste management, especially wastewater treatment, has important implications for South Africa. Standardized treatment processes and better water quality results are ensured by clear regulations and procedures, which also increase the efficacy and efficiency of wastewater treatment plants. In resource-constrained environments such as South Africa, where poor management can have serious environmental and public health problems, this is important.

"We use rapid gravity sand filter." (T1/P5/Q2)

"We do backwashing..." (T1/P9/Q2)

"screen-removal 24 h/grits removal daily, desludging the sludge to drying beds daily and disinfecting final effluent 24 h..." (T1/P14/Q2)

4.3.2. Theme 2: Educational and demographic profile

Participants displayed varying degrees of qualification, with other participants displaying the highest levels. The educational differences between the water management employees in the Vhembe district with no formal education and those with tertiary education emphasize important problems with human capital inefficient resource management. Historical and socioeconomic issues, such as the legacy of apartheid, which has affected access to high-quality education, and financial constraints that keep people from pursuing higher education, are at the basis of these inequities. The issue is, further, made worse by institutional obstacles, such as the scarcity and poor quality of training programs and hiring procedures that might not give priority to educational background. This is important because, as stated by Spellman (2020) and Hrudey *et al*. (2006), more education and training are associated with enhanced problem-solving abilities, technical knowledge, and adherence to safety and quality standards. According to Rivas *et al*. (2014), the quality and quantity of water delivered in Africa are frequently insufficient because operators are unable to manage some of the complicated water technologies now in use. This is because there are insufficiently experienced operators and technicians (Malima *et al*., 2022).

"…I am not educated…" (T2/P2/Q4)

"...I have grade 6..." (T2/P13/Q4)

"...I have (NQF level 7) BSc in Water and Sanitation..." (T2/P17/Q4)

Access to education and training is made more difficult by intersectional factors such as gender and geographical location, which can provide additional challenges for women and those living in rural areas. This is grounded in Ostrom's framework ensuring that the community's attributes are effectively used to accomplish sustainable and efficient water management, which eventually improves operational effectiveness and adherence to water quality regulations (Sarr *et al*., 2021). Certain approaches can be taken to overcome these challenges, by drawing on empirical studies that have effectively applied Ostrom's framework. In Uganda, for example, Meinzen-Dick and Nkonya (2007) emphasized the significance of local training programs that integrate gender-sensitive techniques and traditional knowledge. By making training available to women and people living in rural areas, these programs improved community engagement and compliance with water use restrictions. Pahl-Wostl *et al*. (2007), also talked about adaptive management techniques in water governance, putting a focus on ongoing education and involving stakeholders to address challenging water management issues.

4.3.3. Theme 3: Water quality assessment

The analysis of attributes and methods used by the participants to assess the quality of the water in their treatment plants reveals several significant patterns and trends through their responses. Specifically, there is a lack of consistency in testing techniques among treatment plants, as seen by different testing methods that participants reported employing, including measuring turbidity, testing pH, and chlorine, and monitoring the levels of ammonia, nitrate, and chlorine, as shown in Table 3.3.

Table 4.3. Testing parameters in water and wastewater treatment plants (Vhembe district municipality).

Participant	**Water Quality Parameters**									
	pH	**Chlorine**	**Turbidity**	**Temperature**	**Electrical Conductivity**	**Coliforms**	**Nitrate**	**Ammonia**	**Chemical Oxygen Demand (COD)**	**Phosphate**
T3/P8/Q14	✓	✓	✓		✓					
T3/P10/Q14	✓	✓	✓							
T3/P11/Q14	✓	✓	✓							
T3/P13/Q14	✓	✓	✓							
T3/P15/Q14	✓	✓		✓		✓	✓	✓	✓	✓
T3/P18/Q14	✓	✓						✓	✓	

✓ represents the parameters that participants test in their treatment plants.

The responses showed a crucial problem with water quality monitoring where only chlorine is tested, and other tests are ignored. According to Ostrom's framework, regarding the importance of institutional arrangements and community attributes in resource management, effective governance requires well-established regulations that are constantly followed (Adekola *et al*., 2023). In South Africa, there are key institutions responsible for establishing and implementing water quality standards. Unfortunately, there are deficiencies in these regulations that reduce their efficacy. For instance, the National Water Act (36 of 1998) requires extensive water use licensing, but insufficient enforcement and administrative obstacles usually cause the process to be delayed (Myburgh, 2018). Furthermore, even though the Water Services Act mandates that municipalities supply clean water, many treatment plants struggle with inadequate financing and poor infrastructure maintenance, which frequently results in water shortages and quality problems (Botha, 2020; Mapeyi, 2023). These regulatory deficiencies are made worse by insufficient resources for ongoing enforcement and monitoring as well as insufficient quality control procedures.

The lack of transparency and standardization in water quality monitoring methods is a serious problem that is demonstrated by this variability. However, the satisfaction of participants with achieving "recommended ranges" raises questions. The standards need to be clarified, as does whether they align with national drinking water standards (SANS 241:2015) (SANS 241). The South African National Standard (SANS) 241:2015 (SANS 241) specifies that critical criteria for drinking water include pH values between 5 and 9.7, turbidity levels below 1 NTU, and chlorine residual levels between 0.2 and 0.5 mg/L. It is essential to check whether these standards include all required water quality measures and are updated often to address emerging contaminants. In the North West province, Gumbi (2020) conducted a study that focused on several physicochemical parameters. The overall results for both research sites after the water treatment processes were consistent with the SANS 241 residential water quality criteria, except for the Mmabatho Water Treatment Plant's turbidity, electrical conductivity, total hardness, and calcium levels. The staff's educational and training backgrounds are closely related to the differences in testing methods and transparency, emphasizing the importance of human capital in Ostrom's framework for efficient water management.

"I am satisfied since we meet the provided standards. That standard is within recommended ranges" (T3/P17/Q10)

Participants expressed that they do consume the water treated at their plants, suggesting a certain degree of confidence in the safety and purity of the treated water. This shows that they are satisfied in the efficiency of their quality control and water treatment procedures. It also takes into account the practical aspects of their workplace, where drinking treated water might be the easiest or most convenient way for them to stay hydrated throughout their shifts.

"We do drink the water. We also do have a tap in the plant" (T3/P1/Q11)

"We do drink the water in the plant. The water is very safe because we are releasing it into the households" (T3/P2/Q11)

Five participants disclosed that they avoid consuming water from their plants due to their recognition of them as wastewater treatment plants but the water only being safe to be released into the environment. This offers significant insights into their understanding of the facility's purposes and their perspectives on water safety.

"Water is not safe to drink but to the environment is safe" (T3/P12/Q11)

"It is a wastewater, so we do not drink water from here" (T3/P15/Q11)

One participant has mentioned that since the plant is for wastewater treatment, they are being provided with water tankers for drinking water.

"We had a borehole, but it has broken due to load-shedding. Now we are being provided with water tankers" (T3/P17/Q11)

Two participants identified wastewater treatment works at Dzindi and military houses as sources of contaminated water that enter the natural environment. This shows that there are pollutants in the sources which could compromise water quality and require efficient treatment methods to ensure human and environmental health safety.

"Contaminated water from the Dzindi River" (T3/P3/Q12)

"Contaminated water from military houses" (T3/P18/Q12)

4.3.4. Sub-theme 4.1: Meeting river quality standards

According to the responses, the wastewater the plants treat meets river quality standards, indicating a dedication to protecting and preserving water resources. This also shows that treatment procedures aim to meet quality requirements for surface water. Following these guidelines shows that the plants prioritize the health of the water bodies downstream in addition to adhering to environmental requirements. Wastewater treatment plants help to preserve the area's water resources and lessen the possibility of harmful consequences from wastewater discharge by treating wastewater to these criteria. The dedication to fulfilling river quality criteria is outstanding, but it is crucial to monitor and evaluate how well these treatment methods are working. It is essential to guarantee the constant efficacy of treatment procedures and to adjust them in response to modifications in water quality standards or new contaminants.

"The water is treated to the standard of river quality" (T3/P15/Q10)

4.3.5. Sub-theme 4.2: Impact of load shedding on water quality

One participant indicated that during load shedding, water quality declines, especially at stage 6, when the treatment process is stopped. This emphasizes how susceptible water treatment plants are to power outages and how important backup measures are. Wastewater treatment is one of the industrial processes that uses the most energy, accounting for approximately 1% of the energy consumed in Europe and 4% of that consumed in the USA (Maktabifard *et al.*, 2018; LIacer-Iglesias *et al.*, 2021). The introduction of restrictive standards for the quality of water effluents has led to a significant increase in the energy demand for this process, requiring the use of advanced technologies to remove pollutants (Maktabifard *et al*., 2018; LIacer-Iglesias *et al*., 2021). South Africa, like other countries in Southern Africa, is undergoing a severe energy crisis that frequently results in regular power outages. As a result, load-shedding is implemented to control electricity consumption and avert grid failure (Du Venage, 2020; Berahab, 2021). To balance supply and demand, load-shedding has been enforced in phases 1 through 8 by Eskom, the primary electricity provider in the country (Du Venage, 2020). According to Vrzala *et al*. (2022), the quality of wastewater discharged and non-compliance with discharge limitations can occur from prolonged power outages, which indicates a reliance of wastewater treatment plants on electrical supply. In certain WWTPs, wastewater may be emergency discharged within 6–8 hours to a recipient (often a river) in the event of a power failure. If there is a lot of rain at this time, the discharge will happen right away (Vrzala *et al*., 2022).

> *"…The water quality is good though, during load-shedding stage 6, the quality deteriorates because the process stops"* (T3/P17/Q10)

4.3.6. Sub-theme 4.3: Perceptions and impacts of water quality issues

There are differing opinions about whether water quality is considered a problem, according to the responses given. One respondent made it clear that there is a problem with the quality of the water, especially in rivers where people are swimming in contaminated water. Numerous waterborne illnesses, including cholera, typhoid fever, shigellosis, salmonellosis, campylobacteriosis, giardiasis, cryptosporidiosis, and viral infections causing hepatitis A, can be spread by contaminated water (Momba *et al*., 2009). These have impacts on the socioeconomic and healthcare sectors, including a significant level of morbidity and death in various age groups (Momba *et al*., 2009). This suggests that people are aware of the problems with water contamination and are worried about how it may affect the local community's health. The answer implies that the respondent does consider the water quality to be an issue.

> *"…Yes, there is a water quality problem, especially in rivers. People are swimming in polluted water"* (T3/P2/Q13).

On the other hand, several participants stated that they do not consider water quality to be an issue. It is critical to understand the motivations underlying this belief. It may result from a lack of knowledge or worry about possible problems with water pollution. A participant brought up operational difficulties with chlorine disinfection, pointing out situations in which they are short of chlorine, which impacts water quality. This emphasizes the difficulties in successfully managing water treatment procedures, which might affect water quality, even though it does not directly address whether or not water quality is seen as a concern.

> *"…Yes, sometimes they don't give us chlorine to disinfect and that affects quality"* (T3/P15/Q13)

4.3.7. Sub-theme 4: Operational performance and regulatory compliance

The participants indicated that they obtain their water for treatment from different sources. One respondent stated that the Albasini reservoir provides them with water, but they are concerned that the plant's capacity is insufficient to fulfil their daily requirements. Despite the country's constitution that states that everyone has the right to clean and safe drinking water, millions of South Africans do not have sustained access to a source of drinkable water (Heleba, 2011; Edokpayi *et al*., 2018).

> *"Albasini Dam. No, our plant does not have sufficient capacity to meet everyday needs"* (T4/P5/Q15)

Other respondents stated that the plants do not have enough capacity and identified the Phiphidi Dam and Vondo Dam as their water sources.

> *"…Vondo Dam and not sufficient…"* (T4/P9/Q15)
>
> *"…Phiphidi Dam and No…"* (T4/P10/Q15)

According to a study by Khabo-Mmekoa *et al*. (2019), the Ugu District of South Africa supplies water to both rural and urban areas through the same treatment plant. However, urban areas benefit from direct tap access in their homes, while rural areas rely on standpipes and household containers for water collection. This demonstrates a clear disparity in water service access between urban and rural areas in South Africa. Small water treatment plants, which are described as water treatment systems constructed in poorly serviced areas that typically do not fall inside the borders of urban areas, are typically used to supply water to rural areas (Momba *et al.,* 2009). Among them are boreholes that supply water to rural clinics, schools, hospitals, and forestry stations (Momba *et al*., 2009; Odiyo and Makungo, 2012; Edokpayi *et al*., 2018). However, several technical and managerial issues hinder the effectiveness of small water treatment plants (Momba and Thompson, 2009). These issues include the inability of plant managers to perform basic equipment repairs or to calculate chlorine dosages, flow rates, and free chlorine residual concentration estimations (Momba and Thompson, 2009). The detection of *E. coli* in the water boreholes utilized at the local clinics, as reported by Edokpayi *et al*. (2018), suggests that patients are at risk of re-infection whilst admitted.

The effectiveness and sustainability of water treatment systems are severely affected by the operational compliance in municipal water treatment management. Some participants expressed concerns about challenges including equipment failures, financial limitations, load-shedding and restricted resource accessibility, which may affect the supply of water to the communities. According to the Water Research Commission (2021), inadequate infrastructure investment over the previous 20 years, management, and planning were the main causes of these losses. As stated by Adams *et al*. (2018), state-controlled water supplies run by public water companies face challenges like corruption and inefficient administration, which makes financial constraints even worse. Another major worry raised by participants is maintenance, with many calling for quicker repairs to avoid recurring equipment failures. The Water Research Commission (2021) has highlighted the recurrent environmental and public health crises caused by inadequate management techniques and delayed maintenance. According to Murei *et al*. (2022), insufficient infrastructure hinders treatment plants from efficiently managing the wastewater load, and treatment plant functioning directly affects the plants' ability to provide water to communities. Institutional arrangements increase these operational inefficiencies. According to Haldar *et al*. (2021), the development of efficient wastewater management systems is made difficult by unclear institutional arrangements and inadequate coordination between national and local organizations.

> *"No, the dosing pumps are not functioning well, we only test chlorine and others are not tested. The filter pump is only one, so the provision of a filter pump should improve. Loadshedding is affecting us. Safety during load-shedding"* (T4/P1/Q15)
>
> *"Yes, there are challenges with water leakages. The municipality should quickly fix all machines"* (T4/P2/Q15)
>
> *"No, some of the machines are not working such as lime feeder, dry beds and the plant is not maintained"* (T4/P18/Q15)

4.3.8. Sub-theme 5: Water volume in waterworks plants

The responses given on the volume of water and/or wastewater processed daily shed important light on the size of the treatment plants' activities. One respondent indicated that they were treating 10.36 megaliters (mL/day). Another participant disclosed that they treat 43 mL of water every day. Furthermore, one responder reported treating 13 megaliters each day, and another indicated treating 0.8 megaliters per day. Despite water from the Albasini reservoir, Mutshindudi River, Vondo reservoir, Phiphidi reservoir, and other nearby sources, the biophysical conditions (Sarr *et al*., 2021) differ between the plants. There are significant variations in resources and capabilities between the treatment capacities, which vary from 0.8 mL/day to 43 mL/day. The plants' capacity to meet their daily water needs and maintain treatment standards is directly impacted by these conditions.

> *"…10.36 megaliters per day (mL/day)…"* (T5/P5/Q16)
>
> *"…43 megaliters per day…"* (T5/P9/Q16)
>
> *"…13 mL/day…"* (T5/P10/Q16)
>
> *"…0.8 mL/day…"* (T5/P14/Q16)

One participant expressed uncertainty regarding the amount of water they treat daily due to malfunctioning flow meters, suggesting a possible problem with the monitoring and measurement apparatus. As it comes to breakdowns, the respondent suggested taking a reactive strategy by contacting mechanics and electricians as problems arise. Another participant brought up phoning engineering when a breakdown occurs.

> *"I am not sure, in and out flow meters not working. When there is a breakdown, we call the electrician and mechanics..."* (T5/P11/Q16)
>
> *"Report to engineering…"* (T5/P8/Q16)

One of the key management issues identified by Meme (2010) was the failure to maintain equipment. According to Momba and Thompson (2009), the lack of routine maintenance was mentioned by around 60% of the small water treatment plants (SWTPs) operators interviewed in all the provinces, including the Eastern Cape, Free State, Western Cape, Mpumalanga, and Limpopo Provinces. In the study conducted in the Greater Giyani Local Municipality, households and public institutions in the area struggle daily to obtain water since municipal pipes and boreholes are insufficient to supply enough water for the entire community (Mmbadi, 2019. The finding from Mmbadi (2019) is strongly linked to this study's investigation into resource management and water governance in the Vhembe District Municipality and is strongly linked to this study's finding. The Vhembe District Municipality faces difficulties with water scarcity and irregular water supply, which are comparable to those in Greater Giyani. This emphasizes the significance of efficient institutional arrangements and governance, as examined by Ostrom's Institutional Analysis and Development (IAD) Framework.

The responses suggest that there are differences in the capacity and source of water amongst treatment plants. Concerns over infrastructure sufficiency to meet water treatment demands are raised by the capacity problems described. To guarantee the efficient and long-term functioning of water treatment plants, this insight emphasizes how crucial it is to evaluate and resolve capacity constraints.

Table 4.4 provides an analysis of the problems with water management that different countries (South Africa, Ethiopia, India, Pakistan, Malaysia, China, Libya, and Brazil) are facing. The institutional arrangements show a pattern of unclear responsibilities, inadequate coordination, and problems with governance that limit efficient water management in these areas. In Ethiopia, Pakistan, and the Vhembe District, for example, there is a lack of institutional capacity and inadequate coordination, while Brazil has multiple agencies and complicated administrative challenges.

The operational challenges that are common in Vhembe District, as well as in Ethiopia and Malaysia, include breakdowns of equipment, insufficient capacity, and limited budgetary resources. Key obstacles include insufficient financial and technical resources as well as an ineffective management strategy, particularly in public facilities. Brazil is one example of this, where ineffective planning and operational skills worsen water management problems.

Significant challenges arise from compliance issues as well, especially in the Vhembe District where regulatory monitoring and water quality testing are inconsistent, while in Brazil, standards are stricter yet unworkable. These countries' operational inefficiencies are a result of social and political problems, such as poor public engagement and insufficient awareness of water and wastewater treatment. The declining water quality in the Vhembe district, as well as improper wastewater management and waterborne illnesses observed in countries such as China, are among the environmental concerns raised.

Table 4.4. Comparison of institutional and operational challenges in water management studies.

Parameter	Current Study (Vhembe District Municipality)	Ethiopia (Worasa *et al*., 2024)	India (Schellenberg *et al*., 2020)	Pakistan (Khan and Kalid, 2016)	Malaysia (Rashi *et al*., 2021)	China (Liang and Yue, 2021)	Libya (Alsadey and Mansour, 2020)	Brazil (Stepping, 2016)
Institutional arrangement	Unclear roles, poor coordination between stakeholders	Weak institutional coordination	Confusion and hesitation amongst sectoral stakeholders, deficits in institutional capacity	Absence of institutional responsibility, governance malfunctions	Weaknesses in water management	Inappropriate governance	Poor government plans	Complex bureaucracy with multiple agencies and bureaucratic levels hindering wastewater management processes
Operational challenges	Equipment breakdowns, load-	Limited human resources,			Lack of capacity	Financial unsustainabilit	Inefficiencies of treatment	Limited planning, insufficient

Parameter	Current Study (Vhembe District Municipality)	Ethiopia (Worasa *et al*., 2024)	India (Schellenberg *et al*., 2020)	Pakistan (Khan and Kalid, 2016)	Malaysia (Rashi *et al*., 2021)	China (Liang and Yue, 2021)	Libya (Alsadey and Mansour, 2020)	Brazil (Stepping, 2016)
	shedding insufficient capacity, limited financial resources	insufficient financial resources				y, technical challenges	plants, drainage networks not in good standard	technical and managerial capacity, and lack of operational skills in public utilities
Compliance issues	Inconsistent water quality testing, lack of regulatory oversight		Inadequate monitoring, insufficient risk assessment, frequent changes and inconsistencie					Strict de jure legislation complicates practical implementation; regulations often do not reflect

Parameter	Current Study (Vhembe District Municipality)	Ethiopia (Worasa *et al*., 2024)	India (Schellenberg *et al*., 2020)	Pakistan (Khan and Kalid, 2016)	Malaysia (Rashi *et al*., 2021)	China (Liang and Yue, 2021)	Libya (Alsadey and Mansour, 2020)	Brazil (Stepping, 2016)
			s in water standards					operational realities
Social and political issues	Low public engagement, limited awareness of water management		Lack of awareness of the wastewater risks					Low connection rates to public sewerage are socially problematic, sewage becoming a higher political priority but still competing with other public concerns

Parameter	Current Study (Vhembe District Municipality)	Ethiopia (Worasa *et al*., 2024)	India (Schellenberg *et al*., 2020)	Pakistan (Khan and Kalid, 2016)	Malaysia (Rashi *et al*., 2021)	China (Liang and Yue, 2021)	Libya (Alsadey and Mansour, 2020)	Brazil (Stepping, 2016)
Environmental concerns	Deteriorating water quality						Mismanaged wastewater, water-borne diseases	Water scarcity pressures showing the need for wastewater reuse, but reuse potential remains untapped

4.4. Conclusions

The findings show the significant operational, environmental and institutional challenges faced by water and wastewater treatment plants. The key issues such as load-shedding, inadequate maintenance, and equipment breakdowns result in treatment facilities not functioning properly. It was observed that workers are knowledgeable about treatment procedures; however, institutional issues like insufficient resources and poor institutional support affect the effective functioning of treatment plants. These challenges do not only threaten water quality but also pose risks to public health and environmental sustainability. To address these complex challenges, this study emphasizes the importance of strengthening institutional arrangements, investing in infrastructure upgrades, adopting proactive management practices, improving maintenance plans, enforcing strict regulatory oversight to ensure that water quality regulations are adhered to, and implementing training programs for all workers. The application of Ostrom's IAD frameworks offers a strategic approach to managing these challenges by promoting effective monitoring, stakeholder engagement, and clearly defined responsibilities. Municipalities should prioritize establishing strong governance frameworks, encouraging local stakeholders to participate in decision-making, and ensuring the resources are available. Additionally, using local talent through targeted recruitment and training programs, including internships and apprenticeships for young professionals, can close skills gaps and improve operational capacity. For broader application, the findings can serve as a guide to other sub-Saharan African countries facing similar institutional arrangements breakdowns and water management challenges. Future research should explore cross-regional collaborations to share best practices and develop solutions that enhance water security and environmental sustainability. By integrating these into policy and practice, municipalities can improve the operational efficiency of their water treatment facilities, preserve water quality, and ensure sustainable access to clean water for all communities.

CHAPTER FIVE: PERCEPTIONS AND KNOWLEDGE OF WATER AND WASTEWATER TREATMENT PLANT WORKERS REGARDING PLASTIC POLLUTION AND REMOVAL

This chapter is currently "in press": Mabadahanye K*, Dalu MTB, Munyai LF, Dondofema F and Dalu T. Perceptions and knowledge of water and wastewater treatment plant workers regarding plastic pollution and removal. Sustainability*

5.1 Introduction

Pollution from plastics has become a global problem (Lau *et al*., 2020). Plastics are now found in various forms in oceans, lakes, rivers, soils, sediments, the atmosphere, and even within animal biomass (Lau *et al*., 2020). The widespread occurrence of plastics is driven by the exponential increase in their production and use, along with economic models that neglect the external costs of waste (Geyer *et al*., 2017; Lebreton and Andrady, 2019). Plastics offer several advantageous qualities that are difficult to achieve with other materials, such as the ability to be heated, sterilised, and worked with without losing their structural properties, depending on the kind of polymer (Horton, 2022). Today, plastics are essential for many modern applications, including construction, healthcare, technology, and performance apparel (Horton, 2022). However, the problem was worsened by a dramatic increase in the usage of single-use plastics (SUPs) and a growing "throw-away" practice (McDermott, 2016). Single-use plastics, including cutlery, plastic bags, straws, sachet wrappers, polystyrene-like cups, and food containers, have been shown to cause significant environmental harm, with 80% accumulating on coastlines and the ocean floor, posing a severe threat to aquatic life (Adam *et al*., 2020). Despite widespread recognition of the environmental damage caused by plastic overuse and mismanagement, plastic production continues to rise rapidly (Geyer *et al*., 2017).

Over the past 50 years, plastic production peaked between 2005 and 2017 (Geyer *et al*., 2017). Plastic pollution poses severe risks to both human health and marine ecosystems, contributing to habitat degradation (Tekman *et al*., 2022) and entangling marine organisms (Lusher *et al*., 2018). The ingestion of plastics by marine life can lead to digestive obstructions and false satiation, affecting species across trophic levels (Schmaltz *et al*., 2020). Plastics can carry hazardous chemicals, including production additives and environmental contaminants, which bioaccumulate in the food chain, endangering both aquatic organisms and humans through the consumption of microplastics (Gallo *et al*., 2018; Cox *et al*., 2019). Floating debris, a common issue related to wastewater, consists largely of plastic waste washed into rivers and lakes (Jodar-Abellan *et al*., 2019). It might be discouraging for people to try to cut back on or completely avoid using plastic because of the essential role that plastic products play in daily life (Tang, 2023).). Understanding public perceptions of plastic pollution is crucial for predicting their reactions to initiatives aimed at addressing the issue and fostering their participation in collective efforts to reduce plastic waste (Tang, 2023). Since wastewater treatment plants (WWTPs) and waste treatment plants (WTPs) are located at the end of the plastic lifecycle, they primarily manage residual plastic pollution (Tang and Hadibarata, 2021). Therefore, increasing public knowledge and engagement in sustainable plastic practices is essential to minimize plastic inputs, and reducing the environmental burden on these mainstream facilities. According to Mihai *et al*. (2022), there are still knowledge gaps regarding the effects of widespread plastic use in food packaging and the specific impacts of plastic pollution on rural areas. Wastewater treatments are crucial in protecting people from using contaminated water (Sun *et al*., 2016).

Wastewater treatment plants are at the forefront of efforts to remove contaminants, including plastics, from water sources (Silva, 2023). Several stages are involved in treating municipal wastewater including preliminary, primary, secondary and tertiary treatments (Nikiema and Asiesu, 2022). These stages also involve a combination of chemical, physical, and biological processes to ensure high-quality effluent that can be safely reused or returned to the environment (Nikiema and Asiesu, 2022). While WWTPs are recognized as contributors to microplastic pollution in aquatic environments (Mrowiec, 2018; Mabadahanye *et al*., 2024), they are not the primary source. Most microplastics originate from the breakdown of larger plastic waste generated by human activities and exacerbated by inadequate solid waste management. In 2016 alone, an estimated 23 million tons of plastic entered aquatic environments worldwide, challenging waste management systems and increasing the prevalence of microplastics as these larger plastics degrade (Borrelle *et al*., 2020). Despite increasing research on wastewater treatment, little attention has been given to how it fits into sustainable resource management (Issaoui *et al*., 2022). According to Issaoui *et al.* (2022), most recent studies have focused on technical treatment methods rather than the broader issue of sustainability. Additionally, while the environmental impacts of wastewater treatment remain under-addressed in today's world, there is a pressing need to raise public awareness about the importance of these processes (Sun *et al*., 2016).

The study aimed to investigate the perceptions and knowledge of water and wastewater treatment plant workers regarding plastic pollution and its removal. To achieve this aim, the study focused on understanding the challenges these workers face in removing plastics from water and wastewater treatment plants and assessing their attitudes towards current plastic removal technologies and methods. It is hypothesized that workers with greater exposure to plastic removal processes within specific areas of the treatment plant will view the issue of plastic pollution as more serious than those who are less involved. Workers' attitudes toward adopting innovative treatment methods are expected to align with their knowledge of emerging plastic removal technologies. By assessing the perceptions and knowledge of workers with both high and low exposure to plastic removal processes, the study aims to identify any knowledge gaps that might hinder effective plastic removal in water and wastewater treatments plants and provide insights for improving plastic pollution mitigation strategies.

5.2 Methods

5.2.1 Research ethics (refer to the previous chapter)

5.2.2 Study area (refer to the previous chapter)

5.2.3 Sampling and data collection (refer to previous chapter)

5.2.4 Data analysis

5.2.4.1 Thematic analysis

The study used a thematic approach to analyse and interpret the data. Thematic analysis involves identifying themes or patterns in qualitative data. The goal of thematic analysis is to find and apply key themes to understand the study or discuss a subject (Maguire and Delahunt, 2017). The thematic analysis offers an accessible and systematic approach to deriving codes and themes from qualitative data (Clarke and Braun, 2016). Codes are the smallest unit of analysis that can be used to identify relevant aspects of the data related to the study topic (Clarke and Braun, 2016). They are the fundamental elements of themes, which are (bigger) patterns of meaning supported by a common organising concept (Clarke and Braun, 2016).

Table 5.1. Interview questions were administered to water and wastewater treatment employees

Do you think that plastic pollutants should be prioritized similar to other-to-other quality pollutants such as e–coli? Why? (Probe: do you think that there is a lot of plastic waste in South Africa to warrant its prioritization?
Do you perceive plastic pollutant removal to be expensive and otherwise wasteful of resources?
Do you know of or suspect that any of the following pollutants (i.e., plastics) affect either surface or groundwater quality?
In your opinion, which of the following are the most responsible for existing pollution problems in rivers and lakes in your area?
Do you know about plastic pollution? Do you think your treatment facility is able to remove even the smallest plastics, i.e., microplastics which pass through initial screening?
Do you screen plastics and other materials before treatment? What kinds of materials do you normally remove?
Have you received water resources or pollution information from your organisation or other?
Do you get learning opportunities to learn more about water pollution issues? If so, which one would consider having been the most useful in the past year or two?
Do you know about plastic pollution? Do you think your treatment facility is able to remove even the smallest plastics, i.e., microplastics which pass through initial screening?
Have you ever changed your mind about water pollution issues after joining your organisation?
Do you have any institutional documents with regards to pollution to help staff? Can I have a copy?

5.3 Results and discussion

The results of semi-structured interviews with process controllers and managers from eighteen (18) water and wastewater treatment plants in the municipality of Vhembe district were categorised into five major research themes: (1) Perceptions and knowledge of plastic pollution; (2) Limited resources and economic difficulties; (3) The effects of plastic pollutants on water systems; (4) Lack of information and training; and (5) Lack of institutional support documents. These observations were divided into several themes, each highlighting significant aspects of their work settings and attitudes (Rowley, 2014:4). As part of the coding process, specific codes were allocated to each response based on the topics and interview questions. For example, the code T2/P12/Q2 represents theme 2 (Limited resources and economic issues), participant 12, and question 2 (Table 5.1). This section was separated into five sections to analyse the results per the themes.

The analysis of the interviews conducted with employees working in the water and wastewater treatment works in the Vhembe district municipality provided insight into workers' perspectives, knowledge, challenges, and operational procedures concerning plastic pollution in the water and wastewater treatment works.

5.3.1 Perceptions of plastic pollution

Eleven water and wastewater treatment workers expressed huge concern regarding plastic pollutants in the water systems and should be prioritised due to the negative impacts on the treatment plants. This concern about plastic waste is reflected in the data that compares South Africa to other African countries. According to 2019 data from Our World in Data, based on Miejer *et al*. (2019), South Africa mismanages 708,467 tonnes of plastic waste annually, higher than other African countries like Mozambique (434,432 tonnes), Angola (236,946 tonnes), and Libya (188,535 tonnes). This mismanagement largely reflects broader issues in solid waste management, leading to plastic entering the environment. While WWTPs and WTPs play a role in managing these plastic wastes, they are not the primary source of plastic entering ecosystems. However, when compared to other countries, South Africa's data is higher than that of the United States (267 469 tonnes), and the United Kingdom (29 914 tonnes). As a result, plastic wastes end up overwhelming water treatment plants because South Africa cannot control them. One participant said that:

> "…*Yes, because they can block water pumps in the plant*…" T1/P3/Q1

The fact that plastic waste is so common in South Africa was brought up by the participants. One participant stated that:

"…*Yes, plastics should be prioritised as is a serious challenge in South Africa and local communities*…" T1/P2/Q1

This indicates that significant action must be taken to reduce plastic pollution. A study done in Australia showed significant concerns about plastic pollution, especially in water, with the creation and management of plastic waste seen as major problems (Dilkes-Hoffman *et al*., 2019). Similarly, a study in Europe found that most respondents were aware of the harmful effects plastic waste has on both the environment and human health (Filho *et al*., 2021). Participants suggested that plastic pollutants should be prioritised like other pollutants.

Participants identified different sources that contribute to the existing plastic pollution in their local rivers, these included washing in the rivers and domestic waste. Disposing of plastic waste, diapers and washing in the rivers were noted as the main contributors to pollution in the local water bodies. One participant also mentioned that "*because they live in a rural area, municipalities do not even collect plastic waste on the street*" T1/P15/Q4. This shows inadequate waste collection services in Vhembe district municipality causing plastic wastes to build up in streets and rivers, worsening environmental pollution. According to the study conducted by Jacoba *et al*. (2021) in Northern Cape, it was found that the local municipality does not supply communities with refuse bags for solid wastes, and municipal trucks do not collect the solid waste from the communities. This shows that there is a serious problem with solid waste management in many rural areas in South Africa, which is caused by local municipalities that fail to take responsibility resulting in waste being dispersed.

"…Washing clothes and millies in the river…" T1/P1/Q4

"…Dumping of plastics, and diapers. There is a big issue on pollution in Dzindi river…" T1/P2/Q4

5.3.2 Water resources pollution

Nine participants agreed that surface water quality is impacted by plastic pollution. Participants emphasised that plastic wastes can harm aquatic ecosystems and that plastics are physically present in water bodies.

"…*Yes, surface water is polluted by plastics*…" T2/P1/Q3

"…*On surface water, they do pollute and cause detrimental effects in aquatic organisms*…" T2/P17/Q3

Participants expressed great concern when asked if their treatment facilities could remove even the smallest plastics, or microplastics. They stated that current treatment technologies are limited, especially when screening out microplastics, which frequently bypass initial filtration processes. This is supported by a study conducted by Mabadahanye *et al*. (2024), which found that WWTPs in various countries continue to release microplastics. For instance, one WWTP in Lithuania had concentrations of 994.0 microplastics per liter (MP/L) in its effluent, while another in Spain had a concentration of 38.6 MP/L. These findings indicate that these treatment plants are not designed to effectively remove microplastics, as they cannot eliminate them entirely. One participant shared this concern by stating that their treatment plant does not effectively remove microplastics hence larger plastics are usually captured during screening. Participants also mentioned the items usually taken out during the screening process, such as sticks, plastics, condoms, bottles, and other trash (Figure 5.2). The effective screening and retention of these items upstream in the treatment process is a positive sign, as it indicates that the facility is managing solid waste efficiently. By removing larger debris early on, the treatment plant can prevent damage to equipment and enhance the overall effectiveness of the wastewater treatment process.

"…*No, the treatment facility cannot even remove the smallest plastics from initial screening*…" T2/P12/Q5

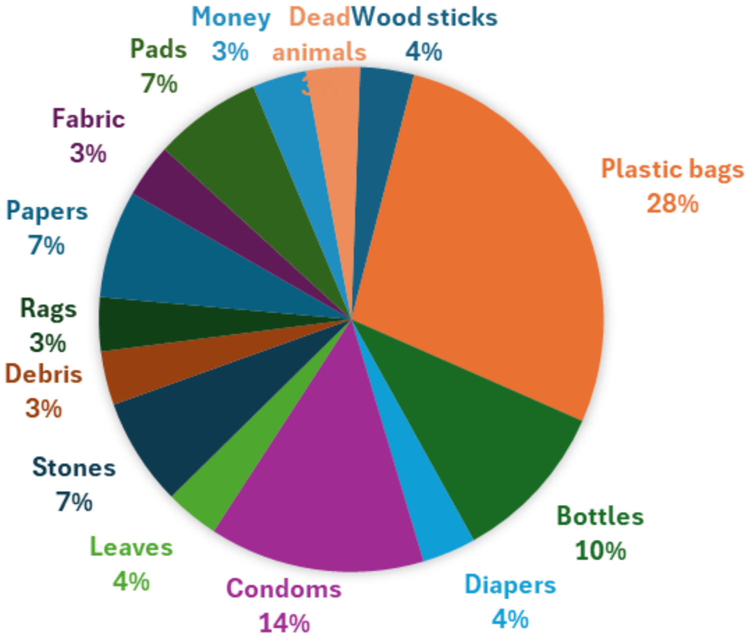

Figure 5.1. Types of materials screened during the wastewater treatment. This figure represents the items identified by participants during interviews conducted at the wastewater treatment plants as part of this research.

According to the responses from the participants, plastic bags (28%), condoms (14%), and bottles (10%) were dominant during screening in their treatment facilities (Figure 5.1). Maw *et al.* (2022) observed retained plastic wastes such as packaging plastics, water bottles, straws and cups before automatic fine screening in wastewater when undertaking on-site sampling. Pollutants such as condoms and sanitary products were also found in a study conducted in Sydney, Australia, by Besley and Cassidy (2022), using a trash net to collect sewage-style gross pollutants in the sewage, where the net captured items such as paper products, condoms, hair, sanitary products, and wet wipes. According to Gouda (2014), sanitary products like tampons, applicators, panty liners, and sanitary towels, as well as common bathroom waste like cotton bud sticks, baby wipes, and condoms, are being disposed of in toilets.

In another study by Weideman *et al*. (2020), gross pollutants from urban stormwater runoff were collected using trash nets in Cape Town, South Africa. They discovered that single-use plastics accounted for 40 to 78% of these contaminants. Food wrappers, polystyrene packaging chips, takeaway containers, lids, plastic bags, cotton bud sticks, bottles, straws, industrial pellets, cable ties, and hard plastic pieces were among the products made by these plastics. The observations made by the participants during the screening procedure align with the findings by Weideman *et al*. (2020) and Besley and Cassidy (2022). Both draw attention to how prevalent different types of waste are in wastewater and urban runoff systems, especially plastics. These plastic wastes should be removed during screening process and directed to appropriate disposal methods such as a landfill.

According to another participant, large plastics pass through the final stage of wastewater treatment during the rainy season, and they remove the plastics manually in the final stage before the treated water enters the river.

> "*…No, even large plastics pass through the final stage during the rainy seasons. We must go to the bush and pick them before entering the river…*"
> T2/P18/Q6

Rainy seasons increase the difficulty of controlling plastic contaminants in water treatment plants, as the participant mentioned serious operational problems during heavy rains by stating that even large plastics pass through the final stage during rainy seasons and have to be picked up before entering the river. The response shows the serious issues with the infrastructure currently in place for treating wastewater, particularly the inadequacies of the current systems in managing the increasing amount of plastic waste generated during periods of heavy rainfall. The effects of heavy rain on WWTPs were also noted by Hughes *et al*. (2021). They found that heavy rainfall increased inflows, which caused more frequent bypassing in WWTP and increased blockages and breaks in pump stations. The use of manual intervention as a last option demonstrates the failure of municipalities to manage pollution in WWTPs. The responses show the importance of implementing waste management strategies beyond treatment plant limits. To mitigate the impact of heavy rainfall on WWTP operations, municipalities could explore collaborative approaches with local communities to develop sustainable waste management practices and improve infrastructure to handle stormwater runoff. According to Mihai *et al*. (2022), the impact of plastic pollution on rural communities must be considered when investigating domestic sources of macroplastic pollution of freshwater environments such as ponds, lakes, rivers and streams. These areas face severe problems with plastic contamination and plastic bottles and other plastic items covering water bodies due to the lack of waste management services in rural areas or nearby cities, particularly in low- and middle-income countries (Mihai *et al*., 2022). Strengthening waste collection and disposal systems in rural areas is important to prevent plastic waste from entering water bodies and establishing efficient recycling systems can help to divert plastic waste from landfills and the environment.

5.3.3 Limited resources and economic difficulties

The economic and resource burden of addressing plastic pollutants was a recurring theme among participants. In WWTPs, the removal of plastic pollutants remains a significant challenge not only due to the installation and operation of screens and sieves, which may not be the primary cost drivers, but also because of the broader financial and resource limitations. These constraints affect the ability to implement sustainable plastic waste management solutions, especially within current budgets and operational capacities. Respondents' perceptions of these costs and the allocation of resources also vary. One participant mentioned that removing plastic pollutants is expensive, which captures different opinions about the cost of removing plastic pollutants.

> "…*Yes, it is expensive*…" T3/P12/Q2

To properly manage plastic waste, this point of view draws attention to expenses related to the staff, maintenance, and equipment needed. While plastics are generally retained by screens and sieves to protect critical equipment like pumps, WWTPs still face costs associated with maintaining and frequently clearing these screening systems. Many water and wastewater treatment plants, particularly those in rural areas with less financial resources, may put their restricted budgets under pressure by these costs. Massoud *et al*. (2009), stated that wastewater treatment plants in developing countries operate inadequately due to limited local budgets, a lack of knowledge, and a lack of investment. In various regions, WWTPs are scarce, and existing plants are typically designed only to comply with basic regulatory standards, which often do not include microplastic removal requirements.

On the other hand, other participants mentioned that removing plastics is not expensive since they remove them manually. The responses demonstrate that in developing regions, managing plastic pollutants often relies on manual labour and non-mechanical equipment, which can reduce initial costs associated with advanced machinery. However, this strategy is labour-intensive and may not be effective for all contaminants, particularly microplastics, which are difficult to detect and remove manually. Although this approach may address immediate cost constraints, it may not offer a long-term solution for effective plastic management within treatment plants.

"*…No, it was not expensive because we remove them manually..*." T3/P15/Q2
"*….We are now using manual removal of plastics. The mechanical system of removal has been broken down. Abattours are the problem, they dump them and it affects machinery…*" T3/P17/Q2
"*…Initial no, since we use hand rake…*" T3/P11/Q5

Even though manual techniques could seem less expensive at first, they may have unanticipated costs in the long run due to labour expenditures, worker's health and safety risks, and the environmental degradation caused by insufficient plastic removal.

5.3.4 Lack of Information and training

To ensure that workers from water and wastewater plants have the skills and knowledge required to manage and eliminate plastic pollution in their plants, they must get training and information on plastic pollution. Based on the responses from participants, it was observed that there are differences in the accessibility of information and training received across different plants.

One participant mentioned that "*No training and learning opportunities were provided*". This response indicates a major lack of organisational support for knowledge sharing and training. Workers might not have the most up-to-date information and recommended procedures to properly control their plants' plastic pollution if they do not receive frequent training and updates. Because they may not be up to date on the newest techniques and technology, workers may not be able to effectively remove plastics from water systems, which could result in failures. According to Rodriguez and Walter (2017), one of the most important tools for individual and organisational motivation to assist them in achieving their short- and long-term goals and objectives is through employee training and development.

"*…No training and learning opportunities were provided…*" T4/P1/Q8 *"…No, I am old and I cannot read…"* T4/P2/Q8

On the other hand, another participant stated that they receive essential information and training from different departments. This response suggested that although some organisations might not have internal training programs, external bodies that provide workshops and training sessions, such as the Department of Environmental Affairs (DEA) and the Department of Water and Sanitation (DWS), fill this gap. However, the experience of receiving training among participants was rare. Training programs guarantee that workers acquire the most recent knowledge and skills required for efficient water treatment and pollution management. There are several advantages to employee training and development, such as increased motivation, confidence, and morale. It minimises waste, improves job security, lowers absenteeism and turnover, and promotes employee participation in change processes, all of which lower production costs (Bapna *et al*., 2013).

> "*…Department of Environmental Affairs (DEA) always come to visit and provide some information…*" T4/P17/Q7
> "*…DWS provide training and invites us…*" T4/P17/Q8

Not all participants have equal access to external training options, even with its many benefits. One participant, for instance, stated that they relied mostly on accumulated experience and had not had any training opportunities since their initial induction in 1989. This response brings up the important point that long-term workers do not get ongoing professional development, which could result in outdated techniques and knowledge gaps. This response brings to light a crucial issue. The workforce may not be adequately prepared to tackle current difficulties in water pollution management if it only depends on accumulated experience without periodic upgrades.

> "*…We never got any learning opportunities. I was trained once in 1989 and since I use my experience…*" T4/P15/Q8

5.3.5 Lack of institutional support documents

To guarantee that workers are knowledgeable and competent in controlling plastic pollution, the organisation must provide documentation on plastic pollution. None of the participants reported getting any institutional documentation about plastic pollution to assist their work, which suggests a substantial gap in this area based on their responses. The lack of such documentation poses a serious concern that could requires workers to use ad hoc approaches and personal experiences due to the absence of standardised operating procedures and guidelines.To identify sustainable measures to reduce plastic pollution, Sandu *et al*. (2020), emphasise that stakeholders and local authorities should be involved in the exchange of knowledge and experience sharing regarding the plastic cycle (production, distribution, collection, recycling, and reuse).

5.4 Conclusions

The findings from this study emphasise the challenges that Vhembe district municipality faces in managing plastic pollution in the water and wastewater treatment plants. Workers confront significant challenges because of inadequate infrastructure, lack of skills and training, and scarce resources, especially when handling microplastics, even though they are fully aware of the negative consequences that plastic waste has on their plants. These problems are made worse by a lack of institutional support materials and ongoing training, which force many employees to rely only on outdated procedures and firsthand knowledge. Poor waste management services is another factor contributing to the growing problem of plastic pollution, particularly in water and wastewater treatment plants located in rural areas. Effective approaches that involve treatment technology upgrades, improving waste management systems, offering continuous training, providing plastic pollution information and clear operational standards are needed to address these issues. Closing these gaps will improve treatment plant performance and further the larger goal of reducing plastic pollution and protecting aquatic environments.

CHAPTER SIX: ASSESSING MANAGERS' PERCEPTIONS OF ATTITUDE IMPACT AND WORK EFFECTIVENESS

6.1 Introduction

In today's society, the importance of leadership cannot be underestimated (Jomah, 2017). Strategic leaders play a vital role in the cultural, political, and socio-economic development of a country (Jomah, 2017). To effectively lead, top management in an organisation must use power, knowledge, inspiration, and influence in interactions and communications with their teams (Bornman, 2017). Leadership is the process by which an individual influences a group to pursue a common goal, becoming crucial for organisations aiming to compete nationally and internationally (Northouse, 2010). Effective leaders provide reliable guidance to their organisations, increasing the likelihood of long-term improvements in profitability and performance (Faraci *et al*., 2013). In pursuit of increased revenue from improved performance, every organisation strives for operational efficiency and effectiveness (Jomah, 2017). Although perceptions of efficacy may vary, the goal of improving operations for better outcomes remains common (Hariri *et al*., 2013). The ability of management to align the business model with operational effectiveness is essential for achieving corporate goals (Uzonwanne, 2014).

Managers, especially middle and senior, face a number of challenges that are fundamental to their development and effectively the functioning of the organisation, which include improving managerial effectiveness, inspiring employees, mentoring and coaching, managing change, and navigating internal politics (Gentry *et al*., 2014). However, in South Africa, high labour turnover and a shortage of adequately trained staff hinder the government's ability to provide quality services (Thusi and Chauke, 2023). Furthermore, managers of small rural water systems face additional difficulties, including staffing shortages, inadequate resources, strained public relations, and complex regulations (Cosgrove and Loucks, 2015; Jones, 2023). Research in South Africa has shown that roughly half of small treatment plants are not producing the required amount or quality of water because of inadequate technology, poor operation, a lack of training, financial limitations imposed by the municipality, a lack of operator motivation, and a lack of understanding of fundamental water treatment procedures (Momba *et al*., 2008; Makungo *et al*., 2011). According to Swartz (2009), rural water treatment plants' (WTPs) sustainability and performance have been affected by both technical and non-technical (management) aspects of operation, maintenance, and management in South Africa.

This study aims to assess the perceptions of managers and supervisors working in water and wastewater treatment plants, focusing on the challenges they face and the resources available to them. To achieve the aim, the study evaluated the manager's professional background and experiences, identified technical and operational resources available, and explored how these factors affect their performance.

6.2 Methods

6.2.1 Research ethics (refer to Chapter 4)

6.2.2 Study area (refer to Chapter 4)

6.2.3 Sampling and data collection

The study employed a qualitative methodology that comprised semi-structured, in-depth interviews (Alsaawi, 2014; Dalu *et al*., 2020; Mabadahanye *et al*., 2024), to evaluate and investigate the viewpoints of managers regarding water and wastewater treatment, professional background and experiences, technical and operational resources available, and staff expertise. In-depth interviews were conducted with six senior employees (i.e., chief process controllers and supervisors) for the two municipalities. The plant's chief process controllers and supervisors were interviewed for between 30 and 45 minutes during the day, either in English or TshiVenda. Data saturation was reached after conducting six interviews to fulfil the defined objectives because no new or relevant information surfaced (Dalu *et al*., 2020; Mabadahanye *et al*., 2024).

6.2.4 Data analysis

6.2.4.1 Thematic analysis (refer to Chapter 4)

Specific codes were assigned to every response during the coding process based on the themes and interview questions. For example, the code T3/P13/Q7 represents theme 3 (staff shortage and expertise), participant 13, and question 7 (Table 6.1).

Table 6.1. Interview questions administered to water and wastewater treatment managers

Questions	**Theme**
What is your position within the company?	1
How long have you been with the company?	1
What resources are available to help you conduct your job properly in terms of water/wastewater treatment?	2
What resources and information are available to support water/wastewater treatment?	2
What level of financial resources do you have to conduct your work?	2
Do you have enough staff to ensure that water/wastewater treatment goes smoothly?	3
Do your in-house staff require expertise in and what gaps do you want to be filled?	3

6.3 Results and discussion

The analysis of the interviews conducted with managers working in water and wastewater treatment plants in the Vhembe District Municipality provided a detailed overview of operational issues and challenges they face. The three themes that developed from the data were (1) professional background and experiences; (2) technical and operational resources, and (3) staff shortage and expertise (Rowley, 2014). These themes were crucial to understanding the workers' perceptions and the challenges they face daily in fulfilling their work duties.

6.3.1 Professional background and experiences

The managers held positions such as chief process controller and supervisor indicating that they play a major role in managing the day-to-day operations of wastewater and water treatment plants. Flux *et al*. (2020) stated that managers have a big impact on employees' career experiences. Based on participants' responses, 83 % of managers have more than 20 years of experience working in water and wastewater treatment plants, with one participant having 40 years of experience. According to the Yildiz *et al*. (2020) and Porkodi *et al*. (2024), the experience of the employee has a huge impact on the productivity of a company.

> "*I have been working here for 40 years*" T1/P5/Q2.

Managers demonstrated an extensive understanding of the day-to-day operations and challenges associated with water treatment through their long-term experience. They have learned to handle unexpected situations, solve issues, and manage various tasks.

However, managers stated that they have not received any training or professional development recently despite their long-term experience. This indicates that while participants have a lot of practical knowledge, they may not be up to date with the modern technologies used in water and wastewater treatment plants. Relying on their previous training can lead to outdated practices, which might not meet the required water treatment standard. Insufficient training and development opportunities could also result in a skills gap when it comes to implementing effective water treatment techniques. According to Ganesh *et al.* (2015), training and development play important role to the organization's efficacy and to enabling experienced employees to perform their jobs well. Percival *et al*. (2013) stated that the company must invest in training to sustain its current level of worker productivity.

6.3.2 Technical and operational resources

There are differences in accessing resources such as chemicals (i.e., chlorine and lime) and water quality equipment (i.e., pH and turbidity meters) across the plants. One manager expressed concern over the lack of documentation and institutional support, however, two managers mentioned that they received blue-drop information from the water quality department.

> "*We receive a blue drop information from the water quality department*" T2/P8/Q4

Participants stated that they have a daily logbook to record the data. This indicates that although operational data is recorded, there is little assistance available in the form of current information or reference materials to help with decision-making. Logbooks serve as a written record of significant events and a channel of communication between plant operators (Strande and Brdjanovic, 2014).

When it comes to financial resources, participants were unsure about the level of funding available for their department. This lack of involvement in budget planning makes it more difficult for the workers to request or allocate resources appropriately.

"*I am not involved in the budget*" (T2/P11/Q5)

One manager stated "*I am not sure about the budget*" T2/P5/Q5, which shows a gap between those who handle the technical aspects of water treatment and those who manage the finances. The challenge of inadequate technical and operational resources is also supported by Snyma *et al*. (2006) findings, which found that wastewater treatment plants in South Africa are not adequately maintained and often operate without necessary knowledge to optimise processes. The study also highlighted the need for financial intervention to improve operations in wastewater treatment plants.

6.3.3 Staff shortage and expertise

Staff shortage was one of the most significant challenges as managers stated, "*They do not have enough staff to ensure smooth operations*". This finding aligns with a study by Kalimanzila *et al*. (2019), where inadequate staffing was identified as a challenge in the water sector affecting the quality of water service and the national economy in Tanzania. Staff shortage in water and wastewater treatment plants can lead to increased workloads for existing employees thereby making it difficult for them to manage the challenges of water and wastewater treatment operations, which often require efficient and detailed interventions, especially during equipment failures and emergencies. Previous studies (i.e., Boyne *et al*., 2011; Hur, 2013; Cheema and Asra-ul-Haq, 2017) have found that a key predictor of organisational effectiveness is a staff deficit. According to Nebo *et al*. (2015), it was noted that retirement or death of old staff and recruiting of unqualified staff was having a negative impact on the Water Corporation in Awka, Nigeria.

"*We don't have enough staff to ensure water treatment goes smoothly*" (T3/P9/Q6).

Managers expressed concerns about the expertise of the current staff, for example, one manager highlighted, "*no, introduce staff training*" (T3/P8/Q7). This highlights the need for ongoing training programs that can equip workers with the necessary skills to handle daily routines and unexpected challenges in water and wastewater treatment processes. The lack of sufficient training is concerning given the critical role that staff expertise plays in maintaining water quality and ensuring the efficient operation of treatment plants. Without regular staff training, employees may struggle to keep up with modern technology or new regulatory requirements. Manoharan *et al*. (2020) also found that the lack of training facilities and staff motivation are key factors affecting labour performance in the construction industry in Sri Lanka. The shortage of trained, skilled and process controllers and maintenance staff are the most pressing challenges in wastewater treatment plants in South Africa (Snyma *et al*. 2006).

The need for professional development was emphasized by managers, with one manger stating, "*they need to attend courses to fill the gaps*" (T3/P9/Q7). Although the value of training is acknowledged, workers are not given many opportunities to participate in relevant training and courses. Increasing staff capacity and closing knowledge gaps were mentioned by one manager and Manoharan *et al*. (2020) also, highlighted the need for training programmes to improve labour operations.

> "*Provide training and hire enough staff*" (T3/P5/Q7)

6.4 Conclusions

The findings reveal serious issues regarding the chief process controllers and supervisors' professional background, technical resources, operational resources, and workforce staffing at the water and wastewater treatment plants in Vhembe District Municipality. Despite workers having long-term experience, they require continuous training to stay up to date with the current water sector practices and technologies. The inconsistent availability of resources, and lack of financial clarity, can delay their operations. Improving how resources are managed, increasing budget transparency, and implementing ongoing training programs are crucial in improving the efficiency and effectiveness of water/wastewater treatment processes. Through investing in both employees and resources, there would be an improvement in the quality of service offered to the communities by the municipalities. Municipalities should hire more people in the water sector to address skills shortages and implement ongoing training programs for employees regarding the latest technologies used in water sectors. The government should allocate more funds and resources to water and wastewater treatment plants to improve the effectiveness of the plant's operations.

CHAPTER 7: PUBLIC KNOWLEDGE AND ATTITUDES TOWARDS WASTEWATER TREATMENT WORKS (WWTPS) AND REMOVAL OF PLASTIC POLLUTION IN THE VHEMBE DISTRICT, SOUTH AFRICA

This chapter is currently "revision submitted": Mabadahanye K*, Dalu MTB, Munyai LF. Dondofema F, Dalu T. (****Revision submitted****) Public knowledge and attitudes towards wastewater treatment works and removal of plastic pollution in the Vhembe District, South Africa. Scientific African.*

7.1 Introduction

Wastewater treatment is the process of removing contaminants from sewage or wastewater and transforming it into effluent that can be reused for various purposes or safely returned to the water cycle with minimal environmental impact (Akpor and Muchie, 2011). A major issue threatening humanity in the twenty-first century is the pollution caused by plastics (Golwala *et al*., 2021; Rasmussen *et al*., 2021). When plastic is not properly managed, it presents numerous risks to human health and the environment (Villa *et al*., 2022). The primary purpose of WWTPs is to eliminate potential pathogens and remove nutrients, such as nitrogen and phosphorus, along with easily biodegradable dissolved organic matter, suspended particles, and solid wastes such as plastics from wastewater (Margot *et al*., 2015; Silva, 2023). Municipal wastewater can also be affected by non-domestic contaminants, including heavy metals, pesticides, and hydrocarbons, which may infiltrate the water system through rainwater runoff from buildings, highways, gardens, and urban parks (Margot *et al*., 2015; Soni *et al*., 2020). A large portion of municipal wastewater is produced by households, which includes human waste like urine and faeces, even from disease-carrying individuals (Poopedi *et al*., 2023).

Farming communities and society as a whole can benefit greatly from the use of wastewater and its nutrient content for crop production (Akpor and Muchie, 2011). Wastewater treatment is essential to the circular economy, which views wastewater as a resource rather than a problem (Silva, 2023). This approach prioritizes reusing and regenerating materials and products to reduce pressure on natural resources and promote environmental sustainability (Silva, 2023). Wastewater treatment has become a significant source of clean water, fertilizer, and energy (Smol *et al*., 2020; Obaideen *et al*., 2022). For instance, treated wastewater is a key source of biogas used in households and industries, reducing the strain on natural resources and decreasing the need for fossil fuels (Kamali *et al*., 2019; Silva, 2023). Additionally, wastewater is rich in raw materials for the fertilizer industry, containing high levels of minerals such as calcium (Ca), magnesium (Mg), potassium (K), and phosphorus (P) (Smol *et al*., 2020).

However, the use of wastewater can also negatively impact ecosystems and communities (Akpor and Muchie, 2011). Greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ammonia, and volatile organic compounds (VOCs), are released during the operation stages and construction of WWTPs (González *et al*., 2011; Khan *et al*., 2024). These emissions are major contributors to global climate change and anthropogenic warming (Khan *et al*., 2024). Emissions from WWTPs also significantly affect aquatic environments, contributing to environmental degradation (Campos *et al*., 2016). For years, unpleasant odours emitted by WWTPs have been a growing concern, particularly in highly populated communities (Czarnota *et al*., 2023). These odours, linked to the formation of secondary particle emissions and photochemical smog, can lead to health issues and negatively impact nearby communities (Ren *et al*., 2019; Fan *et al*., 2020). Compounds emitted by WWTPs may cause psychosomatic symptoms, such as headaches, nausea, dizziness, anxiety, loss of consciousness, and tension (Byliński *et al*., 2019). Recently, odours from WWTPs have been recognized as air pollutants (Liu *et al*., 2020). Despite the strong fertilizing properties of wastewater-derived waste, the presence of heavy metals, such as nickel (Ni), arsenic (As), mercury (Hg), cadmium (Cd), and lead (Pb), can disqualify it from direct use as fertilizer (Hukari *et al*., 2016). Moreover, WWTPs are energy-intensive, consuming up to 20% of the total energy used by public utilities and municipalities worldwide (Castellet-Viciano *et al*., 2018). This significant energy requirement is crucial for WWTP operations, with advanced WWTPs using even more energy than conventional municipal plants (Gu *et al*., 2017; Yu *et al*., 2019).

Understanding community perceptions regarding wastewater treatment initiatives and the reuse of treated wastewater is essential. Acknowledging these perspectives helps in understanding people's actions, beliefs, knowledge gaps, and the challenges related to current water reuse practices (Michetti *et al*., 2019). This insight is important for developing strategies that promote public acceptance of wastewater treatment technologies and the beneficial use of recovered resources. In some regions, a lack of awareness about community safety associated with wastewater reuse creates significant barriers. This often contributes to the global failure of wastewater treatment systems, especially when treated wastewater is used in agriculture (Msaki *et al*., 2022). This study aimed to assess social perceptions, attitudes and knowledge gap concerning WWPs and plastic pollution within the local communities of Thulamela Municipality in Vhembe District, South Africa. We hypothesized that residents of the Thulamela Municipality have limited awareness of WWTPs and plastic pollution, as well as their environmental impacts and the potential effects on communities living near these plants.

7.2 Methods

7.2.1 Research ethics (refer to chapter 4)

7.2.2 Study area

The study was conducted in the Vhembe District Municipality, which comprises four category B local municipalities: Collins Chabane, Thulamela, Makhado, and Musina. According to Statistics South Africa (Vhembe District Municipality, 2020/21; Statistics SA, 2022), the population size of the Vhembe District Municipality is 1 653 022. The Vhembe district municipality has 28 wastewater treatment works (WWTW), 13 of which are not owned and run by the Water Services Authorities (WSA) (Vhembe District Municipality, 2020/21). In this study, Thulamela Local Municipality (TLM) was selected (Table 7.1).

Table 7.1: Demographics of selected local municipalities within Vhembe District Municipality. Data Source: (Statistics SA, 2022).

Population size	**Sex ratio**	**Age Structure**	**Education**	**Number of Houses**
575 929	Male (46,6%) Female (53,4%)	Young children (0-14 years) (31,8%) Working age population (15-64 years) (61,7%) Elderly (65+ years) (6,5%)	No schooling (20+ years) (13,4%) Higher education (20+ years) (13,9%)	1427

7.2.3 Sampling and data collection

Qualitative data for the study were collected through in-person interviews with 150 local community members aged 18 and older. The study employed a qualitative methodology, using questionnaire forms to assess public knowledge and attitudes regarding wastewater treatment plants (WWTPs) and the removal of plastic pollutants. Each questionnaire took approximately 10–15 minutes to complete. After 150 questionnaire forms were filled out, data saturation was achieved, as no new or relevant information emerged (Dalu *et al*., 2020).

7.2.4 Data analysis

The data obtained from the survey were analysed using Microsoft Excel and IBM SPSS Statistics software. Microsoft Excel was used to organise the data and generate charts and graphs, providing clear visual representations of public knowledge and attitudes regarding wastewater treatment plants (WWTPs) and removing plastic pollutants.

IBM SPSS Statistics was employed for statistical analysis. Spearman's rank-order correlation was used to examine the relationships between sociodemographic variables (e.i., gender, age, and education), awareness of WWTPs, and environmentally conscious behaviours, such as attitudes toward plastic pollution. This method was chosen because it is non-parametric and does not require data to meet assumptions of normality or linearity.

To examine the connections between sociodemographic factors, attitudes toward wastewater treatment facilities, and environmentally conscious activities, the study used the Theory of Planned behaviour (TPB). The TPB framework's descriptions of attitudes, subjective norms, and perceived behavioural control were tested to see if they affected public knowledge and behaviour around plastic pollution using Spearman's rank-order correlation.

7.3 Results

7.3.1 Sociodemographic

One hundred and fifty local communities of Thulamela LM completed hard copies of questionnaires. Based on the collected data, the majority of respondents were female, accounting for 57.3% (n = 86), compared to 41.3% (n = 62) male respondents; 1.3% of participants chose not to disclose their gender. The age group of 25-34 years was the most represented, making up 31.3% of respondents, while the 55+ age group was the least represented at 9.3%, with 1.3% of respondents preferring not to specify their age. Regarding educational background, 23.3% of respondents held a degree, 19.3% had a postgraduate degree, 16.6% possessed a diploma, 1.3% had completed only primary school, and 7.3% were uneducated. Employment status data revealed that 32% of respondents were employed, followed by 22.6% who were unemployed, 22.0% who were self-employed, 18.6% who were still studying, and 4.6% who were retired (Table 7.2).

Table 7.2: Sociodemographic of local communities of the Thulamela Local Municipality.

Variables	Number	Percentage (%)
Gender		
Male	62	41.3
Female	86	57.3
Prefer not to say	2	1.3
Age group		
18-24	44	29.3
25-34	47	31.3
35-44	26	17.3
45-54	17	11.3
55+	14	9.3
Prefer not to say	2	1.3
Education level		
Uneducated	11	7.3
Primary school	2	1.3
High School	20	13.3
Certification	28	18.6
Diploma	25	16.6
Degree	35	23.3
Postgraduate degree	29	19.3
Employment Status		
Student/Unemployed	28	18.6
Self-employed	33	22.0
Retired	7	4.6
Unemployed	34	22.6
Employed	48	32.0

7.3.2 Awareness and knowledge of wastewater treatment plant

Sixty-one percent of respondents indicated that they had heard of wastewater treatment plants (WWTPs), while 39% reported that they had not heard about WWTPs (Figure 7.1a). Forty-eight percent of participants are aware of WWTPs in their area, 33% are unaware of any wastewater treatment works nearby, and 19% are unsure (Figure 7.1b). The findings revealed that 78 respondents were unsure of their proximity to wastewater treatment works (WWTW). Sixteen respondents reported living less than 1 km from a WWTW, 29 indicated they live between 1-5 km away, and 20 stated they reside more than 5 km away (Figure 7.1c). This highlights a lack of knowledge among local communities on the locations of nearby WWTWs, which may be important for understanding how the environmental impacts of these WWTWs affect locals.

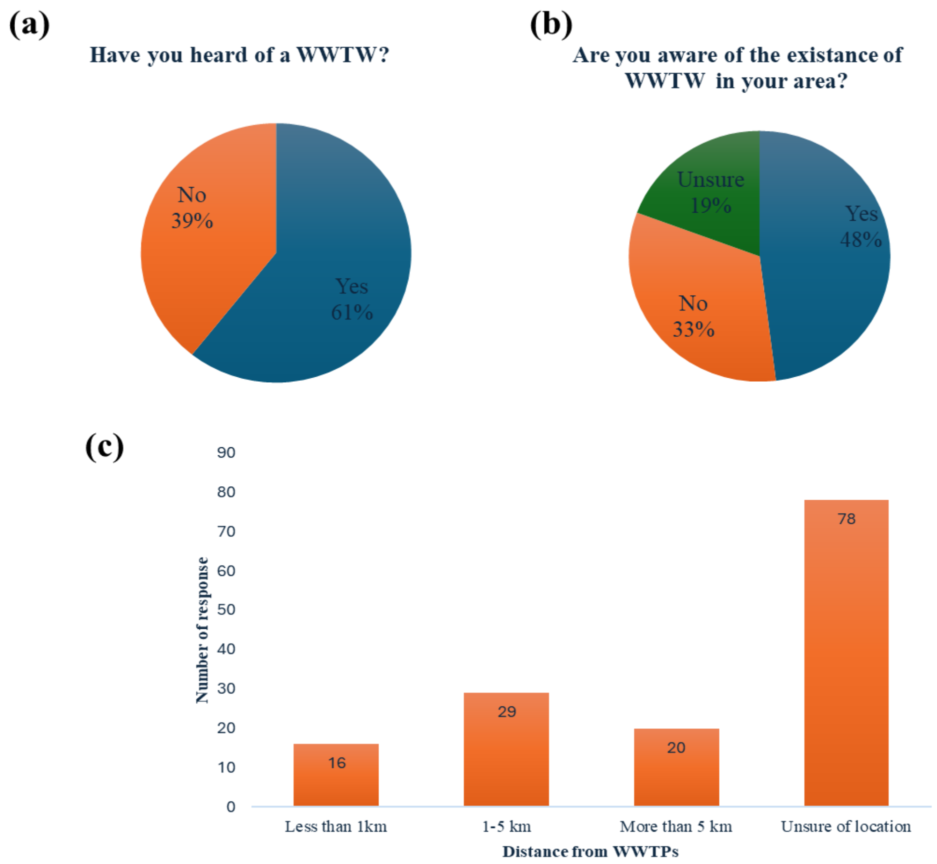

Figure 7.1: Responses regarding awareness and knowledge of WWTPs: Familiarity, awareness and distance to WWTPs.

7.3.3 Perceptions of Wastewater Treatment Plants

Forty-six participants strongly agreed that WWTPs are unpleasant and produce smells, making it difficult to live nearby, while only three participants strongly disagreed with this statement. Additionally, 39 participants agreed with the perception that WWTPs are a "necessary evil" for modern society, though 16 respondents strongly disagreed, highlighting a division in perceptions about their importance. When asked if WWTPs can positively impact the environment, 59 respondents strongly agreed, emphasizing awareness of the environmental benefits these WWTPs can provide, while only two respondents strongly disagreed. Furthermore, 52 participants expressed concern about the potential impact on property values if a WWTP were constructed in their neighbourhood, indicating a worry about the infrastructure. Interest in understanding how WWTPs operate was high among participants, with 77 respondents expressing strong interest in learning more, compared to just 3 respondents who were uninterested (Figure 7.2a).

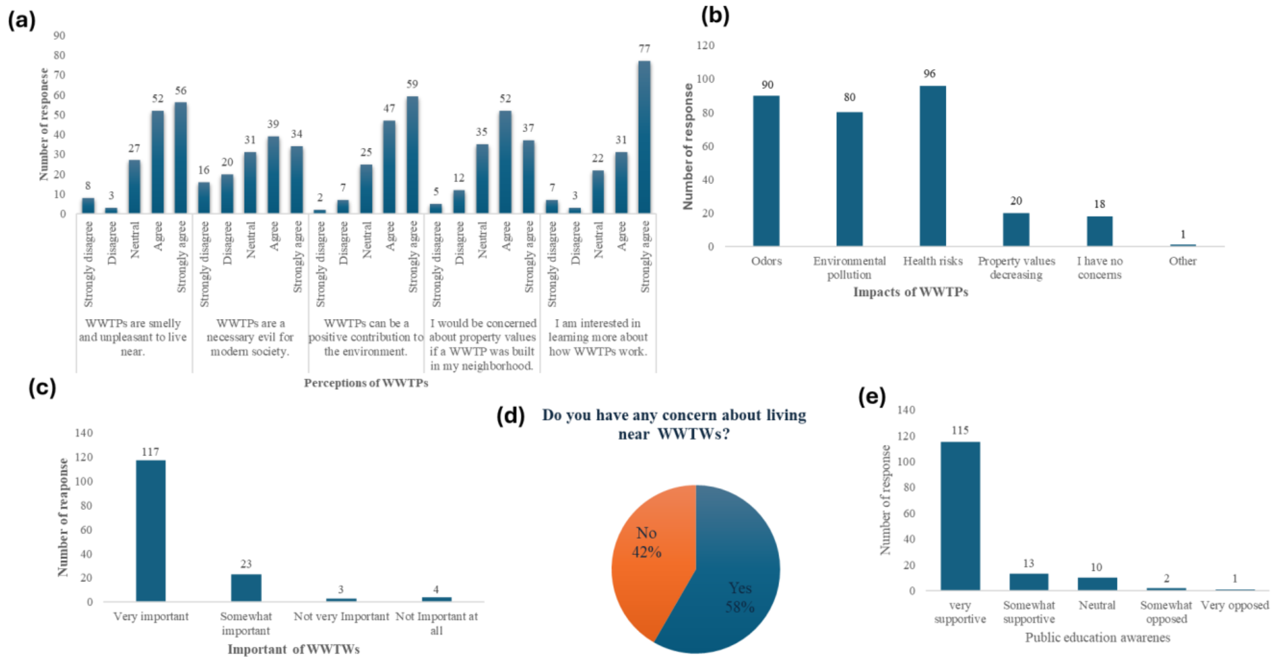

Figure 7.2: Participants' perceptions of WWTPs: Impacts, importance, concerns about distance, and support for public education awareness.

Most participants (117) recognised the importance of wastewater treatment works (WWTWs) to their community, though four respondents believed these treatment works were not important at all (Figure 7.2c). Fifty-eight participants expressed concerns about living near wastewater treatment works (WWTWs), while 42 participants indicated they had no concerns (figure 7.2d). When it comes to concerns about living near WWTWs, 96 participants expressed worry about potential health risks, and 90 participants were troubled by the odours emitted. Additionally, 80 respondents highlighted the contribution of WWTWs to environmental pollution, while only 18 participants indicated they had no concerns about living close to these facilities (Figure 7.2b). The majority of participants (115) expressed strong support for increased public education awareness about the safety and benefits of wastewater treatment works (WWTWs), with only one participant opposing such awareness initiatives (Figure 7.2e). This indicates that community members value understanding the safety measures and benefits associated with wastewater treatment plants.

7.3.4 Willingness to engage

At least 92% of the participants indicated that they would likely attend community outreach events aimed to explain the workings of local WWTPs, while 8% said they would not be interested (Figure 7.3a). Regarding preferred methods for receiving information about WWTPs, 96 participants chose educational websites, 84 preferred public presentations, 67 selected social media updates, and 59 chose informational pamphlets (Figure 7.3b). The responses suggest high community interest in understanding how these WWTPs operate.

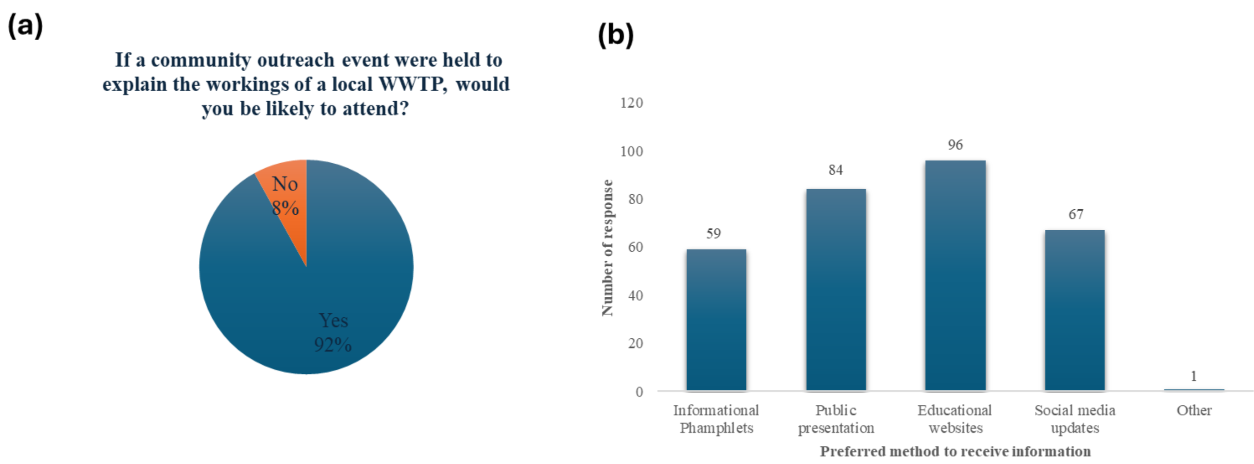

Figure 7.3: Community interest in outreach initiatives and preferred methods for receiving information about WWTPs

7.3.5 Perceptions about the effectiveness of wastewater treatment plants

When asked about the effectiveness of WWTPs in treating wastewater, 81 participants rated them as "very effective," while 32 participants were unsure about their effectiveness (Figure 7.4a). Regarding confidence in the safety of water discharged from WWTPs, 80 participants indicated that they were confident, whereas 19 participants were unsure (Figure 7.4b). In terms of noticing any negative impacts that they believed were related to a wastewater treatment facility such as odours or pollution, 58% of respondents said "yes," 26% said "no," and 16% were unsure (Figure 7.4c). These results demonstrate the significant proportion of community people who believe there are negative impacts of WWTPs, indicating that these worries might affect their perceptions of WWTPs in general.

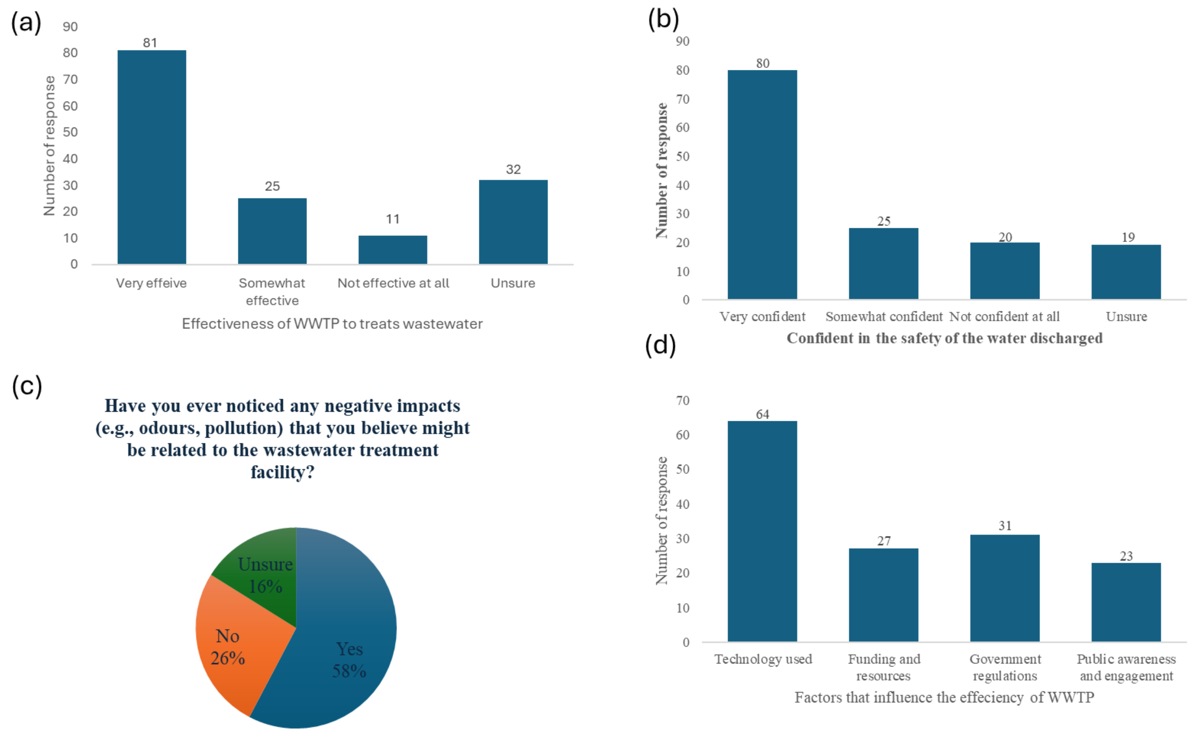

Figure 7.4: Perceptions of WWTP Effectiveness, confidence in discharged water safety, observations of negative impacts, and factors influencing treatment efficiency

When it came to identifying factors that influence the efficiency of WWTPs, 64 participants emphasized the importance of the technology used, 31 pointed out the role of government and regulations, 27 selected the funding and resources, and 23 the importance of public awareness and engagement (Figure 7.4d). This response highlights the complex relationship between

WWTP efficiency and community involvement, financial assistance, proper governance, and technological developments.

7.3.6 Perceptions of plastic pollution

A majority of participants (77%) indicated awareness of plastic pollutants in wastewater, while 22% said they were not aware, and 1% were unsure (Figure 7.5a). When asked about how plastic pollutants enter wastewater systems, 61 participants identified domestic waste, 51 pointed to industrial discharge, and 29 mentioned stormwater runoffs as a key source (Figure 7.5b). Ninety-eight participants regarded WWTPs as very effective at removing plastic pollutants. Meanwhile, 35 participants considered them moderately effective, and 12 participants perceived them as ineffective (Figure 7.5c). Concern about plastic pollution was high, with 106 participants expressing worry, while 13 were unsure (Figure 7.5d). Regarding the public's role in reducing plastic pollution, 132 participants agreed that individuals can make a difference, whereas 5 believed it is solely the responsibility of industries and governments (Figure 7.5e). Lastly, when asked if they had ever received information or education about plastic pollution in wastewater, 54% of participants said yes, while 46% said no (Figure 6f).

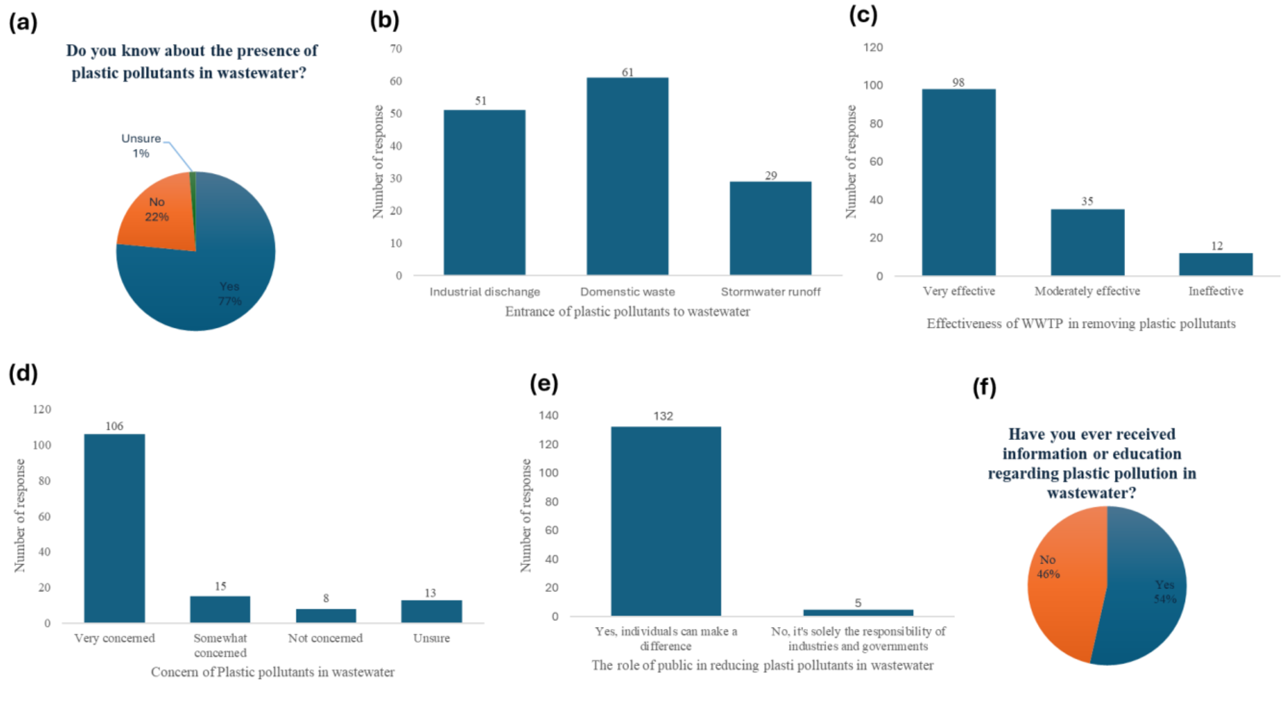

Figure 7.5: Public awareness, sources, concerns, and perceived effectiveness of WWTPs in addressing plastic pollution.

7.3.7 Relationship between education, awareness and environmental consciousness behaviour

Spearman's rank-order correlation analysis revealed several significant relationships among the variables. Education showed a significant negative correlation with awareness and knowledge about wastewater treatment plants (WWTPs) ($r = -0.31$, $p < 0.01$) suggesting that individuals with higher education levels may have lower awareness. A significant positive correlation was observed between awareness and knowledge of WWTPs and plastic pollution information ($r = 0.45$, $p < 0.01$) indicating that greater awareness is associated with increased knowledge of plastic pollution issues. Awareness of WWTPs was positively correlated with concern near WWTPs ($r = 0.122$, $p < 0.05$) and with knowledge of plastic pollutants ($r = 0.12$, $p < 0.05$). Learning about WWTP functions strongly correlated with willingness to engage in WWTP-related activities ($r = 0.62$, $p < 0.01$). Plastic pollution information was positively associated with willingness to engage ($r = 0.35$, $p < 0.01$) and knowledge of plastic pollutants ($r = 0.29$, $p < 0.01$). These results showed the connection between awareness, education, and environmental consciousness behaviour, especially regarding wastewater treatment and plastic pollution.

Table 7.3: Relationship between sociodemographic variables and environmental consciousness behaviour towards plastic pollution and WWTP.

	Sociodemographic			**Environmental consciousness behaviour**							
	Age	**Gender**	**Education**	**Heard of WWTP**	**Aware of WWTP**	**Concern near WWTP**	**Willingness of engage**	**Learning WWTP function**	**WWTP Negative Impacts**	**Knowledge of plastic pollutants**	**Plastic pollution information**
Heard of WWTP	0.09	-0.06	-0.31**	1.00	0.37**	0.25**	0.10	0.12	0.34**	0.15	0.45**
Aware of WWTP	0.05	-0.03	-0.20*	0.37**	1.00	0.12	0.01	0.11	0.22**	0.12	0.39**
Concern near WWTP	-0.06	0.06	-0.11	0.25**	0.12	1.00	0.07	0.10	0.10*	0.14	0.03
Willingness of engage	-0.05	-0.08	-0.19*	0.10	0.05	0.07	1.00	0.62**	0.10	0.09	0.19*
Learning WWTP function	-0.07	-0.05	-0.20*	0.12	0.11	0.10	0.62**	1.00	0.17*	0.09	0.08
WWTP Negative Impacts	-0.08	-0.04	-0.26**	0.34**	0.22**	0.19*	0.10	0.17*	1.00	0.15	0.35**
Knowledge of plastic pollutants	0.11	0.06	-0.04	0.15	0.12	0.14	0.09	0.01	0.15	1.00	0.29**
Plastic pollution information	0.04	-0.08	-0.13	0.45**	0.39**	0.03	0.19*	0.08	0.35**	0.29**	1.00

**. Correlation is significant at the 0.01 level ($p < 0.01$)

*. Correlation is significant at the 0.05 level ($p<0.05$)

7.4 Discussion

The study assessed public knowledge and attitudes towards wastewater treatment plants (WWTPs) and the removal of plastic pollutants in the Vhembe District, South Africa. The hypothesis that public knowledge about WWTPs and plastic pollution would be limited was rejected, as most respondents demonstrated awareness of both topics and their impacts on the environment and communities near WWTPs. Survey data revealed higher female participation (57.3%) compared to males (41.3%), and this is consistent with Mashamba *et al*. (2024), where females comprised 57.5% of participants. This trend aligns with Gender Role Theory, which attributes such participation to traditional roles as caregivers and water gatherers, driving women's engagement with environmental issues (Kray *et al*., 2017; Tien and Huang, 2023). Age distribution showed the largest group of participants was between 25–34 years (31.3%), with a significant decline in participation among individuals aged 55 and older. According to Environmental Literacy (EL), this trend implies that younger people may be more concerned about environmental issues, which could be impacted by increased exposure to environmental education during formative years (Wong *et al*., 2018). The increased involvement rate among younger responders emphasizes how crucial it is to focus on youth in environmental campaigns to maintain support efforts in the future.

Educational background varied, with 42.6% of respondents having higher education, including 19.3% with postgraduate qualifications and 23.3% holding a degree. Spearman's correlation analysis revealed that education was significantly negatively correlated with awareness and knowledge about WWTPs ($r = -0.31$, $p < 0.01$), implying that individuals with lower education levels might rely more on direct community outreach for their environmental knowledge. According to Lazino *et al*. (2006), higher education has been identified as a significant determinant of an individual's degree of environmental concern and behaviour; those with higher levels of education are more likely to exhibit pro-environmental behaviour since they possess greater knowledge about environmental issues. A study by Zhu *et al*. (2019) further supports this, finding that respondents with bachelor’s degrees had higher knowledge levels about water-related issues compared to other educational groups.

Regarding awareness, 43% of respondents reported familiarity with WWTPs, while 39% were unaware, and 19% were unsure. Spearman’s correlation also indicated that awareness of

WWTPs positively correlated with concern near WWTPs ($r = 0.12$, $p < 0.05$) and knowledge of plastic pollutants ($r = 0.12$, $p < 0.05$). This supports the Value-Belief-Norm (VBN) Theory, which links awareness of environmental issues to personal responsibility and pro-environmental behaviours (Chen, 2015). Concerns about health risks (highlighted by 96 participants), unpleasant odours (90 participants), and environmental pollution (80 participants) were consistent with findings from Hachi *et al*. (2022), where 71% of respondents identified odour as a significant issue. Concerns about negative impacts such as odorous emissions align with findings from Czarnota *et al*. (2023), which identified hydrogen sulfide (H_2S) emissions as exceeding safe exposure limits, resulting in adverse health effects like coughing and eye irritation.

On the issue of plastic pollution, 77% of participants reported awareness of plastic pollutants in wastewater, and 106 participants expressed concern. A strong positive correlation was found between awareness of plastic pollution and receiving information about the topic ($r = 0.45$, $p < 0.01$). These findings align with the Theory of Planned behaviour (TPB), which suggests that knowledge and attitudes significantly influence individual actions (De Leeuw *et al*., 2015). However, only 54% reported receiving information or education on plastic pollution, revealing a gap in public education. Educational campaigns could address this gap and increase environmentally conscious behaviours. The study also demonstrated the public's willingness to participate, as 92% of respondents said they would be interested in attending community outreach activities. According to Naughton and Hynds (2014), who emphasized that knowing public views is essential for sustainable environmental management, this study highlights the value of public awareness efforts. Participants preferred a variety of communication platforms, including instructional websites, social media posts, and informational booklets, indicating the necessity of specific communication to reach various demographic groups.

7.5 Conclusions

This study demonstrates that local communities are highly engaged in and are aware of the role WWTPs play in environmental management, even though there are still some significant knowledge gaps. Although WWTPs are widely acknowledged for their positive impacts on the environment, however, some participants were concerned because of health risks, unpleasant odours, and potential property loss. The study also emphasizes how age, gender, and educational background influence public knowledge and engagement with issues regarding WWTP. Higher education levels were found to have a substantial impact, as participants demonstrated a greater understanding of WWTP operations. The findings show that the public is very interested in having access to clear and understandable information on WWTP operations, particularly when it comes to the advantages, safety protocols, and reducing of plastic pollution. The public strongly supports educational outreach, as seen by the participants' preference for a variety of communication channels, including as websites, social media, and public presentations, to promote greater understanding and acceptance. More public education and awareness campaigns are necessary to resolve community concerns, increase environmental awareness, and raise positive perceptions of WWTPs. To bridge the knowledge gap and encourage community engagement in sustainable water management practices, future projects should prioritize open communication.

CHAPTER 8: GENERAL SYNTHESIS

8.1 General introduction

This chapter summarises the key findings from the research study, combining the main results, conclusions, and implications from each section. It provides a clear overview of the research outcomes, highlighting the most important points and their significance.

8.2 General discussion

This study aimed to investigate the occurrence, removal, and management of microplastics (MPs) in wastewater treatment plants (WWTPs) and water treatment plants (WTPs) in the Vhembe District, South Africa. It aimed to assess managerial and worker perceptions, public awareness, and institutional challenges associated with WWTP operations and plastic pollution. Five key hypotheses were proposed in Chapter 1, which have been confirmed as follows:

1. Microplastic removal efficiency varies based on shape, type, and density.
2. Institutional arrangements and clearly defined roles within water and wastewater treatment systems enhance operational performance.
3. Workers' knowledge and perceptions about plastic pollution affect operational outcomes.
4. Managers' attitudes significantly influence decision-making and operational effectiveness.
5. Limited public knowledge about WWTPs and plastic pollutants removal impacts community engagement and support for mitigation strategies.

The systematic review supported the hypothesis by highlighting the significant differences in removal efficiencies across various countries. In more developed regions such as the United States, Finland, and Iran, treatment plants achieved over 90% removal of MPs (Table 3.1) (Lares *et al*., 2018; Conley *et al*., 2019; Oveisy *et al*., 2020), which suggests that advanced treatment technologies can effectively remove MPs, particularly denser particles. In contrast, countries with less advanced treatment infrastructure, such as Turkey, reported much lower removal rates of less than 50% (Table 3.1) (Akarsu *et al*., 2020). These findings highlight the impact of infrastructure and technology on the efficiency of MP removal, with denser and larger MPs being more easily removed through conventional processes.

The study also found that fibres and fragments were the most prevalent types of MPs in both influent and effluent, aligning with findings from previous research (Table 3.2) (Browne *et al.*, 2011). Fibers, in particular, are difficult to remove due to their lightweight and flexible nature, which limits their retention in treatment systems. Similar trends were observed in Morocco, where treatment plants achieved removal efficiencies of 74 and 87%, but still faced challenges in removing certain types of MPs (Table 3.1) (Hajji *et al.*, 2023). Lithuania, for instance, recorded a removal efficiency of 57% despite receiving high concentrations of MPs in the influent (Table 3.1) (Uoginite *et al.*, 2022). This indicates that when WWTPs receive very high concentrations of MPs, particularly fibers and fragments, their removal efficiency is significantly limited by the sheer volume of microplastic pollution. The pressure from such high levels of contamination makes it challenging to remove all types of MPs effectively. On page 33, section 3.3.4, the systematic review revealed regional variations in the color and polymer composition of MPs. As presented in Table 3.3, black, transparent, blue, and red particles were common across various regions, with polypropylene (PP), polyethylene terephthalate (PET), and polyethylene (PE) being the most prevalent polymers found in both influent and effluent (Table 3.3). These polymer types are commonly used in everyday products, contributing to their high concentration in wastewater. These variations in color and type can help trace the sources of MPs and further inform treatment strategies. The study also noted the importance of developing standardized procedures for MP monitoring. A greater understanding of the sources and methods to reduce contamination is crucial for improving removal efficiencies. The Vhembe District's WWTPs, in particular, struggled with low removal rates due to limited resources and workforce skills, similar to challenges observed in developing countries as mentioned in the review (Do *et al.*, 2022). The combination of limited infrastructure, lack of advanced technologies, and insufficient training contributed to the low removal efficiencies observed in this study on page 48, 49 and 51.

The study confirmed that institutional arrangements, including governance and defined roles, play a critical role in operational performance. The application of Ostrom's Institutional Analysis and Development (IAD) framework revealed fragmented enforcement of regulations and insufficient resource allocation, consistent with findings by Mogale *et al.* (2021). These institutional weaknesses limited WWTPs' capacity to address microplastic contamination effectively. Workers' limited knowledge of plastic pollution was another key finding (page 69, section 5.3.1). While workers had a basic understanding of WWTP operations, they lacked awareness of specific environmental impacts, confirming the third hypothesis. Training opportunities were scarce, which participants noted as a significant barrier to improving their performance. These results support Geyer *et al*. (2017), who similarly reported limited worker training as a critical issue in developing regions.

Participants in the study identified several significant sources contributing to plastic pollution in the local rivers, including washing activities, improper disposal of domestic waste, and the dumping of plastic waste and diapers directly into water bodies (page 72, Figure 5.1). These practices underline a significant lack of awareness about the environmental impacts of plastic pollution, not only within the community but potentially within WWTPs as well. The improper disposal of plastic waste and other pollutants directly affects the volume and type of contaminants entering treatment plants, making it more challenging for workers to address them effectively during the treatment process. The results from other regions globally align with the situation in the Vhembe District, where limited waste management infrastructure and ineffective governance contribute to increased plastic pollution. For example, on page 70, paragraph 1, a study in Australia (Dilkes-Hoffman *et al*., 2019) revealed widespread concerns about plastic pollution in aquatic environments, with the generation and management of plastic waste being significant challenges. Similarly, in Europe, Filho *et al*. (2021) found that most respondents were aware of the harmful effects of plastic waste, particularly on environmental and human health. This lack of knowledge likely hinders their ability to efficiently remove plastic pollution, thus affecting operational performance. In the Northern Cape of South Africa, Vilijoen *et al*. (2021) reported similar challenges, where local municipalities failed to provide adequate waste collection services, leading to improper waste disposal that exacerbated pollution, particularly in rural areas (page 74, section 5.3.3). This reflects the situation in Vhembe, where workers at WWTPs may struggle with managing the contamination due to a lack of effective waste management systems and insufficient training on the sources of plastic pollution.

On page 80, section 6.3.1, the study found that managerial attitudes play an essential role in operational decision-making. Managers with strong environmental commitments were more likely to advocate for advanced technologies and stricter enforcement of protocols, supporting the fourth hypothesis. However, resource limitations and institutional barriers often constrain their ability to implement desired changes. This aligns with the findings of Silva *et al*. (2020), who identified similar challenges in low-resource settings.

The study supports the hypothesis that community members in the Vhembe District have limited knowledge and varying perceptions about plastic pollution and its removal, which impacts the effectiveness of wastewater treatment plants (WWTPs). While most participants were aware of WWTPs and plastic pollution, there were significant gaps in knowledge, particularly regarding the plastic pollutant removal process. Although 77% of respondents recognized plastic pollution in wastewater (Figure 7.5a), only 54% had received formal education on the topic, indicating the need for better educational initiatives to address these gaps (Figure 7.5f)

Furthermore, the study highlighted the importance of targeting specific demographics in environmental education. Younger participants showed greater concern for environmental issues, suggesting that youth-focused campaigns may be crucial for sustaining long-term engagement (Table 7.5). Women, who are often more involved in household waste management due to traditional roles, were also more engaged in environmental issues. These findings emphasize the need for improved public education and outreach to increase community knowledge, particularly in rural areas. This aligns with the Value-Belief-Norm (VBN) Theory and the Theory of Planned behaviour (TPB), which suggest that knowledge and awareness are key drivers of pro-environmental behaviour on page 102 (Chen, 2015; De Leeuw *et al*., 2015).

Limitations and Future Research

This study had several limitations. First, the lack of standardized reporting units for MP concentrations limited the comparability of results across different regions. The absence of consistent metrics, such as microplastics per liter (MP/L), hindered cross-country comparisons. Future research should focus on developing universal MP measurement standards to improve data reliability and facilitate global assessments.

Second, the study's reliance on existing literature and secondary data may have introduced biases related to data availability and reporting accuracy. Future research should prioritize primary data collection, including direct sampling and laboratory analysis of MP concentrations in influent and effluent. This would provide a comprehensive understanding of WWTP performance in MP removal.

Third, while the study explored worker knowledge and perceptions, it did not include in-depth interviews or observational studies at WWTPs. Future studies should incorporate qualitative methodologies, such as interviews with policy-makers, to gain deeper insights into governance gaps.

Fourth, the study primarily focused on WWTPs, while broader waste management practices, including landfills and stormwater runoff, were not considered. Future research should examine the role of integrated waste management approaches in reducing MP contamination at the source.

Lastly, the study highlighted the influence of community awareness on plastic pollution but did not assess the effectiveness of existing educational interventions. Future research should evaluate the impact of targeted awareness campaigns and community engagement initiatives on plastic waste reduction.

8.3 Conclusions

To enhance the management of WTPs and WWTPs and address the growing challenge of microplastic pollution, the institutional arrangements that govern these systems must be strengthened. This study identifies key gaps in infrastructure, workforce skills, and regulatory frameworks, which contribute to the varying levels of performance observed among WTPs and WWTPs in the Vhembe district and globally. By focusing on improving public education and awareness, we can support more sustainable water management practices. Applying Ostrom IAD Framework provides a valuable understanding through which to address these challenges. The IAD framework emphasises the importance of understanding the rules, participants, and interactions within a given system, particularly about how decisions are made, who is involved, and how water resources are managed. In the context of WWTPs, the IAD framework can guide the identification of institutional arrangements that promote more effective collaboration between stakeholders (such as government, communities, and industries), ensuring better management of wastewater and microplastics.

To improve the effectiveness of WWTPs, reduce microplastic pollution, and safeguard water quality for future generations, addressing institutional, technological, and community participation challenges is essential. Future efforts should prioritise the development of detailed guidelines for monitoring microplastics, increased investments in advanced treatment technologies, and capacity-building programs to enhance workforce competencies. Additionally, the IAD framework calls for the inclusion of local communities and stakeholders in the decision-making process, ensuring that the rules governing the treatment plants align with both environmental and societal needs. By fostering collaboration and improving institutional arrangements, we can create a more sustainable and effective approach to wastewater management that addresses the complexities of microplastic pollution.

8.4 Recommendations for future works

Workers at water and wastewater treatment plants should receive regular training on new technologies to enhance operational efficiency, while stakeholders should conduct frequent assessments to ensure compliance with regulations. To mitigate the impact of load-shedding, renewable energy should be installed as a backup, preventing the discharge of substandard wastewater and promoting environmentally friendly practices. Routine maintenance of machinery, servicing, and calibration of water testing instruments should be prioritized to meet regulatory standards. The government should allocate additional funding to improve plant operations, invest in advanced treatment technologies, and periodically revise drinking water criteria against WHO standards. Local municipalities should implement strict waste management strategies, such as providing refuse bags for households and imposing fines for illegal dumping, to reduce plastic pollution. Additionally, educational awareness campaigns should be launched to inform communities and WWTP workers about plastic waste management, while residential developments near treatment plants should be restricted to protect public health.

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APPENDIX A: QESTIONNAIRES

A1. Questionnaires 1: Water and wastewater treatment plants survey

Name of Water Treatment Plant: ____

Other worker perception interview

Water perceptions

1. Do you understand the current water or wastewater treatment system at your workplace?
2. Are you satisfied with the standard of treated water at your plant? If no, what do you think needs to be improved?
3. Do you think that plastic pollutants should be prioritised similar to other water quality pollutants such as e-coli? Why? (Probe: do you think that there is a lot plastic waste in South Africa to warrant its prioritisation?)
4. Do you perceive plastic pollutant removal is expensive and otherwise wasteful of resources?
5. Do you drink the water treated at your plant? Would you consider it to be safe to be released into the environment

Protection and preservation of water resources

1. What is the quality of surface waters or wastewater that you treat in your organisation?
2. Do you regard water quantity as a problem?

3. Do you know of or suspect that any of the following pollutants (i.e., plastics) affect either surface or groundwater quality?

4. In your opinion, which of the following are the most responsible for the existing pollution problems in rivers and lakes in your areas?

5. Do you know about plastic pollution? Do you think your treatment facility is able to remove even the smallest plastics i.e., microplastics which pass through initial screening?

6. Do you screen for plastics and other materials before treatment? What kinds of materials do you normally remove?

Learning preferences were assessed through five questions:

1. Have you received water resources or pollution information from your organisation or other?

2. Do you get learning opportunities to learn more about water pollution issues? If so, which one would consider having been the mostly useful in the past year or two?

3. Have you ever changed your mind about a water pollution issues after joining your organisation?

Sociodemographic data

1. What is your gender?

2. What is your age?

3. What is your education level?
4. What is your length of time in post (job)?
5. What is your post (job) or level?

Manager perception interview

1. What is your position within the company?

2. How long have you been with the company?

3. Where do you get your water from that you treat? Do you think your plant has the sufficient capacity to meet every day needs

4. How much water/wastewater do you treat per day? If its wastewater treatment: how often do you have breakdown? And what do you do to mitigate breakdowns and ensure water released into environments meets standards?

5. What treatment methods do you use to treat water or wastewater?

6. Do have the treated water tested? What tests do you do?

7. Do you know about plastic pollution? Do you think your treatment facility is able to remove even the smallest plastics i.e., microplastics which pass through initial screening?

8. Do you screen for plastics and other materials before treatment? What kinds of materials do you normally remove?

9. What resources are available to help you conduct your job properly in terms of water/wastewater treatment?

10. What level of financial resources do you have to conduct your work?

11. What types of water quality data are available?

12. Do you have any institutional documents with regards to pollution to help staff? Can I have a copy?

13. What resources and information are available to support water/wastewater treatment?

14. Do you have enough staff to ensure that water/wastewater treatment goes smoothly?

15. Do your in-house staff have required expertise in and what gaps do you want to be filed?

16. What geographic scale will be used to implement the survey?

17. Is it necessary or possible to classify the waterbodies?

A2. Questionnaire 2: Interview questionnaires for community members

This questionnaire aims to understand public knowledge and attitudes towards wastewater treatment works (WWTPs). Your honest responses will be crucial in shaping future communication and engagement efforts.

As part of the University of Mpumalanga, PhD programme, I, Khumbelo Mabadahanye, am conducting research entitled "Public knowledge and attitudes towards wastewater treatment works (WWTPs) and removing plastic pollutants in the Vhembe District, South Africa". If you over 18 years old and live within the Vhembe District, you are invited to complete the following survey which should take you approximately 10-15 minutes.

The project is supervised by Dr Mwazvita Dalu and Dr Tatenda Dalu. Should you have any questions or concerns please feel free to contact either of us. Dr Mwazvita Dalu: mwazvita.dalu@ump.ac.za, Dr Tatenda Dalu: tatenda.dalu@ump.ac.za or Khumbelo Mabadahanye: mabadahanyek@gmail.com.

Please note the following before completing the questionnaire.

- This questionnaire is completely voluntary,
- You must be 18 years or older to complete the survey,
- All answers will remain anonymous, with no way to identify the respondent,
- You are free to exit the questionnaire without having your answers recorded, simply by exiting the questionnaire at any time,
- The information collected will be used for publication and by answering the questionnaire, you give consent for your results to be used for this research.
- You are entitled to view the results of this study, upon completion (December 2024). You may do so by contacting myself, Dr M Dalu or Dr T Dalu.

Please answer the following questions, selecting the answer which most applies to you.

Part 1: Demographics

1. Age:
    - o 18-24
    - o 25-34
    - o 35-44
    - o 45-54
    - o 55+
    - o Prefer not to answer

2. Gender:
    - o Male
    - o Female
    - o Non-binary
    - o Prefer not to say
3. Highest level of education completed:

- Uneducated
- Primary school
- High School
- Certificate
- Diploma
- Degree
- Postgraduate degree

4. Employment status
    - Student/Unemployed
    - Self-employed
    - Retired
    - Unemployed
    - Employed

Part 2: Awareness and Knowledge

5. Have you ever heard of a wastewater treatment work (WWTP)?
    - Yes
    - No
6. If yes, what do you understand a WWTP to be? (Please answer in your own words)

    …………………………………………………………………………………………
    …………………………………………………………………………………………
    …………………………………………………………………………………………
    …………………………………………………………………………………………

7. If you answered yes to question 1, what is your understanding of what a wastewater treatment works does? (**Select all that apply**)
    - Cleans wastewater before releasing it back into the environment
    - Processes solid waste
    - Generates electricity
    - I'm not sure
8. In your opinion, how important is it for a community to have a functioning WWTP?
    - Very important
    - Somewhat important
    - Neutral
    - Somewhat unimportant
    - Not important at all
9. Where does your household wastewater eventually go? (**Select all that apply**)
    - Public sewer system
    - Septic tank
    - Unsure
    - Other (please specify): ……………………………………………………….
10. Are you aware of the existence of wastewater treatment works in your community?
    - Yes
    - No
    - Unsure
11. How close do you live to a wastewater treatment work (if aware)?
    - Less than 1 km

- 1-5 km
- More than 5 km
- Unsure of location

Part 3: Perceptions

12. Please rate your level of agreement with the following statements: (Use a scale of 1 - Strongly Disagree, 2 - Disagree, 3 - Neutral, 4 - Agree, 5 - Strongly Agree)

Variable	**1 - Strongly Disagree**	**2 - Disagree**	**3 - Neutral**	**4 - Agree**	**5 - Strongly Agree**
WWTPs are smelly and unpleasant to live near.					
WWTPs are a necessary evil for modern society.					
WWTPs can be a positive contribution to the environment.					
I would be concerned about property values if a WWTP was built in my neighborhood.					
I am interested in learning more about how WWTPs work.					

13. Do you have any concerns about the potential impact of WWTPs on the environment or public health?

………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………

How important do you believe wastewater treatment works are for our community?

- Very important
- Somewhat important
- Not very important
- Not important at all

14. Do you have any concerns about living near a wastewater treatment works? (**Select all that apply**)
    - Odors
    - Environmental pollution
    - Health risks
    - Property values decreasing
    - I have no concerns
    - Other (please specify):………………………………………………………..
15. If you answered yes to question 3, how would you feel about increased public education efforts regarding the safety and benefits of wastewater treatment works?
    - Very supportive

- o Somewhat supportive
- o Neutral
- o Somewhat opposed
- o Very opposed

16. Which of the following words or phrases best describe what comes to mind when you think of wastewater treatment works? (**Choose all that apply**)
    - o Necessary
    - o Unpleasant odor
    - o Environmental protection
    - o Public health risk
    - o Outdated technology
    - o Other (Please specify): …………………………………………………….
17. Do you have any concerns about living near a wastewater treatment work?
    - o Yes
    - o No
18. If you answered yes to question 7, please elaborate on your concerns:

    ……………………………………………………………………………………
    ……………………………………………………………………………………
    ……………………………………………………………………………………
    ……………………………………………………………………………………

Part 4: Willingness to Engage

20. If a community outreach event were held to explain the workings of a local WWTP, would you be likely to attend?
    - o Yes
    - o No

21. Would you be interested in learning more about how wastewater treatment works function?
    - o Yes
    - o No
22. What is the preferred method for you to receive information about wastewater treatment works? (**Choose all that apply**)
    - o Informational pamphlets
    - o Public presentations
    - o Educational websites
    - o Social media updates
    - o Other (Please specify): ………………………………………………………
23. How interested would you be in learning more about how wastewater treatment works function?
    - o Very interested
    - o Somewhat interested
    - o Not interested
24. Do you have any suggestions on how wastewater treatment works can better engage with the community?

………………………………………………………………………………………
………………………………………………………………………………………
……………………………………………………………………………………….

25. How important do you believe wastewater treatment works are for your community?
    - Very Important
    - Somewhat Important
    - Not Important
    - Unsure

Section 3: Perceptions of Effectiveness

1. To what extent do you believe the wastewater treatment facility in your community effectively treats wastewater?
    - Very effective
    - Somewhat effective
    - Not effective at all
    - Unsure
2. Have you ever noticed any negative impacts (e.g., odours, pollution) that you believe might be related to the wastewater treatment facility?
    - Yes
    - No
    - Unsure (Please elaborate if you answered yes)
3. How confident are you in the safety of the water discharged from the wastewater treatment facility?
    - Very confident
    - Somewhat confident
    - Not confident at all
    - Unsure

21. How important is it to you that wastewater treatment facilities remove plastic effectively?
    - Very important
    - Somewhat important
    - Neutral
    - Somewhat unimportant
    - Not important at all
22. Do you know about the presence of plastic pollutants in wastewater?
    - Yes
    - No
    - Not sure
23. How do you think plastic pollutants enter wastewater?
    - Industrial discharge
    - Domestic waste
    - Stormwater runoff
    - Other (please specify):……………………………………………………………..
24. In your opinion, how effective do you think current wastewater treatment plants are in removing plastic pollutants?
    - Very effective
    - Moderately effective
    - Ineffective

- Not sure

25. What factors do you think influence the efficiency of wastewater treatment plants in removing plastic pollutants? (**Check all that apply**)
    - Technology used
    - Funding and resources
    - Government regulations
    - Public awareness and engagement
    - Other (please specify):…………………………………………………………..
26. What factors do you believe contribute to the efficiency or inefficiency of wastewater treatment in removing plastic pollutants?
    …………………………………………………………………………………
    …………………………………………………………………………………
    …………………………………………………………………………………
    …………………………………………………………………………………
27. How concerned are you about the presence of plastic pollutants in wastewater?
    - Very concerned
    - Somewhat concerned
    - Not concerned
    - Unsure
28. What do you think should be the top priority for wastewater treatment facilities regarding plastic pollution removal?
    …………………………………………………………………………………
    …………………………………………………………………………………
    …………………………………………………………………………………
    …………………………………………………………………………………
29. Do you think the public has a role to play in reducing plastic pollution in wastewater?
    - Yes, individuals can make a difference
    - No, it's solely the responsibility of industries and governments
    - Not sure
30. What measures do you think individuals can take to reduce plastic pollution in wastewater?
    …………………………………………………………………………………
    …………………………………………………………………………………
    …………………………………………………………………………………
    …………………………………………………………………………………
31. Have you ever received information or education regarding plastic pollution in wastewater?
    - Yes
    - No
32. How effective do you think public awareness campaigns are in addressing plastic pollution in wastewater?
    …………………………………………………………………………………
    …………………………………………………………………………………
    …………………………………………………………………………………
33. How much trust do you have in the information provided by wastewater treatment authorities regarding plastic removal?
    - Complete trust
    - Moderate trust
    - Limited trust
    - No trust