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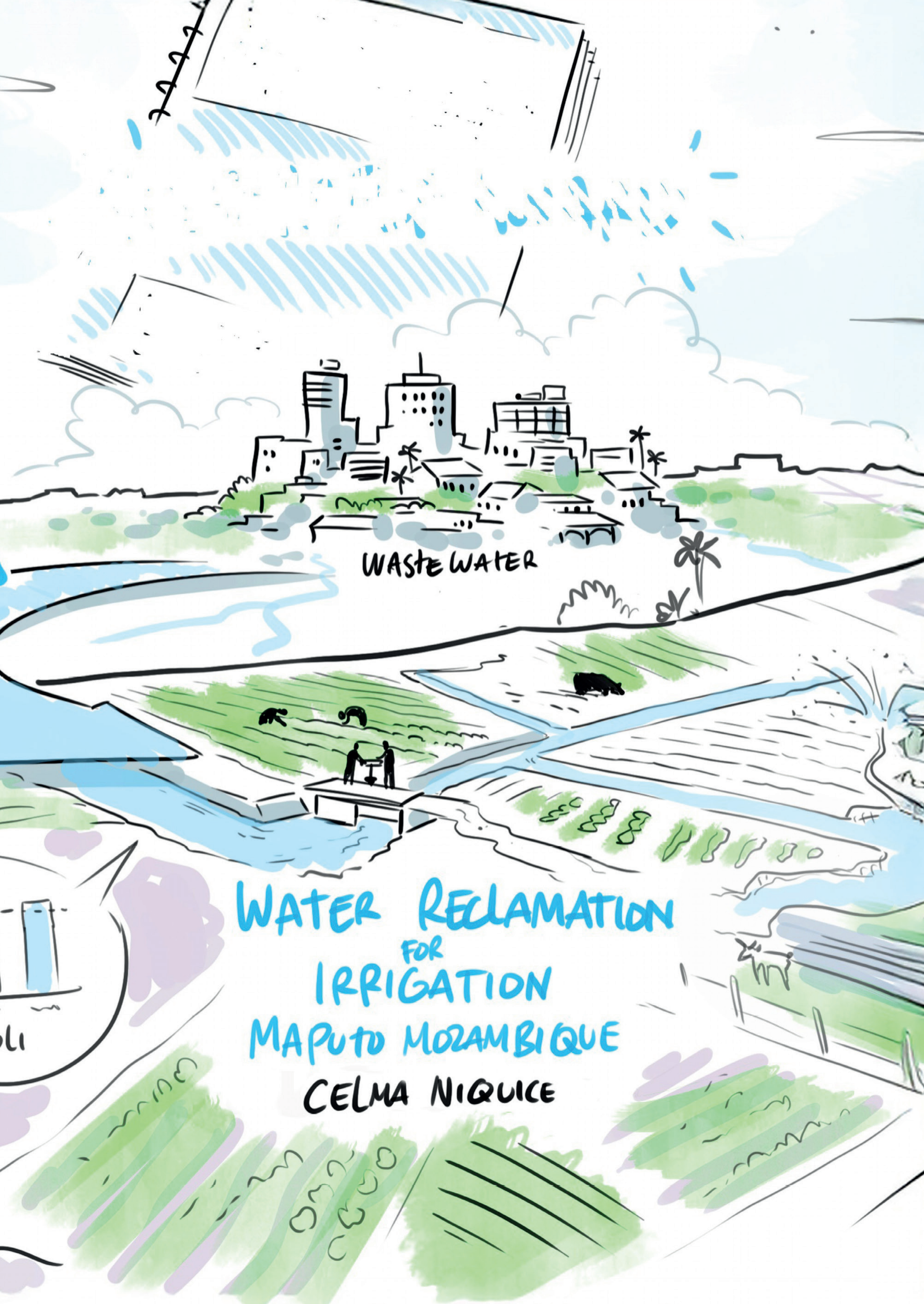
WASTEWATER
WATER RECLAMATION
FOR
IRRIGATION
MAPUTO MOZAMBIQUE
CELMA NIQUICE

Water reclamation for irrigation in Maputo, Mozambique

Dissertation

for the purpose of obtaining the degree of doctor

at Delft University of Technology

By the authority of the Rector Magnificus Prof.dr.ir. T.H.J.J. van der Hagen,

Chair of Board for Doctorates

To be defended publicly on

Tuesday 28 October 2025 at 10:00 o'clock

By

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Master of Science in Water Resources Management

The University of Adelaide

Adelaide, Australia

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This dissertation has been approved by the promotors.

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Contents

Summary

Understanding the potential and constraints of water reclamation is essential for the decision makers to design interventions that improve the process in a safely manner e.g. for Maputo, Mozambique. In this thesis i) the potential and constraints of using (partially) treated wastewater in irrigated agriculture for sub-Saharan Africa (SSA) was analysed; ii) the concentration of the indicator *Escherichia coli* (*E. coli*) in irrigation water, the lettuce (*Lactuca sativa*) produced in the irrigation fields in Infulene Valley, in Maputo, Mozambique, and the lettuce subsequently sold at local markets in Maputo was assessed; iii) and the potential contribution of wastewater-based nutrients to the supply of nitrogen (N), phosphorous (P), and potassium (K) for lettuce production in the Infulene Valley, in Maputo, Mozambique, was studied.

An extensive literature review was performed for existing examples of water reclamation in sub-Saharan Africa, followed by laboratorial analyses of water, soil and lettuce samples collected in the Infulene valley in Maputo. We analysed the faecal coliform contamination considering the *E. coli* as its indicator, the content of nutrients (Nitrogen, Phosphorous and Potassium), and the potential toxic elements (PTE) present in the samples.

Water reclamation is informally practiced in many SSA countries, with wide use of untreated reclaimed wastewater in agriculture. Wastewater quality in most of SSA countries is regulated by the 1989 WHO guidelines, instead of its more recent 2006 guidelines. The 1989 WHO guidelines are based on restrictive effluent criteria, which are more practical to use, compared to the 2006 WHO guidelines. However, the 1989 WHO guidelines are not effective for risk reduction of the farmers' practices, based on the installed wastewater treatment capacity and the vulnerability of contamination along the supply chain. The 2006 WHO

guidelines are more complex to implement for most of the SSA countries. The multiple barrier approach has been proposed for safe water reclamation combining the treatment and the critical points for quality control in the value chain to reduce the health risks. This requires the development of a water reclamation approach, which matches the required water quality at the point of use and the design of an affordable wastewater treatment, which reduces risks on the long term. Overall, it was concluded that there is a potential in SSA countries for water reclamation, although it requires the development of the relatively poor water and sanitation infrastructure to support its implementation.

We found that irrigation water is not the only potential source of faecal contamination in the value chain of lettuce produced at farms and sold at local markets of Maputo. The lettuce produced in the Infulene valley was also contaminated along the value chain, regardless of the irrigation source. The process of washing lettuce in the market presents a potential for re-contamination and it contributes little in risk reduction. Some measures for reducing the risk of contamination such as delaying harvest at the farm, and hygienic practices at the marketplace will impact the contamination levels of the lettuce, irrespective of the use of reclaimed wastewater or other water sources for irrigation in the Infulene Valley in Maputo.

Our analysis revealed further that wastewater is a viable alternative for nutrient supply in the Infulene Valley. It contains higher amounts of essential nutrients (N, P, and K) compared to groundwater. This highlights the potential of wastewater as an effective source to (1) re-plenish nutrients in agricultural systems to meet crop nutrient demands and (2) to reduce reliance on traditional fertilizers. However, careful nutrient management is crucial to avoid excessive nutrient dosing, which can lead to health and environmental hazards such as groundwater pollution, pollution of water ways, and soil degradation. Implementing strategies such as combined source control, frequent water monitoring, and appropriate treatment options can help for ferti-irrigation in peri-urban areas like the Infulene Valley.

Finally, our data showed that PTE were present at low concentrations in the irrigation water and soil. In plants, the concentration of chromium, aluminium, iron and sodium exceeded the recommended levels, suggesting sources unrelated to irrigation water. The high concentration of certain PTE when using river water and wastewater revealed the need for monitoring and understanding the elemental composition of crops, especially when different irrigation sources are used. Additionally, elevated sodium adsorption ratios and electrical conductivity levels across irrigation sources emphasize the need for cautious use of wastewater for irrigation. Monitoring activities are recommended for the Infulene valley, in order to prevent accumulation of Mn, Al, Fe, Cr and Na, which potentially have negative impacts on the crop production, environment, and food security.

Overall, it can be concluded that the promotion of safe water reclamation in SSA countries should be implemented applying a holistic approach, including water treatment and the entire agricultural value chain that includes crop producers (farms), crop handlers, market vendors, and end consumers. Planners should consider the 'farm-to-market-consumer' chain to implement local safety measures that mitigate risks. Change in social behaviour towards reclaimed wastewater also represents an important aspect for inclusion in activities towards the implementation of safe water reclamation. At policy level, persistent behaviours should also be changed to facilitate revisiting infrastructures and policies for reclaiming wastewater. In addition, initiatives for water reclamation should consider all potential end users, such as agricultural and industrial users, while embedding opportunities for a circular economy for a positive impact on farmers, society, and the environment.

Chapter 1: Introduction

1.1. Background and Mozambican context

World water demands are expected to have doubled by 2050 (Bahri, 2012; He et al., 2021) and competition for water resources in urban and peri-urban areas is likely to escalate (Asano, 2005). Multiple water uses or domestic water reclamation present a possible solution to these problems. Water reclamation is the process of treating domestic wastewater up to a specific standard for a specific (high or low quality) use (Ahuja, 2014; Van Ginneken & Oron, 2000). Water reclamation may contribute to the conservation of the water quality, and supplementing water sources (Asano, 2005). Water reclamation may also contribute to fertilisation of agricultural fields, resulting in an increase in crop yields (Chenini et al., 2003). Additionally, it may facilitate urban development under constrained sanitary conditions (Agodzo et al., 2003), since it requires improved collection (sewerage) and leads to controlled discharge of treated urban wastewater when wastewater treatment facilities are implemented.

However, when water reclamation is not adequately managed, potential risks can be identified that, depending on their severity, can pose problems to human and animal health and to the environment. Short term risks include contamination with pathogens, and long term effects may arise when polluted wastewater with chemicals, such as heavy metals, is continuously used e.g. for agriculture (Toze, 2006a). Therefore, the use of non-treated or partially treated wastewater in agriculture requires an integrated approach to minimise possible harm to people and the environment. However, in most areas with limited resources, adequate treatment and reclamation schemes are not present and generally constrained (Shenge et al., 2015), and wastewater in agriculture is usually directly used or after only partial treatment (Huibers & Van Lier, 2005).

Wastewater can be reclaimed for several uses, such as agricultural irrigation, landscaping, industrial use, and indirect or direct potable use (Asano, 2005). This thesis focuses on water reclamation for peri-urban agricultural irrigation in Maputo, the capital of Mozambique. Agriculture is the main source of living for the major part of the population (80%) in Mozambique (Anderson & Learch, 2016; Ismael et al., 2021) and agriculture represents the largest water user (73%) when compared to industry (2%) and domestic uses (25%) (FAO, 2016).

In Mozambique the agriculture sector also contributes to 20 % of its gross domestic product (GDP) (Ismael et al., 2021), making this sector an important contributor to the GDP. Nevertheless, the country's growth in GDP may be undermined by climate and hydrological vulnerability: after all, Mozambique's geographical location at the intertropical convergence zone, with a long coastal zone, and large areas below sea level, makes the country vulnerable to climate change (Zacarias, 2019). Besides, 56% of the water resources running through Mozambique originates from shared rivers that are, therefore, vulnerable to dynamic water changes in neighbouring countries (INGC, 2009). Additional to these GDP-growth limiting factors, the country's water storage capacity is low, reaching only 0.3 % of the renewable freshwater (WB, 2022), which limits the expansion of agriculture, threatening food security. Particularly, the country's southern region, where Maputo is located, is vulnerable to droughts, and the risks of agricultural losses are estimated to be around 50% of total harvests (Armand et al., 2019). Thus water scarcity poses a significant problem for Maputo (Rietveld et al., 2016a) and shortages in water resources can cause a drop in GDP, of possibly 1.1 % per annum (WB, 2005, 2007).

Mozambique's total population was estimated at 33.7 million with around 50 to 60 % projected to be living in cities by 2050 (UNHabitat, 2023). Maputo currently houses around 2 million inhabitants with an annual growth rate of over 1.3% since 1995 (Jacobsen et al., 2013; Rusca et al., 2023). Access to sanitation services both in cities and rural areas is deficient, and overall, 48 % of the population does not have access to improved sanitation systems (Ross et al., 2021).

During the research period, less than 10% of wastewater was partially treated, while the remaining wastewater was discharged untreated (Caltran, 2014; Rietveld et al., 2016). Part of the collected wastewater flows from the urban area to the central wastewater treatment plant in the Infulene Valley (Cabrita et al., 2024; Rietveld et al., 2016). The Infulene wastewater treatment plant consists of a pond system (two anaerobic and two facultative) (Rietveld et al., 2016). Both the partially and non-treated wastewater is used for irrigation in agriculture in the peri-urban areas near the wastewater treatment plant (Rietveld et al., 2016). However, wastewater unsafely used in irrigation may cause health risks for farmers and consumers of the crops that are irrigated. At the same time, wastewater represents a source of nutrients for agriculture (Woltersdorf et al., 2016). This is especially valuable since research on fertilizer use in Mozambique indicates that the country's general use of fertilizers is low compared to that of other African countries (Zavale et al., 2020), which may undermine crop productivity in relation to neighbouring countries. Therefore, water reclamation for irrigation presents a potential opportunity to supply both good quality water and nutrients, as an alternative to fertilizers, in peri- urban agriculture. Droughts are becoming frequent in the Southern Africa region and are expected to increase over the years, which will negatively influence the agriculture sector due to the lack of available water (Ayugi et al., 2022; Gizaw & Gan, 2017). In Mozambique, the precipitation pattern is highly variable with oscillations from 683 to 1276 mm, deeply influenced by the southern intertropical convergency zone, and by the circulation of El Nino southern oscillation (ENSO) which determines the drought years and rainy years. During the Maputo droughts of 2015-2017, the regional freshwater restrictions significantly affected the agricultural sector, which benefitted least in water allocations (Rusca et al., 2023). Population growth and climate change exacerbate the impacts of frequent droughts, compounded by freshwater pollution significantly reducing the availability of water for consumption.

As in most of the countries in Africa, the Mozambican population increase does not run parallel with the expansion of the sewerage infrastructure, and large amounts of sewage are discharged into the environment, thus polluting freshwater sources. Only 10% of the population is connected to the existing sewer built in 1984 (Capone et al., 2019; Rietveld et al., 2016). At the time when the sewer was constructed, the population of Mozambique counted 13.4 million inhabitants (Affairs-USA, 1985), and Maputo city had less than 1 million inhabitants. The country's current population is a little over 32 million with 35 % living in urban areas and 65 % in rural areas with an expected increase of 2.5 % per annum (INE, 2024) pressuring the available freshwater sources. The current population in the capital has reached about 2 million inhabitants (Rusca et al., 2023). The population growth in Maputo is a result of migration from rural areas to the city, where citizens sought for security as a result of the civil war between 1972 and 1992 (Raimundo, 2022). In Maputo's peri urban areas this has contributed to a population increase of people who are mostly unemployed, without access to education and accommodation, laying the foundation for the development of Maputo city's poverty belt with its deficient sanitation, and revealing some problems of urban management (Barros et al., 2014). The sewerage infrastructure has since 1984 remained the same without covering the peri-urban areas. Therefore, several urban and the peri-urban areas rely on onsite sanitation and direct discharge to the environment, causing pollution, and a loss of nutrients that could have been used within the agricultural fields. In addition, uncontrolled discharges to the environment significantly contribute to the pollution in e.g. the Maputo Bay (Scarlet & Bandeira, 2014).

The practice of agriculture in peri-urban areas should guarantee farmers' main source of livelihoods. Some of the irrigation water is partially treated wastewater from the existing treatment facility (Rietveld et al., 2016). Therefore, reclaiming wastewater in peri-urban areas should be a priority to alleviate the water restrictions for the continuity of peri-urban agriculture since wastewater is reliable throughout the year. It also increases the sustainability of agricultural production in areas in close proximity to peri-urban areas, as the existence of market demand near the production areas reduces the need for transport. However, a number of aspects influence the implementation of water reclamation (Adewumi et al., 2010). These include the existence of pathogens and potentially toxic elements such as heavy metals in the urban wastewater. Unrestricted use of treated wastewater in irrigated agriculture is generally accepted when pathogens are removed to a high extent (de Koning et al., 2008). Studies on water reclamation for agricultural use are extensively described in literature (Angelakis & Durham, 2008; Bixio et al., 2006; Bixio et al., 2008) showing the need for technological innovation, establishment of best practices, and the consolidation of the use of structural and non-structural managerial techniques . Others have analysed the water reclamation potential and health risks (Antwi-agyei, 2015; Qadir et al., 2010; Toze, 2006b). Some of these studies have focused on sub-Saharan Africa (SSA) examining the potential for irrigating with partially treated wastewater, monitoring effluent quality of diverse types of wastewater treatment technologies (Adewumi et al., 2010; Agodzo et al., 2003; Kihila et al., 2014), and assessing the potential of treated effluent to serve as a nutrient source (Akponikpè et al., 2011). However, there is still a need for the evaluation of faecal contamination at the farm level and also considering the value chain from farm land to market. In addition, it is unknown to what extend irrigation with treated wastewater contributes to the nutrients' levels for lettuce production and to the contamination of potentially toxic elements in the lettuce. This knowledge would allow to understand the contribution and promotion of safe water reclamation in peri urban agriculture in SSA.

1.2. Research Objectives

The main hypothesis for this research is that water reclamation for irrigated agriculture in Maputo will stimulate agricultural production, and will reduce environmental pollution, provided that human health constraints are adequately addressed. Both the negatively valued water and nutrients in the wastewater should be recovered and valorised for productive use. Therefore, to achieve the overall aim the following specific research questions have been formulated:

- What are the potentials and constraints of using (partially) treated wastewater in irrigated agriculture for sub-Saharan Africa;
- Do high concentrations of the indicator *Escherichia coli (E. coli)* in irrigation water influence the quality of the lettuce *(Lactuca sativa*) produced in Infulene, and the lettuce subsequently sold at local markets in Maputo;
- What is the potential contribution of wastewater-based nutrients to the supply of nitrogen (N), phosphorous (P), and potassium (K) for lettuce production in the Infulene Valley, in Maputo, Mozambique;
- Are potentially toxic elements present in/on lettuce irrigated with wastewater in the Infulene valley.

1.3. Thesis Outline

The thesis consists of the following chapters. **Chapter 2** comprises an extensive literature review on the subject of water reclamation for irrigation in SSA and experiences in wastewater treatment. **Chapter 3** focuses on faecal contamination on lettuce irrigated with different water sources in Maputo, produced in the Infulene valley (Maputo), and sold at nearby markets in Maputo and Matola. **Chapter 4** comprises an evaluation of nutrients availability in wastewater used, for which an evaluation of the amounts of nutrients available for lettuce production was performed in the Infulene valley. **Chapter 5:** focuses on the presence of potential toxic elements, present in various irrigating water sources that are used in the Infulene valley. The thesis ends with **Chapter 6** on the conclusions and outlook.

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Chapter 2*:* Use of (partially) treated municipal wastewater in irrigated agriculture; potentials and constraints for sub-Saharan Africa;

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Use of (partially) treated municipal wastewater in irrigated agriculture in sub-Saharan Africa: potentials and constraints

Abstract

This review identifies the potentials and constraints of using (partially) treated or blended wastewater for irrigation in order to assess the potentials in the context of cities in sub-Saharan Africa, specifically Maputo, the capital of Mozambique. Less than 5% of the wastewater produced in the region is being treated. Nonetheless, untreated, partially treated, and/or blended wastewater is extensively being used for agricultural purposes. Despite the last updated WHO 2006 guidelines for 'wastewater use in agriculture', authorities only consider the different water quality parameters at the point of use. Other aspects such as irrigation type, crop management and post harvesting practices, which clearly influence the contaminant log reduction, are simply ignored. Those parameters, however, are considered alternatives to a classic contaminant log reduction, which may be very beneficial for developing countries. In a more holistic approach, trade-off is favoured between the required water quality for irrigation, use of affordable treatment technologies, and adequate post-harvest strategies to reduce the current health risks to acceptable levels. Such a trade-off makes use of multiple barrier approach, whereby wastewater treatment and critical point barriers throughout the supply chain are combined. Thus, there is a long way ahead to achieve proper water reclamation for productive use; the current paradigm has to change. Current restrictive guidelines are unrealistic given current practices, and approaches more appropriate to the location's situation still need to be developed. A multiple barrier approach in combination with master planning is recommended to consider wastewater treatment and critical point barriers throughout the supply chain.

2.1. Introduction

The global population is increasing, and projections indicate that it will continue to increase to around 9 billion in the year 2050 (Angelakis and Gikas, 2014). Whereas in 1950 only 20% of the world's population was living in cities, in 2016, this proportion had already reached 50% (Orsini et al., 2013; The World Bank Group, 2016). It is predicted that this fraction will raise to around 70% in 2050 (Moir et al., 2014; Orsini et al., 2013; Vairavamoorthy et al., 2008). A commonly referenced implication of urban population increase is the need for more food production in urban areas (Bryld, 2003; de Fraiture and Wichelns, 2010; Orsini et al., 2013; Whittinghill and Rowe, 2011). Urban agriculture is believed to play an important role, to both i) address population increase in the forthcoming century (De Zeeuw et al., 2011; Duran et al., 2003; Orsini et al., 2013) and ii) to provide a reliable source of income for the poor farmers who migrate towards cities (Bryld, 2003; Whittinghill and Rowe, 2011). However, in many locations, water is the major limiting factor for agriculture, which is particularly true for urban agriculture (Orsini et al., 2013). Urban areas typically have high population densities, which translates into high land prices and high water demands. Moreover, urban agriculture must compete for land with other activities such as housing, industry and recreational activities (Zasada, 2011), making it difficult to maintain current urban farms, particularly when it is not part of the city master planning (Aubry et al., 2012). In addition, competitive water claims are common and may result from the fact that the water often has to be pumped from distant areas (Roon, 2007; Vairavamoorthy et al., 2008). As a result, urban farmers often struggle to obtain high quality irrigation water because of competition with potable uses (Moglia, 2014). However, in urban areas, alternative (low-grade) water sources are generally available, such as wastewater originating from households, industries, and storm water (Toze, 2006; van Lier and Huibers, 2010). These alternative sources have frequently been studied for use in agricultural irrigation (Roon, 2007; Srinivasan and Reddy, 2009; van Rooijen et al., 2010; Villamar et al., 2018).

If appropriate safety measures are followed, treated or partially treated wastewater can be used safely, which is referred to as reclaimed water. Therefore, wastewater can be viewed as an alternative and reliable water source with the ability to increase urban water availability, especially during dry periods (Dorta-Santos et al., 2015; Huibers and van Lier, 2005; Jiménez and Asano, 2008a). In addition, the available wastewater quantity is in direct relation to the supply coverage, sewerage coverage, and population size of the urban areas (Huibers and van Lier, 2005). Furthermore, irrigation with adequately treated wastewater will also protect freshwater sources and the environment (Aiello et al., 2007; Qadir et al., 2010a). Reclaimed water is also a source of macro- and micro-nutrients that are important for plant development, soil pH, soil buffer capacity and cation exchange capacity (CEC) (Chen et al., 2013; Mohammad et al., 2007). Therefore, the use of reclaimed water could eventually lead to the reduced usage of commercial fertilizers (Jiménez-Cisneros, 2014a; Qadir et al., 2010a; Srinivasan et al., 2013). This is of particular importance for the case of phosphorous, due to limited available quantities of high-quality phosphorus rock in the world and predicted price increases of artificial fertilisers (Elser and Bennett, 2011; Woltersdorf et al., 2016). Furthermore, water reclamation leads to revenue generation (Jiménez-Cisneros, 2014b), which has the potential to support the improvement of sanitation services, as wastewater works can become revenue sources instead of simply being costly services.

In Africa, an estimated 40% of urban dwellers are involved in some sort of agricultural activity, and this percentage increases to 50% in South America (Zezza and Tasciotti, 2010). In these continents, water reclamation for irrigation is of special importance as it sometimes is the only water source available (Norton-Brandão et al., 2013). Water reclamation in Africa and South America typically involves the use of partially treated or untreated wastewater (Huibers and van Lier, 2005), a practice that is unsafe for farmers, consumers, and the environment alike (Fatta et al., 2005; Norton-Brandão et al., 2013; Weldesilassie et al., 2011). With regard to sanitation, Nansubuga et al. (2016) presented a 2012 estimate that more than 800 million urban dwellers in developing countries live in slum areas that generally fail to provide inhabitants with inclusive, affordable, and appropriate sanitation services. It can thus be argued that water reclamation has the potential to address pivotal challenges that developing countries face, specifically providing safe water for an increasing urban agriculture production, while supporting the improvement of lacking sanitation services. Therefore, this paper aimed at identifying the potentials and constraints of using (partially) treated wastewater in irrigated agriculture for sub-Saharan Africa. The specific aims were to review the current worldwide trends for water reclamation in agriculture, to identify the required water quality of reclaimed water for irrigation and to identify the status of water reclamation in sub-Saharan countries. Special attention is given to the possible translation of global examples into the context of sub-Saharan African cities, particularly Maputo, the capital of Mozambique.

2.2. Methodology

A literature review is conducted on the use of (partially) treated municipal wastewater in irrigated agriculture, reviewing its potentials, and constraints for sub-Saharan Africa. The study considered peer-reviewed international literature, as well as projects dealing with water reclamation linked to agricultural irrigation, conference proceedings, and technical reports. The purpose of this review was to find the examples, trends, potentials, and constraints of water reclamation for irrigation that could be further applied in the SSA region. In addition to searches on 'global trends for water reclamation in agriculture' and 'water quality of reclaimed water for irrigation', we also considered the various international guidelines for irrigation with ((partially) treated) wastewater. Wastewater treatment options with examples were reviewed that were later grouped and classified in regulated and non-regulated water reclamation examples, as well as irrigation and post-harvesting practices. In addition to peer reviewed scientific papers, also practical water reclamation examples, with an irrigation component were include, with special attention for projects concerning sub-Saharan Africa. The variety of project examples and literature hampered a thorough meta-analysis. However, a conclusive state of the art and way forward recommendation is provided regarding the potentials of water reclamation for agricultural reuse in sub-Saharan Africa.

2.3 Results and Discussion

2.3.1. Global trends for water reclamation in agriculture

The amount of wastewater produced around the world is an indicator for potential (peri-) urban water reclamation. Globally, the daily volume of wastewater production varies from 680 to 960 million m^3 with a current maximum treatment capacity of 32 million m^3, representing less than 5% of the amount produced (Lautze et al., 2014). This means that there is a huge need for increasing the collection and treatment capacity and thus increasing the water availability for reclamation. Several authors argue that the main reasons for this gap are obsolete, inappropriate, and /or mismanaged sanitation infrastructure (Scott et al., 2004), lack of inclusion in urban planning (Bahri, 2012), limited financial resources (Raschid-sally and Jayakody, 2008), and lack of capacity to enforce regulations (Qadir et al., 2010b).

As discussed, water reclamation is regarded an affordable alternative for many water-scarce regions (Saldías et al., 2016) and a reliable provision of a consistent nutrient source (Akponikpè et al., 2011; Miller-Robbie et al., 2017; Scott et al., 2004). Given the aforementioned accessibility to wastewater streams, irrigation tends to be an important endpoint for untreated or (partially) treated wastewater in many developing countries (Al-Hamaiedeh and Bino, 2010; Jaramillo and Restrepo, 2017; Keraita et al., 2008; Raschid-Sally et al., 2005; Scott et al., 2004). At the eve of the 21st century, it was estimated that about 10% of the global population consumed crops irrigated with raw, partially treated, or blended wastewater (Smit and Nasr, 1992) coming from over 20 million hectares of arable land in about 50 countries (Hussain et al., 2001; Malik et al., 2015; van der Hoek, 2004). Other estimates indicated that worldwide, the total area irrigated with raw, (partially) treated, or blended wastewater is about 1.5-6.6% of a total irrigated area of 301 million hectares (Sato et al., 2013); and it is predicted that water reclamation for irrigation will have the largest increase compared to other uses such as industrial and domestic (Jiménez-Cisneros, 2014b).

Within Europe, water reclamation for agricultural reuse is typically practiced in the semi-arid regions, which includes most coastal areas, and on the islands in the South of the continent (Angelakis and Gikas, 2014; Bixio et al., 2006; Sato et al., 2013). The amount of reclaimed water predicted for Europe will exceed 3 million km^3 per year by 2025 (Angelakis and Gikas, 2014; Raso, 2013). In non-European Mediterranean countries, the situation is very similar to their European counterparts, namely using the reclaimed water mainly for agricultural purposes (Bedbabis et al., 2010). Water reclamation is highest in Israel, reclaiming almost 90% of the produced wastewater (Powley et al., 2016). Similarly, in western North America and Australia, water reclamation is mostly used for irrigation (Sato et al., 2013). In areas where wastewater treatment is scarcely implemented, farmers use non-treated or diluted wastewater for irrigation. China, India and Mexico are the countries with the largest areas irrigated with untreated or diluted wastewater (Jaramillo and Restrepo, 2017; Keraita et al., 2008; Lautze et al., 2014), covering areas of about 3.5 million hectares in China and more than 1 million hectares in both India and Mexico (Lautze et al., 2014). In Chinese water reclamation programs, the main irrigated crops are vegetables, such as spinach, cabbage, parsley, and cauliflower; and cereals, typically maize, wheat, rice, and brown rice (Zhang et al., 2015). For the case of India, examples include sugar cane fields irrigated with industrial effluents (Pandey et al.,

2016) and vegetables irrigated with municipal wastewater (Gupta et al., 2008; Sharma et al., 2007). In Mexico, untreated or partially treated wastewater is even used to irrigate vegetable crops consumed raw such as radish, spinach, lettuce, parsley, and celery (Castro-Rosas et al., 2012), but also maize, alfalfa, and other forage crops (Chávez et al., 2011).

The potential role of water reclamation for irrigation in Africa is more closely linked to the localized value in the (peri-)urban setting than to the absolute quantitative amounts relative to the national water budgets. (Peri-)urban agriculture is an important economic activity in African cities since it provides agricultural goods at limited distances from the consumers (Raschid-Sally et al., 2005); in some cities such as Accra, Ghana, over 60-70% of the consumed agricultural goods that are consumed in the urban area are also produced there (Agodzo et al., 2003). Water withdrawals for different uses in different regions of Africa show large differences between agricultural water abstractions and urban water uses. In most regions of Africa, the majority of water abstractions are used for irrigation, which comprises 70-90% of the total abstractions on the continent (FAO, 2005). Agriculture contributes to 35% of the GDP in sub-Saharan Africa, and food production is required to double by the year 2050 (Diao et al., 2010; FAO, 2009; Rockström et al., 2010). The average water demand for agriculture is 1,300 m^3 per capita per year, and it is expected to increase to a total value of 8,500-11,000 km^3 per year by 2050 (Rockström et al., 2010). Also, the quantity and quality of water is rapidly reducing across countries in sub-Saharan Africa (Freitas, 2013), resulting in growing water shortages due to increasing water demands for food production as well as industrial and domestic use (Rockström et al., 2010). The agriculture sector is by far the largest freshwater user, and thus, water reclamation for irrigation is an alternative that might reduce pressure on freshwater resources, particularly near and in urban areas, while also preventing non-controlled wastewater discharges to the environment (Pedrero et al., 2010; van Lier and Huibers, 2010). In addition, urban water reclamation is an opportunity to reduce the use of artificial fertilizers, which can serve as an economic benefit to (poor) farmers and help to improve their livelihood. Therefore, it is argued that if the produced wastewater in Africa could be collected, treated and reclaimed for safe irrigation, it could help to ensure food production and to overcome the pronounced cases of water shortages near and in (peri-)urban areas, while also contributing to environmental protection.

2.3.2 Water quality of reclaimed water for irrigation

Health and environmental impact of irrigating with untreated or partially treated wastewater

Wastewater sources include municipal wastewater, which consists of water from households, industries, and storm water, Wastewater characteristics differ from community to community regarding (in)organic matter content, nutrients, salts, heavy metals, toxic chemicals, and pathogens (Capra and Scicolone, 2007; Hussain et al., 2002; Popa et al., 2012). Urban agriculture in developing countries is often practiced by a population living at a low socioeconomic level (Orsini et al., 2013). Frequently, these farmers cannot afford to have safe water sources other than untreated or partially treated wastewater (Qadir et al., 2010b), a practice that has detrimental impacts to soil, groundwater, crops and the health of farmers and consumers alike (Becerra-Castro et al., 2015; Christou et al., 2017).

Soils continuously irrigated with non-treated or partially treated wastewater display soil quality modifications as a result of both structure deterioration (e.g., salinization of clays) and mineral, organic, and bacteriological pollution (Bauder et al., 2007; Jaramillo and Restrepo, 2017; Klay et al., 2010). For example, a soil in the Zaouit Sousse perimeter in Tunisia was irrigated with treated wastewater for a period of four years and demonstrated that irrigation with wastewater with high salinity for long period affects its geochemical properties such as soil salinization and accumulation of heavy metals (Klay et al., 2010). However, the level of capacity deterioration of soils after receiving wastewater for a prolonged period of times varies depending on infiltration capacity, permeability, cation exchange capacities, phosphorus adsorption capacity, water holding capacity, and texture, structure, and type of clay mineral (Emongor and Ramolemana, 2004). In addition, long-term irrigation with untreated or partially treated wastewater led to the increase in sodium, chlorine, and nitrate concentrations in groundwater (Chen et al., 2013).

When wastewater is contaminated with heavy metals, the concentrations in plant tissue tend to increase in a process known as bioaccumulation (Li et al., 2016; Qadir et al., 2010b) and has been shown to lead to phytotoxicity (Bedbabis et al., 2010). Heavy metals uptake by plants can occur either via roots or foliar surfaces (Chauhan and Chauhan, 2014). Leafy vegetables, in particular, are prone to accumulate metals (Parvin et al., 2014). Zinc, cadmium, lead and copper are some of the common metals found in vegetables (Chaoua et al., 2018; Qadir et al., 2010b), and the metals uptake increases with time, depending on soil concentration (Shakir et al., 2016).

Consumers are the final link in the supply chain and might be severely affected by these unsafe practices. For instance, wastewater can be a vector to spread pathogens (Uyttendaele et al., 2015). In the United States, a *Salmonella* outbreak (2008) was caused by contaminated peppers. In Sweden, an *E. coli* outbreak (2013) was caused by contaminated lettuce. Both outbreaks were attributed to irrigation with untreated or partially treated wastewater (Uyttendaele et al., 2015). Using untreated or partially treated wastewater for irrigation is also often cited as a source of gastrointestinal and skin diseases (Naidoo and Olaniran, 2013). Furthermore, the concentration of chemicals in wastewater poses a serious threat to human health (Shakir et al., 2016). For instance, the effects of heavy metals on human health can be quite severe but vary per element. Cadmium and lead have carcinogenic effects to humans, copper and zinc, although essential elements, can be toxic in high concentrations, and a copper surplus can cause acute stomach and intestinal aches (Chaoua et al., 2018). In addition, considering the risk of post-harvest contamination, the control of the water quality is not enough to protect the consumers' safety since the produce might be contaminated due to handling management or unsafe washing practices at the market and household levels (Amoah et al., 2005).

To minimize the negative environmental and human health impacts, it is thus important to analyse the quality of the available wastewater and the necessary level of treatment to create adequate and location-specific regulatory frameworks so that the treated wastewater can be safely used for irrigation. Therefore, guidelines have been developed that define wastewater treatment levels, accurate effluent management practices, restricted agricultural practices related to crops choices, and safe irrigation and harvesting methods (Aiello et al., 2007).

Guidelines for irrigation with wastewater

There are several guidelines around the world to regulate water reclamation for agricultural use (Table 2.1). The most commonly used guidelines were developed by the US Environmental Protection Agency (USEPA) and the World Health Organization (WHO) with the exception of the American state of California, which developed its own guidelines. The USEPA developed guidelines in order to ensure safe use of reclaimed water in irrigated agriculture (Angelakis and Gikas, 2014; Lazarova, 2004; Lazarova and Bahri, 2004). The WHO initially developed its guidelines in 1989 with an updated version in 2006. The WHO guidelines have been widely adopted or used as reference by many countries such as in Latin America (Mateo-Sagasta et al., 2013) and Europe (Lazarova and Bahri, 2004). However, whereas some southern European countries have encouraged water reclamation through the creation of specific regulations (Angelakis and Durham, 2008), other countries such as Italy have established stricter regulations for water reclamation, essentially discouraging its practice (Angelakis and Gikas, 2014).

In the USEPA, WHO, and the California guidelines for the use of treated wastewater for restricted and unrestricted irrigation, various parameters are considered, particularly with respect to microbial parameters (Lazarova et al., 2001). Restricted irrigation includes the use of treated wastewater for the irrigation of industrial crops, animal fodder, trees, and crops that are not consumed raw, whereas unrestricted irrigation includes all crops. The mentioned guidelines (California Department of Public Health, 2014) focus on the presence of limited concentrations of specific components such as total coliforms for both restricted and unrestricted irrigation (Blumenthal et al., 2000; Lazarova and Bahri, 2004). Furthermore, both the USEPA and California guidelines include a disinfection step as a required condition for unrestricted use, which is not mentioned in the 2006 WHO guidelines. In fact, the USEPA and California guidelines only focus on the water quality parameters at the point of, i.e. the water quality at the supply point that it is available for crop irrigation. These guidelines do not take into consideration other aspects of the supply chain from production to consumer site, such as the type of irrigation system, crop management and handling, and domestic disinfection. It can be argued that the application of non-debatable restrictive quality parameters makes the USEPA guidelines stricter, requiring extensive treatment under all conditions. However, the newer WHO guidelines (2006) consider Disability Adjusted Life Years (DALYs) as a metric based on the regional conditions and supported by quantitative microbial risk assessment (QMRA) models (Lazarova and Bahri, 2004). The tolerable risk framed in terms of DALYs is an approach that represents a level of risks that can be approximated and measured based on the lost years due to premature death and/or disability caused by a disease (Busgang et al., 2018; Carr et al., 2004). This metric helps to quantify the population health burden of diseases and to prioritise and evaluate the impact of specific public health interventions (Gibney et al., 2013). Additionally, the 2006 WHO guidelines consider health based targets for the whole supply chain, from production to consumption of wastewater irrigated products, making adjustments relevant to local conditions (Drechsel et al., 2008). As such, the 2006 WHO guidelines better include the reality of a given country as its approach ensures the realistic measure of waterborne diseases on human life, while protecting human health and including a cost effective approach for the wastewater use chain (Blumenthal et al., 2000). Furthermore, various authors and contributors to the 2006 WHO guidelines argue that irrigation water does not have to necessarily meet the quality standards as defined in the guidelines in order to ensure human health protection (Carr et al., 2004; Ensink et al., 2007). The 2006 WHO guidelines include opportunities to use a multi-barrier approach, which might be much more cost-effective in ensuring environmental and human health. In such approach, critical components are addressed throughout the production and supply chain including, but not limited to, the quality of the water source (Huibers and van Lier, 2005). This alternative includes a combined approach for selecting wastewater treatment options followed by post-treatment health protection and control measures, which are comprised of pre-farm, on-farm and post-farm barriers such as, when possible, wastewater treatment to improve water quality parameters, crop restrictions, and post-harvest handling (Huibers and van Lier, 2005; Keraita et al., 2014; Scheierling et al., 2011). In effect, it is only in industrialised countries, where efficient collection and treatment of wastewater is available, that wastewater treatment alone guarantees risks reduction to the defined levels and therefore restrictive effluent guidelines are applied (Angelakis and Gikas, 2014). However, as previously stated, in developing countries, there is a general lack of wastewater collection and treatment (Miller-Robbie et al., 2017) and thus a need to use restrictive effluent guidelines where adequate wastewater treatment exists and a multiple barrier approach where non-treated or partially treated water is utilised (Amponsah et al., 2016; Keraita et al., 2010). Ideally, it can be argued that a combination of these two approaches should be considered. In addition, official water reclamation projects are site-specific and typically motivated by a lack of water to irrigate crops, supplying nutrients to the crops, and protecting the environment from uncontrolled discharges. Moreover, a variety of wastewater sources are being used to irrigate horticultural crops and pastures, with the implementation depending on the specific need in the region (Haering et al., 2009; Martijn, 2005). Finally, it can be concluded that at most locations where wastewater treatment is crucial in the reclamation step, there are efforts to meet the restrictive guidelines in order not to pose risks to the environment and humans. However, in developing countries, water reclamation is still unplanned and uncontrolled, which can often be related to the costs linked to wastewater treatment, lack of institutional frameworks, and the lack of available physical infrastructure.

Table 2.1: Wastewater guidelines for irrigation in agriculture and treatment options

Guidelines	Unrestricted irrigation		Restricted Irrigation		Reference(s)
	Water quality	**Treatment option**	**Water quality**	**Treatment option**	
USEPA (2004)	• pH = 6-9 • ≤ 10 mg/L BOD7 • ≤ 2 NTU* • No detectable fecal coliforms/100 mL • 1 mg/L Cl_2 residual (minimum)	Secondary treatment + Filtration + Disinfection	≤ 30 mg/l BOD**** ≤ 30 mg/l SS ≤200 fecal coliforms/100ml 1 mg/l Cl2 residual (min.)	Secondary treatment + Filtration	(Blumenthal et al., 2000)
WHO (1989)	Intestinal Nematodes <1 eggs/L Faecal coliforms <1000/100mL		Intestinal Nematodes <1 eggs/L N.A for faecal coliforms		(WHO, 1989)
WHO (2006)	$<10^{-6}$ DALY** (pathogen reduction 1-4 logs from 10^7-10^8 to 10^3-10^4 per 100 ml)	Secondary treatment, filtration, and disinfection	$<10^{-6}$DALY (pathogen reduction 3-4 logs from 10^7-10^8 to 10^3-10^4 per 100 ml)	Stabilization ponds for 8-10 days	(Lazarova and Bahri, 2004; WHO, 2006)
California (2014)	≤2.2/100 mL TC*** ≤23/100 mL in more than one sample in any 30 day period (maximum)	Secondary treatment + Coagulation + Filtration + Disinfection	≤23/100 mL TC ≤240/100 mL in more than one sample in any 30 day period	Secondary treatment + Coagulation	(California Department of Public Health, 2014; Lazarova and Bahri, 2004)

*NTU: Nephelometric Turbidity Unit

**DALY: Disability Adjusted Life Years corresponds to the sum of years of potential life lost due to premature mortality and the years of productive life lost due to disability

***TC: Total coliforms

****BOD: Biochemical oxygen demand

Wastewater treatment options

To date, many different wastewater treatment techniques have been developed, leading to incremental levels of treatment: primary, secondary, tertiary, and quaternary treatment.

Secondary or biological treatment can be implemented as a compact mechanised treatment system or as an engineered system in nature, making use of lagoons or wetlands (Kalbar et al., 2012). Examples of secondary treatment technologies are activated sludge, trickling filters, biotowers, upflow anaerobic sludge blanket (UASB) reactors, rotating biological contractors (RBC), sequential batch reactors, aerated lagoons, waste stabilization ponds, duckweed ponds, and constructed wetlands (CWs) amongst other treatment techniques (Kalbar et al., 2012).

Selecting the most appropriate wastewater treatment technology is a complex process and includes many technological and socio-economic parameters. As such, the decision making process can be regarded as contextual and situational (Kalbar et al., 2012; Muga and Mihelcic, 2008) and includes capital costs, operational and maintenance cost, land requirements, and sustainability issues (Kalbar et al., 2012). In industrialised countries, the most important selection criteria for wastewater treatment technologies are efficiency, reliability, sludge disposal, and land requirements (Sperling, 1996). In addition, Massoud et al. (2009) noted that the selection of the most appropriate wastewater treatment technology is based on criteria such as economic affordability, environmental sustainability, and social acceptability. In developing countries, the most critical parameters for the selection of a wastewater treatment technology are construction costs, and operational costs, sustainability, and simplicity (Sperling, 1996).

Current wastewater treatment facilities of major cities in industrialised countries are connected to centralized conveyance systems, which are commonly linked to high investment and operational costs that are prohibitive and not feasible for many developing countries (Zhang et al., 2014). In the latter countries, the number of wastewater treatment facilities are limited due to high costs and a lack of laws for environmental pollution and/or its enforcement (Kivaisi, 2001). Furthermore, existing treatment facilities often are poorly operated and maintained (Wang et al., 2014), which hampers adequate wastewater management and treatment in many developing countries.

Increasing wastewater treatment levels generally reduces environmental and human health risks but is correlated with an increase in treatment costs (VO et al., 2014). Particularly in developing countries, there is a significant need for cost-effective technologies to treat wastewater to a desirable level. In this context, the most common wastewater treatment technologies are stabilization ponds (Kivaisi, 2001), with up-flow anaerobic sludge blanket (UASB) reactors being common in South America and India (Chernicharo et al., 2015; Noyola et al., 2012; van Lier et al., 2010). Stabilization ponds are characterised by the lowest investment and operation costs, provided that the large required areas of land are cheap (WHO, 2001). However, in the vicinity of large cities, the latter is generally not the case. This means that large conveyance systems are required, leading to high investment costs (van Lier and Lettinga, 1999). Moreover, land-based systems are not easily adaptable to accommodate population growth, so treatment performance may deteriorate with time.

When the final use is for irrigation, the selection of wastewater treatment technologies for irrigation should be in accordance with agro-technological, sanitary, and environmental requirements that also include the protection of human health (Norton-Brandão et al., 2013). Different technologies for wastewater treatment can be applied when the effluent is used in a planned agricultural irrigation setting (Table 2.2). In most of these examples, the wastewater is treated before its application to crops. Various methods including (advanced) disinfection are implemented in industrialised countries such as Australia, Israel, and the US for unrestricted irrigation. However, some examples of wastewater treatment in developing countries include solely secondary treatment, with the effluent being used to irrigate crops in an unplanned agricultural irrigation scheme (Table 2.3). The obtained water quality does not always meet the restrictive regulatory standards.

Table 2.2 Worldwide examples on planned water reclamation for irrigation

Scope	Treatments	Crops irrigated	Sources
Municipal wastewater	Trickling filter plant, activated sludge plant, dissolved air flotation filtration, multi-media filtering and chlorination, Anaerobic pond, aerated pond, and network of reservoirs, Waste stabilization ponds, aerated pond, activated sludge or attached growth processes or a combination of both, Flocculation, dissolved air flotation, rapid sand filtration, granular activated carbon filtration, and chlorine disinfection	Horticultural crops, Pasture irrigation, cane farms, pasture, tea tree plantations, sporting fields, and a turf farm, unrestricted irrigation, Citrus, vegetables, bananas, grapes and certain stone fruits	(Ammary, 2007; Bixio et al., 2005; Boake, 2006; Elimelech, 2006; Friedler, 1999; Haruvy, 1997; Indian Institute of Technology (IIT), 2011; Institute for Sustainable Futures (ISF), 2013; Lahnsteiner and Lempert, 2007; Po et al., 2003; Radcliffe, 2010; Woltersdorf et al., 2016)
Domestic +Industrial wastewater	Grit removal, activated sludge process, aeration tanks comprised of an anoxic zone (denitrification) and aerobic zone, maturation ponds, Secondary treatment, aerobic-biological	Horticulture crops, Olive trees	(Bedbabis et al., 2010; Emongor and Ramolemana, 2004)
Domestic wastewater	Synthetic sponge, sedimentation baffled/graded settlement tank, filtration using gravel and sand roughing filtration, aeration and chlorination, Irrigate lawns, plants, shrubs and trees and lettuce	irrigating the food crops, Olive trees and vegetable crops	(Al-Hamaiedeh and Bino, 2010; Indian Institute of Technology (IIT), 2011)
Industrial and Municipal wastewater	Activated sludge	Fish life and farm irrigation	(Indian Institute of Technology (IIT), 2011)

Table 2.3: Worldwide examples of unplanned water reclamation for irrigation

Location	Drivers	Treatments	Scope	Crops irrigated	Findings	Source
Bolivia: Cochabamba	poverty and lack of planning and management capacity, uncontrolled use of wastewater	Diluted or partly treated, limited treatment, wastewater with high contamination of pathogens, heavy metals, and salts	Municipal and industrial sewage wastewater	Fodder crops, including fodder maize and alfalfa, and vegetables for farmers' own consumption	Farmers not confronted with specific health problems related to the use of polluted water, contradicting reports from local health workers.	(Huibers et al., 2004)
Burkina Faso		On-farm technologies	Municipal	Eggplant, tomatoes		(Akponikpè et al., 2011; Keraita et al., 2014)
Cameroon: Nomayos-Yaonde city	Unplanned discharge of sludge	Comprises individual wastewater systems (septic tanks and latrines) and collective wastewater (sewer and treatment plants	Urban sludge	Lettuce	Existing wastewater treatment facilities are not adequately structured and will require further planning	(Mafuta et al., 2011; Tsama et al., 2015)
Eritrea		Untreated		Lettuce cabbage, tomato, carrots		(Srikanth and Naik, 2004)
Etiopia : Kality and Kotebe	Polluted water, economic drivers	Untreated	Municipal	lettuce, Swiss chard, cabbage, carrot, beet root and potatoes	perceived illness prevalence is significantly higher for household members working on wastewater irrigation farms than for those working with freshwater.	(Teklu, 2007; Weldesilassie et al., 2011)

Ghana: Kumasi	Freshwater pollution and Water scarcity in dry season, the need to cultivate vegetable all year round wherever irrigation water is available	Septic tanks, biological treatments	Informal irrigation with Untreated or partially treated domestic/ municipal wastewater	cereals as maize in the rainy seasons and vegetables in the dry seasons.	Sanitation infrastructure in Ghana has been outpaced by population increases, making the management of urban wastewater ineffective	(Agodzo et al., 2003; Buechler et al., 2006; Keraita and Drechsel, 2004; Sato et al., 2013)
India: Ahmedabad , New Delhi, Hyderabad , Kanpur and Kolkata	Population growth and food security	Partial treatment	Municipal wastewater	Horticultural crops, cereals, Paddies, flowers	Wastewater management and treatment cannot be planned in isolation	(Amerasinghe et al., 2013)
India: Vadodara, Gujarat	Lack of freshwater sources	Little treatment; None of the three sewage treatment plant is fully functional	Municipal sewage	Vegetables, fruits, cereals, flowers and fodder	Uncertainty associated with water use for marginalised farmers would be overcome with a planned .	(Bhamoriya, 2004)
Kenya: Nairobi		Untreated or partially treated, stabilization ponds or system comprises of discrete units of barrels that allows for filtration, flocculation, sedimentation and disinfection.	Municipal Wastewater	mixed vegetable farming	Heavy metals were recorded mostly in the stem and leaves farming and non-farming households are predisposed to infection from these contaminants,	(Hide et al., 2001; Karanja et al., 2010; Kariuki et al., 2011; Mafuta et al., 2011)
Mexico : Tula Valley in The	Lack of water	Activated sludge systems/Stabilization ponds	Municipal	alfalfa and maize (60%), but oats, barley, wheat, beans and some	Wastewater must be treated and managed wisely	(Jiménez, 2008)

Mezquital Valley				vegetables (chilli, Italian squash and tomatoes)		
Nepal : Kathmandu Valley (Kirtipur and Bhaktapur)	Water scarcity	Lagoon system	Bhaktapur: direct utilization of wastewater Kirtipur: indirectly by gravity flow from polluted rivers	Rice, wheat and vegetables	Quality of wastewater used varies from diluted wastewater to raw sewage. Wastewater use in agriculture is not regulated	(Rutkowski et al., 2007)
Pakistan : Haroonabad and Faisalabad-	Absence of a suitable alternative water source, high nutrient value obtained from wastewater, reliability proximity to urban markets	Untreated wastewater (80% of wastewater irrigated schemes)	Municipal Wastewater in two cases (Haroonabad: small town without major industry) and (Faisalabad: large and industrialised city)	Haroonabad: Vegetables (cauliflower), cotton and fodder Faisalabad: fodder, wheat, cotton and vegetables (cauliflower, spinach, and aubergine).	Untreated wastewater irrigation poses serious health risks. For the case of Pakistan, there are some benefits. It is unlikely that Pakistan will be able to treat all wastewater currently used by farmers up to WHO guidelines standards	(Ensink et al., 2004)
Vietnam	Unplanned discharge of wastewater into natural water courses, drainage canals or irrigation canals	Stabilization ponds	Municipal wastewaters	Paddy rice	Wastewater agriculture provides a primary or secondary source of income to 1% of the urban population although there is need for a typology to effectively capture characteristics	(Raschid-Sally et al., 2004)

Harare-Zimbabwe	Secondary - trickling filter and modified activated sludge	Greywater	Vegetable and pasture irrigation	Regulations for use of wastewater exists, but proper enforcement is lacking and there is need for comprehensive guidelines specifically addressing the safe use of wastewater in agriculture	(Jiménez and Asano, 2008b; Muchuweti et al., 2006; Nansubuga et al., 2016; Thebe and Magore, 2015)

Irrigation and post-harvesting practices

Irrigation methods and post-harvesting practices are crucial for the reduction of contamination risks associated with the consumption of wastewater irrigated produce (Keraita et al., 2007a, 2007b). Contamination can occur at several levels in the supply chain such as at the production site, transportation, crop handling, and market display (Faour-Klingbeil et al., 2016; Gil et al., 2015). Contamination at the production site can originate from the farm leading up to the harvest when unsafe water sources are used for irrigation, manure is handled inappropriately, and sanitation practices are unsuitable at farm level (Faour-Klingbeil et al., 2016; Gil et al., 2015). During transportation, contamination may occur when a proper cooling system is not available along the supply chain, or when the containers are not or improperly sanitized that are either used to transport the products, or to pile the produce at the market entrance after distribution (Faour-Klingbeil et al., 2016; Gil et al., 2015). Contamination during crop handling at the market occurs due to inadequate market structural facilities or during the washing process, when there is an inability to maintain a clean water supply, while washing large volumes of fresh produces (Faour-Klingbeil et al., 2016; Gil et al., 2015). At the consumer level, contamination occurs when consumers fail to wash the produce before eating (Gil et al., 2015).

In a situation where conventional wastewater treatment is not available, irrigation and post-harvesting practices should be considered as complementary and are of practical importance in the context of developing countries to reduce the risk of contamination (Amoah et al., 2007; Drechsel et al., 2008; Keraita et al., 2007a). Irrigation methods can have an impact on the reduction of produce contamination and can be used to control the level of contamination by wastewater (Choi et al., 2004). Three irrigation categories can be grouped as i) flood and furrow, where water is applied at the soil surface ii) spray and sprinkler, where water is applied on top of the crop and iii) localized, which refers to drip and trickle irrigation in which water is directly applied to the crop in a localized manner (Keraita et al., 2007a; WHO, 2006b). The irrigation method and nature of the crop to be grown (e.g., to be eaten raw or cooked) can be changed according to the prevailing water quality in order to reduce the risk of contamination (Drechsel et al., 2008; Gil et al., 2015). This means that for crops to be eaten raw, an irrigation method that makes a direct contact with the produce (e.g., spray irrigation in the case of leafy vegetables to be eaten raw) should be avoided (Gil et al., 2015). Furrow and spray irrigation generally leads to 1 log reduction in microbial contamination, whereas a 2-4 log reduction can be expected with localized irrigation, leading to lower risks for the farmers and minimal contamination transfer to the crop surface (Keraita et al., 2008). The lower contamination risk is due to the fact that irrigation water is applied to the root zone of the crop, resulting in minimal direct contact between wastewater and crops (Drechsel et al., 2008; Keraita et al., 2007a). However, localized irrigation methods can be considered an advanced technology that is too expensive for most farmers in developing countries and are characterized by high maintenance cost due to clogging problems (Carr et al., 2011; Martijn, 2005). Sprinklers have medium to high cost, and the water use efficiency is medium (Qadir et al., 2010b). Furrow irrigation is commonly used in peri-urban and rural agriculture, and watering cans are widely used for urban wastewater irrigation, especially in sub-Saharan Africa (Martijn, 2005). Few studies are available regarding the effects of using watering cans in wastewater irrigation, which is a common practice in developing countries (Martijn, 2005). However, Keraita et al., (2007a) showed that using watering cans in wastewater irrigation can reduce contamination by thermotolerant coliforms (bacteria group) up to 2.5 log units.

Post-harvesting practices such as washing and handling before consumption can also influence the final concentrations of contaminants (Qadir et al., 2010a). Simple washing leads to a 1 log reduction, with 2 log reduction is achieved with the use of domestic disinfection solutions, such as using a weak disinfectant dissolved in washing water (Keraita et al., 2008). Finally, cooking leads to a 6-7 log reduction (Keraita et al., 2008). Therefore, considering the potential log reduction in pathogenic organisms, the appropriate irrigation methods, post-harvesting practices, and crop selection should be considered as an alternative for, or a complement to, wastewater treatment for the case of developing countries.

2.3.3 Water reclamation for irrigation in sub-Saharan Africa (SSA)

Potentials and constraints of water reclamation for irrigation in sub-Saharan Africa

Wide-scale proper implementation of water reclamation for agricultural irrigation in SSA will positively address various aspects of the sustainable development goals as outlined by the United Nations (UN, 2015). The main advantages are: 1) wastewater is a secure available water source promoting food production in the (peri-)urban areas; 2) water reclamation promotes better sanitation, protecting human and environmental health; (3) water reclamation improves the famers' quality of life and livelihood. In the below paragraph, these advantages are further discussed in the SSA context.

1) *Increased water availability*. Decreasing freshwater availability with increasing water demand makes wastewater a reliably available alternative water source for irrigation in most of (peri-)urban areas of sub-Saharan Africa (Adewumi et al., 2010; WorldBank, 2013). Examples of wastewater being used untreated or partially treated for irrigation are available in Ghana, Kenya and Mozambique, simply because this water is available in (peri-)urban areas (Alade, 2019; Hide et al., 2001; Karanja et al., 2010). The rapid population increase in SSA cities at a rate of 3,5 % per annum, will lead to 1,26 billion people living in African cities in 2050 (Bougnom et al., 2019; Werner et al., 2019). This will increase the need for water reclamation in the SSA urban regions, particularly for (peri-)urban agricultural uses (Qadir et al., 2020). Other studies researched the potentials for water reclamation in non-agricultural applications, such as landscaping and industrial uses in some areas of Western Cape, in South Africa (Adewumi et al., 2010).

2) *Improved sanitation and health*. The design of water reclamation schemes concomitantly offers opportunities to improve sanitation in African cities, thus protecting human and environmental health. In sub-Saharan Africa, wastewater is limitedly collected and typically disposed into the environment without treatment (Nansubuga et al., 2016). In most cases, the implementation of infrastructure for proper wastewater collection and further management is constrained by limited financial resources in a large number of African countries (Jiménez and

Asano, 2008b). Therefore, most of the population on the continent rely on on-site sanitation, typically latrines (Nansubuga et al., 2016), with local discharge of the produced wastewater to the environment. The huge difference between actual water supply and wastewater collection also limits the available information regarding the quantity of wastewater produced, collected, treated, and reclaimed (Sato et al., 2013).

3) *Improved livelihood*. Application of proper water reclamation schemes will improve the living conditions of local farmers in peri-urban settings. At present, in most SSA countries, (diluted) urban wastewater is commonly used for irrigation without any treatment, creating great risks for microbial contamination and the exposure to other types of contaminants (Dickin et al., 2016). This current practice can have deleterious impacts to the public health, groundwater quality, soil and waterways. Therefore, reclaiming wastewater in a safe manner will improve the working and living conditions for farmers. Moreover, it will contribute to safety in wastewater handling and will improve the quality of the produce. In addition, it has social benefits as it generates employment for most of the (peri-)urban farmers (De Bon et al., 2010).

The major challenge for implementation of regulated water reclamation schemes in SSA region is costs. Capital exploitation costs are derived from the installation of conveyance and sewerage systems, siphons and pumping stations, and wastewater treatment facilities, whereas operational exploitation costs comprise costs for personnel, energy, chemicals and repair (Kihila, 2015, 2014; Kivaisi, 2001). The application of conventional centralized wastewater treatments schemes comes with exorbitant costs associated with the construction, operation and maintenance for both the transportation and treatment of wastewater (Amoah et al., 2018; Qadir et al., 2020). Those schemes are difficult to maintain in many of the less prosperous countries (Akhtar et al., 2018). In fact, the lack of financial and technical facilities undermines the ability of the countries to even supply water that can be reclaimed (Ashraf et al., 2017; Massoud et al., 2009; Wilderer et al., 2000). The poor management of wastewater treatment facilities and insufficient funds that are allocated to these facilities, result in many of them failing (Edokpayi et al., 2015). Furthermore, in many sub-Saharan African countries, there is a lack of regulatory measures to promote water reclamation, coupled to environmental and public health protection. The most striking negatives impacts of non-controlled use of wastewater are deterioration of soil, health hazards, deterioration of groundwater quality and other aspects (Ashraf et al., 2017). As a result of lacking infrastructure for wastewater management, SSA cities produce the lowest amount of wastewater per capita, which is around 46 m^3 and is half of the global average of 95 m^3 (Qadir et al., 2020). This situation limits the capacity for water reclamation for agricultural reuse in SSA (peri-) urban agriculture. Therefore, reclaiming water will contribute to revenue generation covering its costs and sustaining wastewater treatment.

Water reclamation for agricultural irrigation in sub-Saharan Africa: current status and way forward

Typically, wastewater treatment in sub-Saharan Africa consists of pond systems (Kivaisi, 2001) with some examples of activated sludge processes in countries such as Botswana, Ghana, Namibia and South Africa (Adonadaga, 2014; Emongor and Ramolemana, 2004; Lahnsteiner and Lempert, 2007; Nikiema et al., 2013; Salaudeen et al., 2018).

There are only a few available examples of controlled wastewater treatment for irrigated agriculture (Table 2 and Table 3) located in Namibia, Mauritius and South Africa. In Namibia, treated wastewater is used for potable water preparation and irrigation (Lahnsteiner and Lempert, 2007; Woltersdorf et al., 2016). In Mauritius, treated wastewater is used to irrigate sugar cane plantations (Joysury et al., 2012). Some of the many non-regulated examples using uncontrolled untreated, blended, or partially treated wastewater are documented in the literature and can be found in Cameroon, Kenya, Ghana and Mozambique (see below). In the city of Yaoundé (Cameroon), partially treated wastewater is used for irrigation of lettuce (Tsama et al., 2015), whereas in Nairobi (Kenya), lettuce is irrigated with untreated wastewater (Githuku, 2009). Some studies addressed in-situ treatment options in Burkina Faso, Togo and Ghana (Keraita et al., 2014). Water reclamation for irrigation in Maputo is performed unplanned in peri-urban areas. This practice is driven by water scarcity (Rietveld et al., 2016) and, likely, the availability of nutritional water (Agodzo et al., 2003; Huibers and van Lier, 2005), using the partially treated water from the nearby wastewater treatment plant in Maputo (Arsénio et al., 2018; Tauzene et al., 2017). In addition, some examples of on-farm/on-site treatment can be found in Ghana and South Africa. In Ghana, on-farm wastewater treatment options are used for irrigation to produce vegetables (Agodzo et al., 2003; Antwi-agyei, 2015; Keraita et al., 2014). Another example is in South Africa, where the Lynedoch Eco Village uses extensive on-site water reclamation for irrigation (Adewumi et al., 2010).

The many non-controlled uses of blended, non-treated, and partially-treated wastewater in sub-Saharan Africa reveal that there is a significant need for infrastructure that is appropriate for the local conditions. Experiences from Zimbabwe, where centralised treatment systems were implemented, show that adopted wastewater technologies were too sophisticated such that the country could not continue utilising them (Nhapi and Gijzen, 2004). Authors conclude that in such cases, natural treatment methods, such as pond systems, are preferred since they are cheaper and easier to maintain and operate (Nhapi and Gijzen, 2004). However, it is important to note that natural treatment systems have surface-based dimensions and can thus only be implemented where land is available and affordable, requiring large conveyance pipes to outside the urbanised areas.

Considering the points above, it can be concluded that in Sub-Saharan Africa, there is a very large potential for water reclamation, particularly for agricultural purposes. Wastewater is an alternative water supply resource that is reliably available and coupled with several benefits (e.g. presence of nutrients). However, a more proper balance between required water quality and level of required technology for wastewater treatment should be searched for, to cost-effectively reduce current risks using a multiple barrier approach (Amponsah et al., 2016; Keraita et al., 2010). According to Norton-Brandão et al. (2013), a proper reclamation technology for improving the water quality addresses the removal of pathogenic organisms as well as heavy metals, whereas salinity levels are taken into account when adopting technologies for irrigated agriculture. Restricted crops irrigation would be unrealistic under the prevailing societal conditions, but barriers should be placed in critical points throughout the supply chain, combining barriers to reduce the risk in total terms (Keraita et al., 2010). The multiple barrier approach would combine the required water quality for irrigation, use of affordable treatment technologies, and adequate post-harvest approaches and management throughout the supply chain to reduce current health risks to acceptable levels. In addition, guidelines that only take into consideration the water quality at the point of use are unrealistic for the current situation of many African cities and countries. On the long term, there is a need to balance the treatment level with the required water quality level (van Lier and Huibers, 2010). Within this approach, the required quality at the farmer's level would set the boundary conditions for the treatment system, while combining the use of treated wastewater with other protective measures and master planning. The protective measures would consider the irrigation and post-harvest practices to help pathogen reduction. Master planning may require a division of wastewater irrigated areas according to water quality requirements and respective crops to be produced. Such division is in place in several South-Mediterranean countries such as Jordan and Tunisia (Boom et al., 2008; Chenini et al., 2003). The feasibility of this approach will depend on the actual conditions of the country where the protective measures can be applied. Following this approach will likely contribute to sustaining the livelihood of farmers, while improving health conditions for farmers, handlers, consumers, and the environment.

2.4. Conclusions

Urban agriculture is a very relevant activity in many developing countries because it serves as a means for cost-effective food provision to local people in addition to nutrition improvement, economic development, job creation, and food security. In urban areas, water is scarce and expensive, but water reclamation for agricultural use has several benefits that range from alleviation of pressure on freshwater resources, to nutrient recovery and environmental protection benefits. Examples of water reclamation are widespread in the world, and the literature reveals that there is a great opportunity for sub-Saharan Africa to implement water reclamation in a planned manner. In addition, it also serves as an opportunity for developing countries to offer better sanitation services through revenue generation. However, there are also risks associated to water reclamation for agricultural use, such as soil degradation and seepage infiltration, leading to microbial and heavy metal contamination to water, soil and crops, impacting human and environmental health. Therefore, the water quality at the point of use must be considered an important issue.

Informally, water reclamation is widely practiced in many sub-Saharan Africa countries. Some planned and formal examples are available, but mostly untreated reclaimed wastewater is used for agricultural purposes. Thus far, there are no country-specific guidelines to control the quality of wastewater to be used, so the WHO guidelines are generally used. Since the 2006 WHO guidelines are more difficult to implement, most countries still use the 1989 WHO guidelines, which are based on restrictive effluent criteria. However, restrictive guidelines are unrealistic given current farmer practices. Most guidelines consider the water quality at the point of use, which is a limitation because developing countries have inefficient or inexistent wastewater treatment facilities and institutional capacity and contamination is prone to occur throughout the supply chain. In order to achieve the quality requirements for safe water reclamation, the current paradigm for development has to change. Although there is potential for water reclamation in African countries, exploiting these potentials requires leap-frogging developments by planning the future water and sanitation infrastructure to provide support for the proposed approaches. The here proposed multiple barrier approach in combination with master planning is recommended, which combines wastewater treatment and critical point barriers in order to reduce health risks, throughout the supply chain. In addition, for the long term, an approach needs to be developed that considers the required water quality at the point of use to design affordable wastewater treatment systems and reduce risks.

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Chapter 3: Faecal contamination on lettuce irrigated with different water sources in Maputo, Mozambique

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Faecal contamination on lettuce irrigated with different water sources in Maputo, Mozambique

Abstract

Faecal contamination across the lettuce value chain was assessed in Maputo, Mozambique. E. coli was used as an indicator of faecal contamination, with concentrations ranging from 3.4 to 5.7 log units/100mL in groundwater, river water and partially treated wastewater. Municipal tap water used to wash lettuce heads in the markets had lower than 1 log unit/100mL. Irrespective of the source of irrigation water, the lettuce heads were contaminated throughout the value chain, with concentrations ranging between 6.5 and 7.8 log units/100g. Interventions and awareness-raising should be applied at every stage of the value chain.

3.1. Introduction

Urban and peri-urban agriculture has been increasingly practised in many countries due to its contribution to economic development, job creation, and food security (Orsini et al., 2013; Whittinghill & Rowe, 2012). These farming activities take place on small plots within or around urban areas (Orsini et al., 2013; Whittinghill & Rowe, 2012). The high cost of freshwater sources and the availability of municipal wastewater (Niquice Janeiro et al., 2020) are driving forces for the use of wastewater as a source for irrigation in (peri-)urban agriculture (Drechsel et al., 2008; Keraita et al., 2008; Scheierling et al., 2011).

If a wastewater treatment plant (WWTP) exists, there is often a lack of capacity to properly treat the conveyed wastewater (Nansubuga et al., 2016; Niquice Janeiro et al., 2020; Thebo et al., 2017). In Maputo, the capital of Mozambique, peri-urban agriculture is practised in the Infulene Valley, producing mainly horticultural crops such as lettuce and cabbage to supply the local informal markets of Greater Maputo (Halder et al., 2018; Salamandane et al., 2020; Salvador et al., 2016). The sources of irrigation water (each with different quality) are groundwater (GW), river water (RW), and partially treated wastewater (WW) from the Infulene WWTP. Using a specific water source for irrigation in Infulene Valley depends on the location and accessibility of the water source from the farm. Some crops produced in the Infulene area are irrigated with untreated or partially treated wastewater and are consumed raw, which can cause a severe health risk for consumers and farmers (Hamilton et al., 2006; Matangue et al., 2018; Urbano et al., 2017; Woldetsadik et al., 2017).

The WHO guidelines, developed in 1989, are extensively used in many developing countries, including Mozambique, to improve and regulate the use of wastewater in agriculture. Nevertheless, the WHO 1989 guidelines only assess the water quality at the point of use and thus overlook the risk of contamination across the value chain, encompassing agricultural practices, handling, market practices, and consumer practices. Therefore, the WHO updated its guidelines in 2006 to incorporate Disability Adjusted Life Years (DALYs), a metric based on specific regional conditions and supported by quantitative microbial risk assessment (QMRA) models. The 2006 WHO guidelines propose a combination of measures to reduce crop pathogen levels different stages of production, i.e., pre-farm, farm-based and post-harvest (WHO, 2006). The combination of measures depends on the context and needs to be worked out by looking at the hazard analysis and critical control points (HACCPs).

This work follows up on a previous study investigating sewage-contaminated irrigation water for lettuce production in the Infulene Valley (Matangue et al., 2018). Also, a desktop review showed that contamination could occur across the production value chain (Niquice Janeiro et al., 2020). We hypothesized that health risks are not limited to unsafe farm-level irrigation practices but can also arise elsewhere in the value chain, including handling, transportation, and selling practices. This hypothesis is linked to the findings of Sousa et al. (2021), who investigated vegetable contamination within the Maputo markets and recommended an assessment of vegetable contamination throughout the value chain. Our study serves as a fundamental step in shaping the pathways for intervention in collaboration with stakeholders in the lettuce production value chain. This work provides the possibility of understanding the contextual urban irrigation and cultivation (Veldwisch et al.2024) and discusses the potential for hazard analysis, identifying points for health risk reduction.

3.2. Materials & Methods

The study sites in the Infulene Valley (Figure 3.1) were selected based on their differences in irrigation water sources. Four farm sites were selected: two farms located at opposite points across the river irrigating with groundwater (GW), i.e., GW1 and GW2, a farm irrigating with river water (RW3) and a farm irrigating with partially treated wastewater (WW4). The distances between the sites varied between 200 to 700 meters and the sampling plot sizes were 4 to 6 m^2.

3.2.1. Study area description

Infulene Valley, also known as Maputo's green belt for crop production, is a natural depression in the flat land area west of the capital city Maputo, located in the southern part of Mozambique. The Infulene Valley has an extent of 20 x 0.5 km and covers some of the peri-urban areas of Maputo and Matola cities, the two most populated cities in the country (Sitoe & Mina Pinto, 2019). Small-scale agriculture in this area mainly produces horticultural crops such as lettuce, kale, and cabbage. Farmers use manual irrigation, i.e., watering cans to irrigate the crops. The crops are mainly produced for commercial purposes. Lettuce is the most common crop in the area, comprising 64% of all crops grown in Maputo (Smart et al., 2015). The cultivated crops are sold in local markets across the Greater Maputo area, which includes the area of Maputo, Matola and Boane cities, and Marracuene districts (Batran et al., 2018; Salvador et al., 2016; Sitoe & Mina Pinto, 2019). Around 86% of the producers sell lettuce during the wet season (September to March), and nearly half of the producers sell during the dry season (April to August) (Smart et al., 2016).

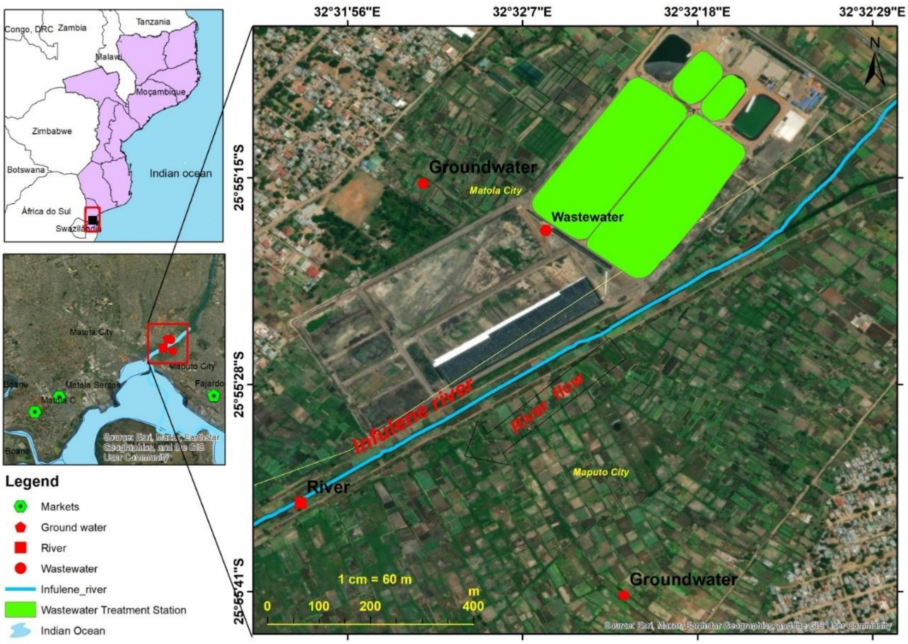

Figure 3.1. Farm sampling sites from irrigating sources (groundwater (GW), i.e., GW1 and GW2, river water (RW3) and partially treated wastewater (WW4)) at the Infulene Valley in Maputo, Mozambique, and markets where the crops were sold in nearby Maputo and Matola.

3.2.2. Type of water sources

This study assesses the quality of water used for irrigation and washing of lettuce (*Lactuca sativa*) heads sold in the markets of Maputo City. Different water sources are used for irrigation in Infulene Valley, classified as groundwater (GW), river water (RW), and partially treated wastewater (WW). GW for irrigation is collected from farmers' artisanal wells and drainage ditches (Salamandane et al., 2020). The Infulene river flows through the valley, which also serves as an irrigation source despite being polluted by the discharges from on-site sanitation systems of houses on the river's banks. The river also receives effluent discharges from factories upstream, for instance, a beverage industry and a pulp and paper industry (Scarlet & Bandeira, 2014). Furthermore, the effluent of the WWTP also discharges into the Infulene river (Salamandane et al., 2020; Taviani et al., 2008). The WWTP, consisting of a pond system, treats 5-10% of the sewage generated in the city of Maputo (Arsénio et al., 2018; Rietveld et al., 2016) but is not well maintained (Rietveld et al., 2016) and lacks quality monitoring. Moreover, sludge removal has never taken place since its construction, and the tanker trucks discharge septic content directly into the anaerobic ponds (Arsenio et al., 2018). As a result, the volume of sediments and the growth of algae and macrophytes in the ponds reduce the treatment capacity and efficiency (Figure 3.1)[1]. Nevertheless, the WWTP effluent is used for small-scale irrigation in the downstream peri-urban areas.

3.2.3. Sampling

This study was conducted in Infulene Valley from February to July 2019 (6 months), which corresponds to the transition period from rainy to dry season. Lettuce handling practices were observed across the entire value chain, and sampling was done accordingly. Farmers were observed for two hours during their farming activities (from 6:30 am to 8:30 am) to understand their irrigation procedures, manure application, and harvesting methods. Further, vendors were observed for 3 hours in the selected markets (from 9:00 am to 12:00 pm) to assess (1) whether they washed the crops to remove farm

[1] It should be mentioned that since the second half of 2023, WWTP maintenance has improved substantially with cleaning and overhauling the pond area

residuals upon arrival at the market and (2) how the crops were displayed and stored. The sampling timing and the sequence were set based on the observed practices.

The duration of sampling was three days per sampling week, and each sampling day was followed by laboratory analysis. Samples were collected for six weeks under normal farming conditions, and the harvested lettuce was followed to the market sites where they were sold. The lettuce samples collected at the market corresponded to those originating from the sites selected for this study. Samples were collected from two markets (one in Maputo city, the other in Matola) and one street vendor in Matola. Lettuce from the GW2 and WW4 sites was sold in one market. At the other market, the lettuce was exclusively from RW3, while the street vendor obtained lettuce from the GW1 site. The weekly sampling routine is described below:

- On the first sampling day, the irrigation water from the sources at the farm was sampled (Figure 3.1).
- On the second day, the lettuce was collected at the farm and market. At the farm sites, the lettuce samples were collected 24 hours after the last irrigation. At the market sites, lettuce samples were taken before and after washing with municipal water. In addition, the fresh municipal water and the water after being used for washing the lettuce heads were collected and further analysed.
- On the third day, lettuce samples were collected only when the impact of delayed harvest was researched. Lettuce samples were then collected 48 hours after the last irrigation at the farm (Table 3.1).

The water and lettuce samples were analysed for the presence and concentration of the indicator organism *Escherichia coli* (*E. coli*). *E. coli* is the commonly used indicator for a public health assessment (Edberg et al., 2000). We only measured the indicator pathogen *E. coli* in this research. Other pathogenic organisms, such as different bacterial indicators, as well as protozoa, viruses, and worms, should be included for a complete understanding of pathogen contamination. Furthermore, it will be essential to conduct research on non-organic contamination, particularly focusing on the presence of heavy metals.

Table 3.1: Overview of microbial monitoring of irrigation water and lettuce heads in Infulene Valley, Maputo, from February to July 2019.

Purpose	Points of sample collection*	Description of samples and sampling regimen	Number of samples
Study the concentrations of *E. coli* in water and on lettuce	Farm: Sampling of water and lettuce at Infulene Valley	Irrigation water from the farm (WF) (n=4) irrigated with groundwater (GW1), groundwater (GW2), river water (RW3) and wastewater (WW4) during six weeks of sampling	24
		Lettuce from the farms (LF) (n=4) irrigated with groundwater (GW1), groundwater (GW2), river water (RW3) and wastewater (WW4) during six weeks of sampling	24
Assess the influence of delayed harvest on the concentration of pathogen		Lettuce from the farms- delayed harvest (n=4) in four farms (LH) irrigated with groundwater (GW1), groundwater (GW2), river water (RW3) and wastewater (WW4) during six weeks of sampling	24
Study the survival or recontamination of lettuce after harvest	Market: Sampling of water and lettuce	Lettuce collected upon arrival at the market (LM_B) (n=4) from known farms irrigated with groundwater (GW1), groundwater (GW2), river water (RW3) and wastewater (WW4) during six weeks sampling	24
		Lettuce displayed after washing (LM_A) (n=4) from known farms irrigated with groundwater (GW1), groundwater (GW2), river water (RW3) and wastewater (WW4) during five weeks sampling	20
		Municipal water at the markets (MWM), (n=3)# where the lettuce from the farms were sold during six weeks of sampling	18
		Municipal water from a bucket used for washing10 lettuce heads (MW_10) (n=4) samples at the market from known farms irrigated with groundwater (GW1), groundwater (GW2), river water (RW3) and wastewater (WW4) four weeks of sampling	16
		Municipal water after washing 120 to 150 lettuce heads (MW_T) (n=4) at the market from known farms irrigated with groundwater (GW1), Groundwater (GW2), river water (RW3) and wastewater (WW4) during five weeks of sampling	20

* Sampling during three consecutive days after cessation of irrigation; # One of the markets received lettuce from two farms; therefore, the same source for washing water.

A total of 78 water samples (Table 3.1) were collected as grab samples at the farm and markets from 07:00 am to 09:00 am. After collection, water samples were placed in 250 mL glass sterile bottles and stored in a cool box with ice packs for transportation. They were kept in the cool box until processing within 2-8 hours after collection. A total of 96 lettuce samples (Table 3.1) were randomly collected early in the morning (7:00-9:00 am). Each sample consisted of two lettuce heads, obtained from the state they were available for consumer purchase. The samples were placed in sterile bags, then stored in coolers with ice packs and transported to the laboratory for analyses.

At the farm, samples were collected at normal harvest and delayed harvest at each site (GW1, GW2, RW3, WW4). In Table 3.1, LF refers to lettuce samples at the farm after normal harvest. The normal harvest corresponds to lettuce samples collected from the farm locations 24 hours after ceasing irrigation. The delayed harvest (LH) corresponds to lettuce samples collected from the farm locations 48 hours after ceasing irrigation. At the market, samples were collected before and after washing. LM_B refers to lettuce heads before being washed and before being displayed at the vendor table. LM_A refers to washed lettuce heads being displayed at the vendor's table. Following this sampling procedure, the contamination in the value chain was studied because the lettuce samples collected at the market were from the selected farm locations.

Following the above-described sampling procedure, each site (GW1, GW2, RW3 and WW4) had corresponding water and lettuce samples WF, LF, LH, LMA, LMB, MWM, MW_10 and MW_T, which were collected along the chain from farm to market. The samples from the different sites were compared after analysis.

Laboratory analysis

The collected lettuce samples were prepared for analysis by removing the outer leaves and core of the lettuce and washing them in distilled water (Bencardino et al., 2018). Approximately 20 g of lettuce were weighed and then washed in 500 mL of distilled water (Bencardino et al., 2018), which involved placing each lettuce leaf in a beaker cup with distilled water, which was then agitated at least ten times. The agitation facilitates the transference of *E. coli* present on the surface of the leaves to the water solution.

The United States Environmental Protection Agency (USEPA) guidelines were followed for all laboratory studies (USEPA, 2010). The following sample volumes were obtained: 0.001, 0.01, 0.1, 1, and 10 mL, and subsequently tested for *E. coli* concentration; sample size depended on the bacterial concentration. If the sample volume was less than 10 mL, 50 mL of sterile buffered dilution water was added to the filter funnel before applying the vacuum. Filter sterility was checked by placing one membrane filter per group of filters on a chromocult plate, after which it was incubated for 24 ± 2 hours at 35°C ± 0.5°C. The absence of growth indicated the sterility of the filter. The samples were filtered using 0.45 μm membrane filters, which were subsequently placed onto chromocult coliform agar plates (media from Merck, Darmstadt, Germany) and incubated for 24 hours at 35-37°C. Plates were checked for growth, and presumptive *E. coli* (blue) colonies were considered positives for *E. coli;* approximately 20 to 200 colonies were counted for each filter. Any counting outside this range was ignored in the calculations (Jensen et al., 2013).

3.2.4. Analytical procedures

The number of *E. coli* colonies was determined according to Equations 3.1 and 3.2 in water and lettuce samples, respectively. EC is the concentration of *E. coli* (CFU/100 mL) in water, V is the volume of water used to wash the lettuce (mL), and Wg is the weight of lettuce samples washed in distilled water (g). A factor of 100 was used to convert *E. coli* counts to CFU/100 mL and CFU/100g for water and lettuce samples, respectively.

$$E.coli\ count\ in\ water = \frac{Number\ of\ E.coli\ colonies}{Volume\ of\ sample} \times 100 \qquad (3.1)$$

$$E.coli\ count\ in\ lettuce = \frac{EC \times V}{W_g} \times 100 \qquad (3.2)$$

3.2.5.Data analysis

The data for *E. coli* concentration in water and lettuce has been analysed using the Statistical Package for the Social Sciences (SPSS) by one-way analysis of variance (ANOVA). The *E. coli* concentrations in this experiment were normalized by log10 transformations and then used ANOVA for multiple mean comparisons when significant differences in group were found, Post Hoc evaluation by Tukey Honestly Significant Differences (HSD) test was employed.

3.3. Results

3.3.1. Lettuce production and market handling

In Infulene Valley, farmers follow specific practices for irrigation, manure application, harvesting, transportation, and market handling. The irrigation sources used in the study were groundwater (GW1 and GW2), river water (RW3), and partially treated wastewater (WW4). Farmers used irrigation cans to water their lettuce crops by fetching water from nearby sources located 5 to 10 meters away. They typically carry about 20 L of water per trip. During the dry period, irrigation is carried out twice per day to ensure adequate moisture for the crops. However, one day before harvest, irrigation is stopped to reduce the weight of the lettuce heads so that transportation to the markets is easier. Occasional rain events occurred during the first two months of the experimental period, and only one rain event (which occurred in the first week) was recorded during sampling. Manure is applied to the lettuce crops approximately two weeks after planting, at least once per cropping period. The application of manure provides essential nutrients to the plants, supporting their growth and development.

Lettuce is typically harvested in the morning. Farmers usually arrive at the field between 4:00 am and 5:30 am to cut and organize the lettuce heads. This early harvesting ensures that the lettuce is fresh when it reaches the market, maintaining its quality and extending its shelf life. After harvesting, the lettuce heads are packed in sacks for transportation. It should be mentioned that transportation is done in open cars where various market products are mixed. It can be hypothesized that this transportation method presents a potential risk as it can expose the lettuce to external contaminants or physical damage during transit. Upon arrival at the market, The vendors collected municipal tap water in a bucket and used it to wash the lettuce, removing any residuals from the farm. The lettuce heads undergo screening and washing processes before being displayed for sale. Screening helps remove damaged or low-quality lettuce heads and ensures that only the best ones are available to customers. Washing the lettuce helps to eliminate dirt and surface contaminants, which enhances its visual appeal and cleanliness.

3.3.2.Concentration of E. coli in water

The lettuce was followed from the different farm plots to the market. Figure 3.2 shows the *E. coli* concentration in water samples collected at (1) Water at the farms (WF), (2) Municipal water at the market (MWM), (3) Municipal water after washing 10 lettuce heads at the market (MW_10), and (4) Municipal water after washing all lettuce heads at the market (MW_T). The results show that all water samples exceeded the WHO 1989 guidelines of 3 log unit CFU/100 mL for irrigation water, except municipal tap water samples used to wash the lettuce heads (MWM samples), which showed *E. coli* concentrations of less than 1 log unit (Figure 3.2). The municipal tap water used for washing is also used for consumption and sourced from the drinking water mains.

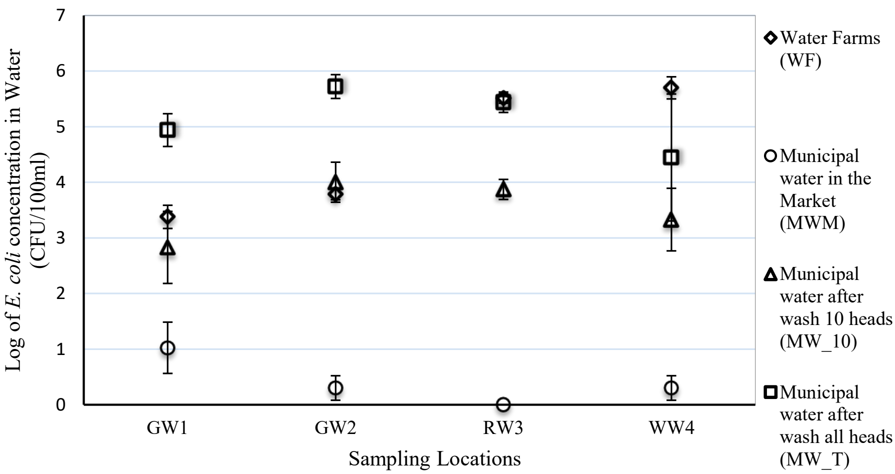

Figure 3.2: Log concentrations of E. coli in water samples (CFU/100 mL) in water at farms (WF), municipal water at the market (MWM), municipal water after washing 10 lettuce heads (MW_10), municipal water in the market after washing all (about 120 to 150) lettuce heads (MW_T)

E. coli concentrations in MW_10 ranged between 2.5 to 4 log units at the market. Whereas for WF and MW_T, the concentrations ranged between 3 and 6 log units. A comparison of sources and wash water (WF, MW_10 and MW_T) showed that the *E. coli* concentration in MW_10 was lower than in WF and MW_T at all sampling locations. The results indicate that washing the lettuce heads with MWM transferred *E. coli* from the lettuce heads to the washing water. Consecutive washing of multiple lettuce heads in the used municipal water significantly declined the water quality, leading to contamination of the subsequently washed lettuce. The results of MW_T and WF showed that the *E. coli* concentration varied among the sampling sites. Results in Figure 3.2 clearly show that for the water quality related to both groundwater sites (GW1 and GW2), the quality of MW_T is worse than that of WF. However, for the wastewater site, MW_T showed an approximately 1 log unit reduction compared to WF, while, for the river water site, the *E. coli* concentration at the market site (MW_T) was similar to the farm levels (WF). Our data shows that for the wastewater irrigated site, *E. coli* concentrations were highest. At the same time, lettuce washing resulted in a transfer of *E. coli* from the lettuce to the washing water. Notably, *E. coli* concentrations in the wash water (MW_10, MW_T) of the WW site were higher but consistently lower than those found at the farm level (WF). The lower *E. coli* concentration can be attributed to the high quality of the municipal tap water (less than 1 log unit *E. coli*) used for washing at the market site.

Overall, washing the lettuce crops did not reduce the contamination when all lettuce heads were washed in the same water. Our findings show that other means of contamination, such as market practices, may affect the product's quality. The water quality reduced after repeated use of the same water for washing, reflected in higher *E. coli* concentrations in MW_T compared to MW_10 (Table 3.2).

Table 3.2: Log E. coli concentrations (mean and P values) of water (CFU/100 mL) in the farm (F), of Municipal water in the market (MWM), of Municipal water after washing 10 heads (MW_10), and of Municipal water after washing all lettuce (MW_T). For each factor, are significant when P values <0.05.

Water Samples	*E. coli* concentration in CFU/100 ml in water samples by location and irrigation water sources				P value
	GW1	GW2	RW3	WW4	
Water at Farm (WF)	3.38 ± 0.51	3.78 ± 0.25	5.51 ± 0.21	5.70 ± 0.49	0.00
Municipal water in the market (MWM)	1.03 ± 1.13	0.30 ± 0.54	0.00 ± 0.00	0.30 ± 0.54	0.09
Municipal water after washing 10 lettuce heads (MW_10)	2.82 ± 1.30	4.00 ± 0.72	3.87 ± 0.36	3.33 ± 1.13	0.32
Municipal water after washing all lettuce (MW_T)	4.94 ± 0.66	5.72 ± 0.48	5.44 ± 0.41	4.45 ± 2.55	0.49

Statistical analysis shows a significant difference between the different water qualities at the various farm sites (Table 3.2). The results reveal two groups with significant similarities in water quality at the farm. The first group, consisting of the sites RW3 and WW4, was characterized by a higher *E. coli* concentration than the second group, consisting of GW1 and GW2. The results show no significant differences in irrigating with river water compared to partially treated wastewater. Moreover, comparing *E. coli* concentrations in the different market water samples revealed differences between samples from MWM and MW_10.

3.3.3. *E. coli* concentration on lettuce

Table 3.3 presents *E. coli* concentrations on lettuce at the four irrigated agricultural sites in Infulene Valley. Following a similar approach to the water samples for each irrigation site, the lettuce samples were collected at: (1) lettuce farms (LF) after 24 hours following the cessation of irrigation (normal harvest period), (2) lettuce at the market before lettuce washing (LM_B), and (3) lettuce in the market after washing (LM_A) all lettuce heads.

The cultivation of lettuce in the Infulene Valley takes place using irrigation water of uncontrolled water quality and using manure as a nutrient source. These practices may contribute to *E. coli* contamination of the irrigation water and exposure of the lettuce. In addition, farmers harvested the lettuce by using a knife to cut and detach it from the roots, which helped reduce contamination risks from the soil as transport of soil particles was prevented. Following this procedure, lettuce was collected and piled in sacks that were transported in a car with other vegetables produced in the valley. The lettuce was not handled differently from other crops during transportation to the market. Potentially, an increase in *E. coli* contamination might have occurred during transport because of cross-contamination from other vegetables.

Overall, the *E. coli* concentration on lettuce varied from 6 to 8 log units/100 g among the different irrigation water sources. This range exceeded the 5 log units CFU/100 g in all samples, referring to the threshold value recommended by the International Commission on Microbiological Specifications for Foods (ICMSF) (Blumenthal et al., 2000). Independently of the sample location in the value chain, GW2 showed a higher *E. coli* concentration on the lettuce than other irrigation water sources (Table 3.3). *E. coli* on lettuce irrigated with groundwater signalized contamination within the value chain. It showed that other factors might influence the quality of the lettuce produced in Infulene Valley than only irrigation water quality, such as manure application and crop handling. Manure is applied around the plant during the lettuce production cycle, and farmers apply it at least once during this stage. The manure is a mixture of animal excreta, coming from, for example, cows or chickens and mixed with plant residues. Although not tested in this study, the manure might have been a potential source of *E. coli* contamination of the lettuce on the farm, apart from the water sources.

Table 3.3: Log E. coli concentrations (means and P values) on Lettuce (CFU/100 g) from the farm - (LF), Lettuce after delayed harvest - (LH) at the farms, Lettuce at the market before wash (BW) - (LM_B), and Lettuce at market after wash (AW) - (LM_A).

Lettuce samples	*E. coli* concentration in lettuce samples in CFU/100g by location and irrigation water sources				P value
	GW1	GW2	RW3	WW4	
Lettuce farm (LF)	7.07 ± 0.86	7.75 ± 0.70	7.08 ± 0.94	6.62 ± 0.73	0.15
Lettuce delayed harvest (LH)	6.03 ± 0.94	6.63 ± 0.97	6.66 ± 0.86	6.43 ± 0.70	0.58
Lettuce BW (LM_B)	6.85 ± 1.25	8.20 ± 0.74	7.11 ± 0.80	7.57 ± 0.53	0.06
Lettuce AW (LM_A)	6.46 ± 1.73	7.68 ± 0.44	7.18 ± 0.40	7.14 ± 0.41	0.17

The results in Table 3.3 show that *E. coli* concentrations in LM_B samples were higher than in the LF samples irrigated with WW4 and GW2. However, for lettuce irrigated with GW1 and RW3, the *E. coli* concentrations were approximately at the same level. The lettuce from WW4 and GW2 were sold at the same market, and the handling practices were like the other markets. Comparison of the LM_B and LM_A samples shows that washing lettuce at the market reduced *E. coli* concentrations by 1 log unit at all sites except the RW3 site, which showed similar concentrations. Traoré et al. (2020) also found that washing lettuce with fresh tap water reduced *E. coli* concentrations. They found similar results when washing for 15 minutes compared with applying chemical disinfectants. Hence, the results show that washing lettuce at the market can contribute to risk reduction if done appropriately, as it is necessary to refresh the washing water regularly. Possibly, the decrease in *E. coli* concentration would have been significant when a reduced number of lettuce heads were washed in approximately 20 L of clean water. This volume was determined based on the storage capacity of the buckets that the vendor used to wash the lettuce in the market. However, this procedure is not followed at the market sites and was not part of our study.

Table 3.3 presents *E. coli* concentrations on lettuce at harvest (LF) and delayed harvest (LH). Stopping irrigation is not a practice in any site of Infulene Valley. Farmers usually rely only on irrigating fields that are about to be harvested the next day. For this study, samples were collected one day after the usual harvest day. Results showed that the reduction in *E. coli* concentration on the lettuce grown at the different sites varied between 0.25 and 1.1 log unit per day. At least 1 log unit *E. coli* concentration reduction was observed for the GW sites, and less than 0.5 log unit reduction was observed in the RW3 and WW4 sites.

Statistical analysis showed similar *E. coli* concentrations on the grown lettuce, considering the different irrigation water sources (Table 3.3). The washing procedures at the market and late harvest did not significantly contribute to reduce the *E. coli* content on the lettuce. In addition, all produced lettuce, irrespective of the irrigation water sources used, exceeded the limits established by ICMSF for *E. coli* concentrations allowed for human consumption.

3.4.Discussion

In the Infulene Valley, farmers use groundwater, river water, and partially treated wastewater (depending on the location of their farm) as irrigation sources for lettuce production. All irrigation water sources had elevated levels of *E. coli* at varying levels, which indicated faecal contamination. Water sources were possibly contaminated by the indiscriminate dumping of garbage, discharge of farm effluents, partially treated water from WWTP plants, and or overflows from onsite sanitation systems into the river. Also, the irrigated lettuce was contaminated regardless of the irrigation water source. The results indicate that all water sources used for irrigation in the Infulene Valley were a potential source of faecal contamination. While irrigation water was not the only source of contamination, improving the quality of irrigation water alone may be insufficient to ensure an acceptable level of contamination of the crops. At the farms, groundwater sources showed less contamination (i.e., less than 2 log units of *E. coli*) than river and partially treated wastewater sources. Faecal contamination in groundwater may be due to manure application for nutrient supply and the lack of sanitary infrastructure in the area.

Similar studies have been carried out in other countries. The Faisalabad city region in Pakistan is characterized by agricultural practices similar to Infulene Valley regarding the use of wastewater for irrigation. There, smallholder farmers irrigate crops (including vegetables) with wastewater from the city (Ensink et al., 2005). A study carried out in Faisalabad showed high levels of *E. coli* concentrations in wastewater and partially treated wastewater as expected but low crop contamination levels. Compared with studies carried out in Ghana, Mexico, and Israel, the authors concluded that lower contamination levels could be attributed to the applied irrigation method (Ensink et al., 2007). In Faisalabad, the irrigation water was conveyed via furrows with minimal contact with the produce, whereas in other countries, sprinklers or watering cans increased the potential for contamination. Maputo's case may reflect the conditions in countries like Ghana, where irrigation was carried out using watering cans. The present findings have implications for r farmers irrigating with contaminated water. The use of contaminated water could affect their health, leading to various diseases, such as diarrhoea and skin diseases (Mengesha et al., 2021). Also, Amoah et al. (2005) suggest that vectors for water-borne diseases can breed in these water sources and should be carefully considered. The public health concerns highlight the importance of addressing the issue of pollution and ensuring the availability of clean and safe water for irrigation purposes.

At the market, the *E. coli* concentration on lettuce before washing (M_B) was higher than the *E. coli* concentration on lettuce at the farm (LF), except for the RW3 and GW1 sources. This suggests that contamination happens during the handling and transport of lettuce, highlighting the need for improved measures along the value chain to reduce consumers' health risks. Such measures may also include adopting protective measures during crop handling at the farm (Caponigro et al., 2010). The current production and handling practices in Infulene Valley present potential risks for *E. coli* contamination, which can subsequently affect the water and the vegetables produced. In addition, the harvesting process, where lettuce heads are cut from the roots using a knife, followed by piling them in sacks for transportation, may pose a risk for cross-contamination. If any initial contamination of the lettuce or other vegetables occurred at the market, the lack of handling or separation during transportation could contribute to the spread of contaminants, including *E. coli,* at the marketplace (Amoah et al., 2005). *E. coli* can reproduce under favourable non-host conditions, such as those in humid tropical areas like Maputo. The resulting natural bacterial growth can increase the total *E. coli* concentration on lettuce along the value chain (Keraita et al., 2007). The outside temperatures, prevailing humidity, and transportation methods in cities like Maputo enhance the growth of bacteria and demand a critical look at the agricultural value chain. Studies in low- and middle-income countries show that unsanitary conditions contribute to increased levels of bacterial contamination (Winfield & Groisman, 2003).

If appropriately managed, practices along the value chain, such as washing the produce and strategically delaying the harvest, can contribute to risk reduction. For example, proper washing procedures must consider the proportion of lettuce versus water and the duration of the washing. However, the results indicate that the current implementation of washing and refreshing in the market can also introduce contamination. The primary reason is that washing several lettuce heads in the same water deteriorates the quality of the washing water and, therefore, results in possible cross-contamination. These findings indicate that lettuce heads are contaminated if the washing water is not regularly refreshed, resulting in cross-contamination of the produce (Dao et al., 2018). Similar research conducted in other developing countries, such as Ghana and Pakistan, describes that market vendors even use water of much lower quality for lettuce refreshments than observed in our present work (Ensink et al., 2007; Keraita & Drechsel, 2009). Nonetheless, the washing procedure using fresh water decreased the *E. coli* concentrations on lettuce at the marketplace. This indicates the washing practice's potential to contribute to reducing health risks (Amoah et al., 2007). A similar finding was observed in Ouagadougou, Burkina Faso, where clean water was used for post-harvest washing of lettuce. The washing procedure was optimized by adding additives such as a chlorine solution to the wash water (Dao et al., 2018). Results from our present research suggest the need to adopt additional measures, like regular refreshment of the washing water, to reduce *E. coli* concentrations.

In addition to proper handling methods at the market, a delay in harvest may contribute to risk reduction to acceptable levels for consumption (Table 3.3). Post-irrigation and pre-harvest periods contribute to the deactivation of *E. coli* by sunlight (Dao et al., 2018; Keraita et al., 2008). The observed *E. coli* reduction was within the ranges suggested by WHO, indicating a range of 0.5 to 2 log units per day for *E. coli* dieoff (Keraita et al., 2008) for all water sources except for partially treated wastewater. For partially treated wastewater, results showed an *E. coli* reduction of 0.25 log units per day, which is below the averages indicated by the WHO. Our results are possibly influenced by the time the samples were collected, which coincided with the transition from the wet to the dry season when rain events occur and solar radiation is not optimal. In fact, the cessation of irrigation practice is ineffective in reducing contamination during the wet season due to the re-contamination of vegetables as result of splashes from soils, while wet conditions generally allow longer pathogen survival (Keraita et al., 2007). Therefore, late harvest only contributes to risk reduction in dry and sunny seasons. Keraita et al. (2008) recommended longer periods of, for example, four days for delayed harvest compared to the two days used here to achieve improved risk reduction. However, this methodology is not feasible for lettuce, as a longer cessation of irrigation will negatively impact the lettuce's quality and result in a loss of profit for farmers (Drechsel & Karg, 2013). Hence, further research is needed to optimize the pre-harvest period that will reduce the *E. coli* concentrations in Maputo's local (climatological) conditions.

3.4.1.The importance of hazard identification in the critical contamination pathway and awareness raising

Our research results on irrigation and wash water reveal potential health risks along the agricultural value chain and also indicate that post-harvest practices could help in risk reduction. While assessing the indicator of hazardous condition such as *E.coli*, it is important to identify the critical control points for intervention. Our findings emphasize the need for complementary actions to reduce contamination along the value chain. Safeguarding irrigation water quality will not be sufficient to control the risks along the value chain for lettuce production in Infulene Valley. At the farm level, agricultural practices need to be amended to irrigation water quality, while current market practices regarding produce washing did not improve the produce quality. Like other sub-Saharan countries, Mozambique faces challenges to adopt the updated WHO guidelines and is still using the 1989 WHO guidelines for wastewater irrigation practices adopted by countries with unplanned use of wastewater (Drechsel & Qadir, 2022). The updated

2006 guidelines have not yet been implemented due to the perceived notion that they are complex and impractical, given the lack of infrastructure, and capacity within the country. Thus, the results of this study were assessed using the WHO 1989 guidelines. Nonetheless, our findings may change the perception of irrigation water quality and produce safety and may influence the stakeholders' role in guaranteeing produce safety along the value chain.

3.4.2.Possible interventions to improve the policy recommendations

The findings of this study suggest that contamination risks can only be addressed effectively with a holistic risk management approach, which includes considering the entire value chain and adopting a multiple barrier approach (Abaidoo et al., 2010; Niquice-Janeiro et al., 2020). Such an approach considers and manages risks at each step of the chain, including the irrigation source, production practices, transport, market handling, and consumers' habits. Required measures may include implementing appropriate treatment technologies to treat irrigation water before it is used in agricultural practices. Technologies of interest may involve filtration systems, disinfection methods, or other advanced treatment processes to remove contaminants and pathogens. In addition, adopting improved irrigation methods may also help to reduce crop contamination. These methods may include drip irrigation or other precision irrigation techniques that minimize direct contact between water and plants, reducing the risk of contamination (Abaidoo et al.,2010).

Another management strategy of interest is promoting self-awareness among farmers and vendors at the market. By offering education and training programs to farmers, handlers, vendors, and other stakeholders involved in the production and distribution chain, awareness is raised about good agricultural practices, proper handling and washing. Such provision will enable the different stakeholders to make informed decisions, minimize contamination risks, and enable the implementation of a multibarrier approach and HACCPs in the chain. Further, regulatory agencies or institutions should establish monitoring programs to assess water and produce quality at the source, irrigated agricultural plots, and marketplaces. Regulatory institutions are mandated to check compliance with relevant regulations, guidelines, and standards pertaining to water quality and food safety. This involves adhering to local, regional, and national regulations concerning irrigation practices and quality control measures.

By implementing the above measures, it should be possible to mitigate contamination risks, help and protect farmers and consumers, and ensure the production of safe and high-quality agricultural products. Particularly, collaboration between stakeholders, including farmers, vendors at the market, water authorities, and relevant agencies is pivotal to implement and sustain these measures successfully.

3.5.Conclusions

This study assessed faecal contamination of lettuce produced at farms and sold at local markets of Maputo, Mozambique. The *E. coli* concentration served as an indicator for faecal contamination in both water and lettuce samples. Our results show that, regardless of the water source used for irrigation, all irrigation water sources in Infulene Valley are contaminated and the lettuce was contaminated throughout the entire value chain. The average *E. coli* concentrations in irrigation water were 3.4-3.8, 5.5, and 5.7 log units/ 100 mL for groundwater (GW1 and GW2), river water (RW3), and partially treated wastewater (WW4), respectively. The *E. coli* concentration on lettuce was 7.1-7.8, 7.1 and 6.6 log units/100 g for the groundwater, river water, and partially treated wastewater irrigated lettuce, respectively. We also showed that washing lettuce at the marketplace has little effect on risk reduction and a high likelihood of re-contamination of the produce. This requires actions to be adopted at the market in order to reduce contamination, such as reducing the number of lettuce heads being washed with the same water.

The results clearly show that the lettuce sold in the market might be contaminated by handling practices. Apparently, irrigation water is not the only potential source of contamination in the value chain. Improved hygiene at the marketplace will significantly impact the contamination levels of the lettuce, irrespective of the use of reclaimed wastewater or other water sources for irrigation in Maputo. In addition, we found that delayed harvest contributes to risk reduction. At least 1 log unit

E. coli concentration reduction was observed for the GW sites, and less than 0.5 log unit reduction was observed in the RW3 and WW4 sites. Delayed harvest may compromise product quality due to dehydration problems, reducing the value of the produce.

To date, the government is still adopting the 1989 WHO guidelines. This work can pave the way to plan a multibarrier approach for Maputo, as the 2006 WHO guidelines suggest. The establishment of risk reduction interventions with different stakeholders could be applied at several steps along the value chain, i.e., from irrigation water to farm practices, crop handling, transportation, and vending at the market, to reduce the risks of *E. coli* contamination while preserving the livelihood of the (peri-) urban farmers. Also, awareness activities involving farmers, vendors, and municipal officials of Infulene Valley are required to safeguard crop contamination levels in the value chain. We recommended that future studies address viable solutions along the value chain to reduce the current contamination risks.

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Chapter 4: Wastewater-based nutrient supply for lettuce production in Infulene valley, Maputo Mozambique;

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Wastewater-based nutrient supply for lettuce production in Infulene valley, Maputo Mozambique;

Abstract

This research investigated the contribution of wastewater-based nutrients supply, viz., nitrogen (N), phosphorous (P), and potassium (K), for lettuce production in Infulene Valley, Mozambique, from July to September 2019. The research was conducted in groundwater and wastewater irrigated agricultural plots. Water samples were collected weekly, soil samples were collected before planting and after harvest, and lettuce samples were collected at harvest time. The nutrient content (N, P, K) was measured, and a mass balance method was applied. Wastewater had distinctly higher nutrient contents than groundwater, which guaranteed crop nutrition during the growing stage. Wastewater contributed with 88%, 96% and 97% to the N, P, K requirements, respectively. The crop yield in the wastewater irrigated areas was 43,8 ± 16 tons/ha, which was higher than the 35 ± 8 tons/ha observed for the groundwater irrigated areas, but results showed no statistically significant differences. Conclusively, wastewater led to reduced soil-nutrient gap and can be a source of nutrients. Therefore, wastewater is regarded as an alternative nutrient source of interest and if properly applied, it might reduce environmental health hazards, resulting from run-off or leaching of excess nutrients.

4.1. Introduction

Wastewater is an alternative source for agricultural irrigation to compensate for water shortages (Ilahi et al., 2021; Saidan et al., 2020; Zhang & Shen, 2019) or the lack of proper irrigation sources. In most low-income countries and arid regions, wastewater is widely used in (peri)urban agriculture, either (partially) treated or non-treated Dreschel et a., 2008; Keraita et al., 2008, Schierling et al.,2011; Niquice Janeiro et al.;2020; Poustie et al.; 2020). The use of wastewater results in the availability of reliable water sources and increased nutrient availability for agricultural fields, improving the farmers' livelihood and crop development (Adewumi et al., 2010; Bedbabis et al., 2014; Poustie et al., 2020; Qadir et al., 2010).

Nitrogen (N), phosphorous (P) and potassium (K) belong to macronutrients that are commonly present in (treated) wastewater at agriculturally relevant concentrations (Boom et al., 2008). N is commonly present in ionized forms, such as NO_3^-, NO_2^-, and NH_4^+, while it might also be present in gaseous forms, such as NO_x, NH_3, N_2O, and N_2. N in its different forms can become available in the soil through processes such as biological fixation, ammonia deposition, nitrification, and denitrification (Chen et al., 2010). Under aerobic conditions NO_3^-, is considered a relatively stable and mobile ion and can be transported with soil water, while NH_4^+, is more easily absorbed to the negatively charged soil clay particles. Soil also receives N in organic form through plant residues, which can be mineralized by saprotrophic organisms (Boberg et al., 2011). Plants uptake N mainly as NO_3^- and NH_4^+ (Woltersdorf et al., 2016). P does not have gaseous forms (Chen et al., 2010), and exists as mineral in the ortho-phosphate form (PO_4^{3-}) with H^+, Fe^{3+}, Ca^{2+} or Al^{3+} as counter ions or as organic P bound in plant matter (Woltersdorf et al., 2016). P has lower mobility and is mostly found in phosphate rocks, soil and marine sediments (Chen et al., 2010). Plants uptake P as PO_4^{3-} (Woltersdorf et al., 2016). K is readily absorbed by plants in the form of K^+ and is highly soluble in soil and water. However, the concentration in soil is low, requiring frequent supplementation by manure, artificial fertilizers, and/or wastewater (Boom et al., 2008).

The organic matter in (treated) wastewater that is used for irrigation, contributes to improved soil structure, water infiltration, prevention of surface sealing, and increased biological activity, resulting in better crop yields (Khalil et al., 2015). Organic fertilizers are used in agriculture for the same reason, in addition to meet crop nutrient demands (Joshi et al., 2017; Mwangi, 1996; Stewart et al., 2005; Woltersdorf et al., 2016).

Nutrient supply through inorganic fertilizers contributes around 30 to 50% of the crop yield (Stewart et al., 2005). However, in many countries in sub-Saharan Africa (SSA) the use of fertilizers remains low (Benson & Mogues, 2018; Cedrez et al., 2020; Mapila et al., 2012; Waithaka et al., 2007). The lack of fertilizer use is seen as the major cause for low agricultural production in countries like Mozambique (Zavale et al., 2020). The main reasons for this low fertilizer use include limited awareness regarding the benefits of using fertilizers, and high purchase costs (Zavale et al., 2020). Only 5% of smallholder farmers use fertilizers, and they do so at very low application rates, such as 5.7 kg/ha from the regional target of 65 kg/ha (Benson & Mogues, 2018). The remaining farmers in the country produce crops without applying any type of fertilizers, while others apply organic fertilizers based on manure. In most SSA countries including Mozambique, manure application depends on smallholder's economic resources, manure availability, type of crops produced, i.e., fodder crops or cash crops, like high value crops (e.g., Maize) and vegetables (Maria et al., 2017). However, relatively little data is available on manure application coverage. For example, data from Mozambican Integrated Agricultural Survey in 2014/2015 season indicated that manure application in cereals rated 1.8% of a total of 4,000,000 smallholders farmers (Maria et al., 2017). The variability on manure application may result in high differences in nutrient concentrations in soils among farmers (Chikowo et al., 2014; Vanlauwe et al., 2015).

The state of nutrients supply for crops in developing countries in irrigated agriculture is not well known and there is lack of detailed on-farm nutrients balances to quantify pathways of both nutrients input and loss over time, under the prevailing management practices (Vitousek et al., 2009; Werner et al., 2019). Therefore, monitoring nutrients at farm level is essential to estimate nutrients supply, which is rarely done for untreated or partially treated wastewater (Qadir et al., 2010). Boom et al. (Boom et al., 2008) described the fate of nutrients using a simplified nutrients balance in wastewater irrigated plots in Jordan, finding a mismatch between the applied amount via the nutrients present in wastewater and the required amount of macronutrients for crop growth, resulting in nutrients over-dosages, which potentially have negative impacts on the environment and crops. Similar studies were conducted for the Chivero catchment area, Zimbabwe, where Nhapi et al. (Nhapi et al., 2002) assessed the major water and nutrient flows using nutrient balances. The nutrient flows for Maputo at the Infulene valley are still unknown, due to the limited information in the area concerning the amount of nutrients that may be present in irrigation water in the area.

In our research, we investigated the potential contribution of wastewater-based nutrients for the supply of N, P, and K in lettuce production in Infulene Valley, Maputo, Mozambique, which is located in a peri-urban area of Maputo (Niquice Janeiro et al., 2020a). In the area, agriculture is heavily practiced with diversified irrigation water sources such as groundwater, river water, partially treated, and untreated wastewater. In this area, a wastewater treatment plant (WWTP) is constructed, consisting of a pond system, comprising two anaerobic and two facultative ponds, that receives 5–10% of Maputo's city wastewater for treatment (Rietveld et al., 2016b). However, the WWTP is not functioning well due to severe overloading and poor management; with the anaerobic ponds full of sludge and facultative ponds covered by hyacinths jeopardizing proper treatment (Arsénio et al., 2018). Even though, the final effluent is informally used to irrigate the crops including lettuce (Rietveld et al., 2016b). Despite its poor quality (Arsénio et al., 2018; Rietveld et al., 2016b), the use of wastewater for irrigation might have the potential benefit of being a source of indispensable nutrients for crop cultivation with positive impact on soil structure, biological activity, and crop yields.

4.2. Materials and Methods

4.2.1. Sampling and Experimental Design

The experiment was carried out in Infulene Valley in Maputo (Figure 4.1), in a peri-urban agricultural site for lettuce production. The experimental area is in the farmer's fields and simulated their own natural environment where they grow lettuce using their plant management practices. Two areas were selected with different irrigation water sources, one applied groundwater from shallow wells as irrigation source and the other one applied secondary stage treated wastewater effluent, collected from the facultative pond at Infulene WWTP. The WWTP is a lagoon system comprising two anaerobic and two facultative ponds which treats 5–10% of the effluent of Maputo's city and discharge its effluent in Infulene river (Arsénio et al., 2018; Rietveld et al., 2016b). The total experimental area was 22 m^2 and 19.6 m^2 for groundwater and wastewater areas, respectively. Each of them had four replicates and, the samples were collected from soil, water, and fresh lettuce heads. Each plot in the groundwater area had an average area of 5.5 ± 0.6 m^2, while the plots in the wastewater area had an average area of 4.9 ± 0.2 m^2, with average dimensions of 3.6 × 1.5 m and 3.1 × 1.6 m for groundwater and wastewater, respectively. Regular field visits were conducted in each irrigated area to ensure that the practices were consistent. The applied crop management practices were similar for the groundwater and wastewater irrigation areas, from initial crop growth to crop harvest. These practices included the type of crops produced (lettuce), the use of manure from mixture of animal excreta such as cow or chicken, mixed with plant residues, the applied irrigation method, sample collection and the harvest procedure. The use of watering cans is the commonly practiced irrigation method in the area. During the experiments, farmers initially irrigated the crops with four watering cans once after planting. As the crops grew, the irrigation frequency increased to twice per day, using six cans per plot, and continued in this manner until harvest. The volume of irrigating can used was 10 L, at the pick of the irrigation period each plot received up to 12 cans equivalent to 120 L per plot (24 L/m^2/day). Some advantages of using this irrigation method include portability, low cost, and no need for electricity or fuel to function. However, some disadvantages of this method are that it is labor-intensive, time-consuming, and inefficient for larger areas. Therefore, the amount of water applied was quantified by observing the number of watering cans applied in the producing area. Manure is the most common organic fertilizer, which is applied manually. The source of manure was the same as commonly used by the farmers. The estimated manure amounts applied in the experimental area were 40 kg for wastewater-irrigated soil and 30 kg for groundwater-irrigated soil. Soil preparation, weeding and harvest is also done manually—a common practice among most small-scale farmers in Mozambique, due to the lack of capacity to invest in machinery and sometimes due to the geographical characteristics of the area.

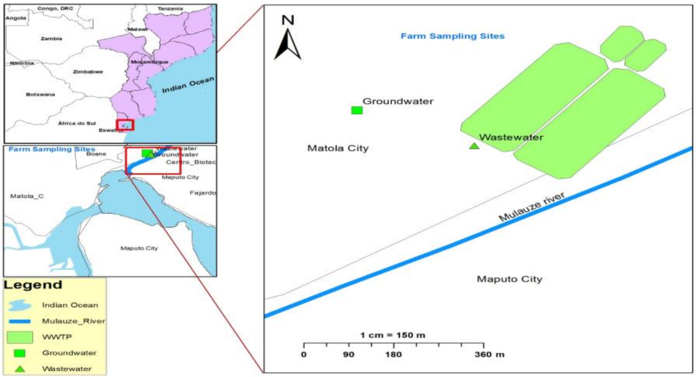

Figure 4.1. Experimental location for groundwater and wastewater irrigated areas in Infulene Valley.

Soil samples were collected before planting and after harvest per site. A total of 48 soil samples were collected using a hand-driven auger. The samples were collected in two irrigation sources (one groundwater, one wastewater). For each location, four (4) replicate soil samples were collected at three (3) depths at two periods (corresponding before planting and after harvesting). The three different depths which are further referred to as top, medium and bottom layer, i.e., 0–20 cm, 20–40 cm, and 40–60 cm. These depths were selected according to lettuce root depth which is around 0 to 60 cm (Sutton & Merit, 1993). The applied sampling schedule helped to describe temporal variations in the concentrations of nutrient in different soil layers. Samples were air dried for one week, until they reached a constant weight. Hereafter they were passed through a 2 mm sieve and mixed thoroughly.

Water samples were collected weekly during the entire experimental period, i.e., from plantation until the harvest. The water sampling procedure was used to capture possible temporal variations in the water quality throughout the experiment. In each week, two duplicate irrigation water samples were collected per site using glass bottles of 250 mL volume, giving a total of 28 during the 7 weeks of sampling. The samples were placed in a container with ice packs, to maintain their integrity while being transported to the laboratory.

Manure was applied in solid form around the plant, two weeks of after planting and the amount of manure was registered in both irrigated areas. Manure samples were collected when it was applied to the soil, and manure was analyzed to give approximate estimates on the amount of nutrients (N, P, K) supplied by the manure during the experiment. Lettuce samples were selected randomly in the plot when ready to harvest. Each lettuce sample consisted of three lettuce heads. This standardized sampling method was used throughout the experiment. Therefore, a total of 8 lettuce samples were collected for analysis, corresponding to 24 lettuce heads resulting from collection of 3 lettuce heads per plot, in 4 replicates at two sides with different irrigation water sources. The samples were stored in sterile plastic bags, then inserted in a container (one container for each source to avoid contamination) and transported directly to the laboratory. Lettuce samples after the harvest were dried at 60 °C for 7 days, until they reached a constant weight. Hereafter, they were homogenized by grinding for reaching small sizes for further analysis. To prevent contaminations during the transportation each sample was appropriately labeled and separated from the other samples in a closed container.

4.2.2. Laboratory Analysis

Soil, water, manure, and lettuce samples were analyzed for nutrient content of N, P and K, following the methods as described in Table 4.1.

Table 4.1. Nutrient estimation methods used in soil, water, manure, and lettuce analysis.

Nutrient Forms	Soil	Plants and Manure	Water
Total N	Kjeldahl method (Houba et al., 1989; Okalebo et al., 2002; Pansu & Gautheyrou, 2006)	Kjeldahl method (Houba et al., 1989; Okalebo et al., 2002; Pansu & Gautheyrou, 2006)	Hach test kits (TNT 828) detection limit detection 20–100 mg/L
NO_3^-	Extraction KCl and distillation and titration (Okalebo et al., 2002)		Hach LCK 339 (0.23–13.5 mg/L NO_3-N/1–60 mg/L NO_3)
NH_4^+	Extraction KCl and distillation and titration (Okalebo et al., 2002)		Hach LCK 303 (2–47 mg/L NH_4-N or 2.5–60 mg/L NH_4)
Total P	Spectrophotometer (digested with H_2SO_4 and Salicylic acid, selenium, and Hydrogen peroxide) (Houba et al., 1989; Okalebo et al., 2002; Pansu & Gautheyrou, 2006)	Spectrophotometer (digested with H_2SO_4 and Salicylic acid, selenium, and Hydrogen peroxide) (Houba et al., 1989; Okalebo et al., 2002; Pansu & Gautheyrou, 2006)	
Available PO_4^{3-}-	Olsen (Olsen et al., 1954)	-	Hach TNT 845 (2–20 mg/L PO_4-P or 6–60 mg/L PO_4)
Total K	Flame photometric method (digested with H_2SO_4 and Salicylic acid, selenium, and Hydrogen peroxide) (Houba et al., 1989; Okalebo et al., 2002; Pansu & Gautheyrou, 2006)	Flame photometric method (digested with H_2SO_4 and Salicylic acid, selenium, and Hydrogen peroxide) (Houba et al., 1989; Okalebo et al., 2002; Pansu & Gautheyrou, 2006)	
Available K^+	Flame photometric method (Extraction method using ammonium acetate) (Okalebo et al., 2002; Zhou et al., 2022)		Hach LCK 328 (8–50 mg/L K+)

Soil Chemical and Physicals Analysis

Soil samples were analyzed for N, P and K nutrient content as well as for texture, organic matter (OM), cation exchange capacity (CEC), pH, electrical conductivity (EC). The nutrient content was analyzed by measuring the concentrations NO_3^-, NH_4^+, total N, total P, PO_4^{3-}, total K and available K.

The soil texture was determined using the pipette method by Robinson (Pansu & Gautheyrou, 2006).

The organic matter (OM) content in soil is related to the nutrient storage capacity and was measured by using the Walkley & Black method (Pansu & Gautheyrou, 2006; Ramamoorthi & Meena, 2018).

The cation exchange capacity (CEC) shows the soil fertility and nutrient retention capacity (Razzaghi et al., 2021) and correlates positively with organic matter content (Ramos et al., 2018). The CEC was measured using the ammonium acetate method (Pansu & Gautheyrou, 2006; Schollenberger & Dreibelbis, 1930).

Soil pH influences soil physical properties, e.g., a low pH facilitates OM decomposition and increases the availability of soil nutrients (Khalil et al., 2015). The soil pH was determined potentiometrically in (1:2.5 p/v) soil: water suspension and KCl. The electrical conductivity was determined using an electrical conductivity meter (Pansu & Gautheyrou, 2006).

The determination of N content of soil was done by measuring the mineral concentrations of NO_3^- and NH_4^+. The NH_4^+ and NO_3^- were extracted using potassium chloride and analysed by steam distillation and titration. Total N, P and K were extracted using sulfuric acid, selenium, salicylic acid and hydrogen peroxide following the procedure described by Walinga et al. (Walinga et al., 1995) and Okalebo (Okalebo et al., 2002). The total N was analyzed using the Kjeldahl method [37].

P types analyzed in these experiments were available PO_4^{3-} and total P. Total P was determined by spectrophotometry by measuring P in the solution of a simple colorimetric method based on ascorbic acid reduction of the ammonium phosphomolybdate complex (Houba et al., 1989). For the determination of PO_4^{3-} the Olsen's method was used (Olsen et al., 1954).

K types analyzed in the experiment were available K^+ and total K determined by flame photometer (Okalebo et al., 2002). The available K was determined by the ammonium acetate (NH_4Ac) extraction method (Okalebo et al., 2002; Zhou et al., 2022).

Water Analysis

The water samples were analyzed for N (total N, NO_2^- and NO_3^-), PO_4^{3-} and K^+ using test kits (Hach Lange GMBH, Germany) and analyzed using UV-VIS spectrophotometer DR 3900. The concentrations of macronutrients were multiplied by the respective amount of water used for irrigation to quantify the nutrient input from irrigation water (wastewater and groundwater). The pH and electrical conductivity of the water was determined using a pH meter and an electrical conductivity meter (Thermo Scientific, Orion STAR A215), respectively.

Lettuce and Manure Analysis

To compare the productivity of both areas, the lettuce yield was recorded after harvest from the groundwater and wastewater sites. At each site, each lettuce sample was analyzed for total N, P and K. The plant material was digested using a mixture of sulfuric acid, selenium, salicylic acid and hydrogen peroxide (Okalebo et al., 2002). The Kjeldahl technique was used for measurement of total N. The total P was measured through the molybdenum blue method and determined colorimetrically using a spectrophotometer (Houba et al., 1989; Wieczorek et al., 2022). The total K was measured using a flame photometer. The same procedure was applied for manure collected two weeks after planting. The nutrient uptake in lettuce was determined multiplying the plant dry weight by the measured concentration.

Statistical Analysis

Changes in soil nutrient levels resulting from irrigation were assessed using a paired T-test with a significance level of 5%, using SPSS statistical software version number 26. Nutrient concentrations were compared between different irrigation types, applying an independent T-test at a significance level of 5%, using SPSS statistical software. The analysis of yield data, a T-test was used and compared means using the least significant difference method at the 5% significance level, using SPSS statistical software.

4.2.3. Nutrient Balances

A nutrient balance was conducted to quantify the N, P and K fluxes during a single cropping season in the peri-urban area of Infulene Valley, Maputo. The focus of this balance in the agricultural system was on assessing the input and output of N, P, and K in farmers plot irrigated with groundwater and wastewater. Inputs into the system included the addition of manure and the supply of irrigation water. The system's outputs considered nutrient removal through crops. Other factors such as leaching losses, erosion, runoff, wind erosion, and the volatilization of nitrogen (resulting from denitrification and NH_3 volatilization) were not considered due to temporal duration of experiment (Boom et al., 2008; Sainju, 2017). A nutrient balance was conducted using input (irrigation water and manure) and output (plant uptake) of nutrients for both groundwater (GW) irrigated site and wastewater (WW) irrigated site. The soil condition, for both before planting and after harvest was analyzed to investigate the influence of the irrigation source on nutrient supply. The used conceptual framework, considers the soil as a nutrient storage that can accumulate or reduce nutrients because of the irrigation source. Accordingly, the soil irrigated with wastewater is referred to as SIW (Soil irrigated with wastewater) and the soil irrigated with groundwater as SIG (Soil irrigated with groundwater). This categorization allows us to distinguish and evaluate the impact of these two distinct irrigation sources on soil nutrient dynamics.

Soil Balances

To evaluate the nutrient supply to the crops, a nutrient balance was performed from sowing to harvest. A mass balance model (4.2) was used, adapted from Zhang and Shen (4.1).

$$\text{Soil nutrient balance} = S_{fert} + S_{min} + S_{irri} + S_{dep} - S_{plant} \quad (4.1)$$

where S_{fert} is the amount of chemical fertilizer applied in the site (kg/ha). This value was assumed to be zero since no fertilizers were used in the study sites. S_{min} is the nutrient input from mineralization of manure (kg/ha). S_{irri} is calculated by multiplying the nutrient content of the irrigation water by the total amount of water supplied. S_{dep} is the nutrient input from atmospheric deposition (only N). S_{dep} for the analyzed period was calculated based on estimations for atmospheric N deposition of 4.8 kg/ha/year for South Africa (Nyaga et al., 2013). In addition, for sparsely populated areas and non-industrial countries the estimated N deposition is about 5 kg/ha/year (Haileslassie et al., 2005). The range of 20–50 kgN/ha/year is used for countries in western Europe and China, and can reach 60 kg N/ha/year due to proximity of cities, intensive cattle breeding, and the amount of precipitation (Haileslassie et al., 2005). Based on the estimation of 4.8 kg/ha/year the N deposition of 0.7 kg/ha was calculated for the period (49 days) in Mozambique. S_{plant} is the nutrient uptake by the aboveground biomass. The nutrients balance assumes that the nutrients in roots will accumulate as agricultural remains in the field. Therefore, the simplified equation used for the soil nutrient balance is as follows:

For N: Soil nutrient balance = $S_{min} + S_{irri} + S_{dep} – S_{plant}$ (4.2)

For P and K: Soil nutrient balance = $S_{min} + S_{irri} - S_{plant}$ (4.3)

Ratio Calculations

The ratio of nutrients input/output is a quantitative relation between the amount of nutrients input and nutrient output. The nutrient ratio was calculated using the amount of nutrients supplied by manure and irrigation divided the nutrients uptake by the crop.

For N: Ratio (Input/Output) = ($S_{min} + S_{irri} + S_{dep}/S_{plant}$) (4.4)

For P and K: Ratio (Input/Output) = ($S_{min} + S_{irri}/S_{plant}$) (4.5)

4.3. Results

4.3.1. Nutrient Content in Water

The nutrient concentrations in groundwater and wastewater, which were used to irrigate lettuce during the production cycle, are shown in Table 4.2. The nutrient content in wastewater was distinctly higher compared to groundwater, except for the NO_3^- concentration. Crops were irrigated with the wastewater from the facultative pond. However, the results clearly indicate that the wastewater was only subjected to anaerobic conditions in the treatment plant. Almost all N was present in the form of NH_4^+ with negligible amounts oxidised to NO_2^- or NO_3^-. This suggests that the WWTP was lacking nitrification capacity, very likely because of overloading with septic tank content discharged to the anaerobic ponds by tanker trucks.

Table 4.2. Concentration (mg/L) of nutrients present in groundwater and wastewater (partially treated wastewater at secondary stage) used for irrigation in Infulene.

Parameter	**Water Source**	
	Groundwater	**Wastewater**
NO_3^- (mg/L)	3.5 ± 5.3 *	0.9 ± 0.2
NO_2^- (mg/L)	0.1 ± 0.1	0.4 ± 0.4
NH_4^+ (mg/L)	0.1 ± 0.2	231.8 ± 150
Total N (mg/L)	16.4 ± 19.1	461.6 ± 279.5
K^+ (mg/L)	31.8 ± 5	405.9 ± 130
PO_4^{3-} (mg/L)	6.0 ± 2.9	81.1 ± 46.5
pH	7.92 ± 0.25	7.40 ± 0.29
EC (dS/m)	1.95 ± 0.69	1.84 ± 0.42

* NO_3^- highly variable along the sampling weeks in groundwater.

Wastewater showed slightly lower EC and pH values compared to groundwater (Figure 4.2). The pH at the wastewater site ranged from 7 to 8 indicating circumneutral conditions, while that of groundwater was slightly alkaline. EC values of the wastewater were approximately about 0.75 dS/m in week 1 and around 2 dS/m for the remaining irrigation period, while for groundwater it reached 2.5 dS/m. The EC values in irrigation water indicated a moderate risk of salinity hazard, which could have potentially affected the crop productivity. The relatively low EC levels found in week 1 could be attributed to final days of precipitation of the wet season as most of the study was conducted in the dry season.

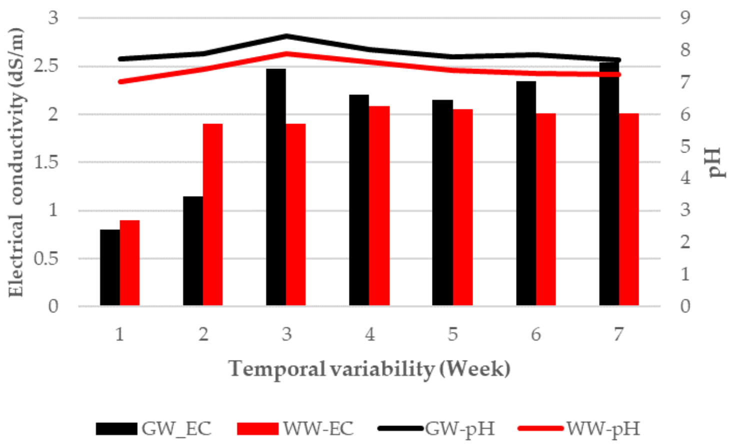

Figure 4.2. Electrical conductivity (EC) and pH in groundwater (GW) and wastewater (WW) during the experimental period.

4.3.2. Physical Proprieties and Nutrients Dynamics in the Soil

For both groundwater and wastewater irrigated areas, the results showed that sand is the main soil constituent in all soil layers (Table 4.3).

Table 4.3. Texture in soils irrigated with wastewater (SIW) and Groundwater (SIG).

Depth	Soil Irrigated Wastewater (SIW)			Soil Irrigated Groundwater (SIG)		
(cm)	Clay (%)	Silt (%)	Sand (%)	Clay (%)	Silt (%)	Sand (%)
0–20	16.3 ± 4.3	4.8 ± 3.0	78.9 ± 3.8	13.9 ± 4.3	6.3 ± 2.6	79.7 ± 4.7
20–40	21.8 ± 10.2	6.7 ± 3.1	71.5 ± 9.4	15.1 ± 2.1	6.5 ± 2.8	78.4 ± 2.8
40–60	17.5 ± 3.2	11.7 ± 3.2	70.9 ± 9.7	29.8 ± 17.9	12.2 ± 8.9	57.9 ± 23.3

The soil irrigated with wastewater (SIW) exhibited lower EC values in the top layer before planting compared to the soils irrigated with groundwater (SIG). In the medium and bottom layers, the EC values were similar between the two irrigation sources. After the harvest, the EC values in the top to bottom layers of the SIG were distinctly higher than those in the SIW (Figure 4.3). Before planting, the EC values of SIG ranged from 0.46 to 0.50 dS/m, and after harvest it ranged from 0.65 to 0.81 dS/m. While for SIW the EC values, ranged from 0.32 to 0.45 dS/m before planting, and increased to the range of 0.52 to 0.62 dS/m after harvest. The results indicate an increase in soil EC during the experimental period, which is likely attributable to evaporation of irrigation water. The increase in EC in the SIG reached up to 76% and was more pronounced in the bottom layer compared to top layer possibly influenced by factors such as the clay fraction in the bottom layer. In the case of SIW, the EC increased by up to 62% in the top layer. There was a change in EC pattern for SIG before planting and after harvest (Figure 4.3).

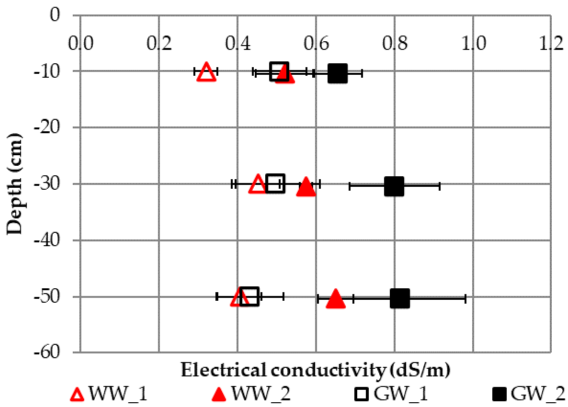

Figure 4.3. Electrical conductivity (dS/m) at different soil depth irrigated with groundwater (SIG) and wastewater (SIW) before planting (1) and after harvest (2).

The average pH values in the soils ranged from 8 to 9, indicating alkaline classified soils (Figure 4.4). After harvest, the pH significantly increased in the SIG, while for SIW an increase was only observed in the top layer (Figure 4.4). Before planting, the pH values in top layer were similar for SIW and SIG, but after harvest, the pH values in the SIG was significantly higher than in the SIW.

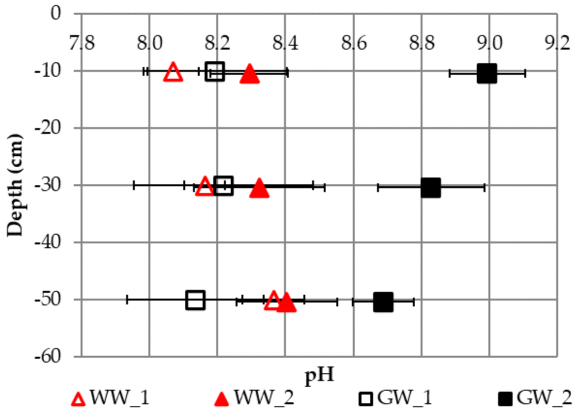

Figure 4.4. pH at different soil depth irrigated with groundwater (SIG) and wastewater (SIW) before planting (1) and after harvest (2).

In general, the organic matter content and the CEC in SIG was higher than in SIW (Table 4.4) both before planting and after harvest. The CEC values in SIG varied from 10.7 meq/100 g in the top layers to 20.7 meq/100 g in the bottom layer. In contrast, no clear pattern was found for SIW. After the harvest, the CEC values slightly decreased in SIW (Table 4.4).

Table 4.4. Organic matter (OM) content and cation exchange capacity (CEC) in soil irrigated with wastewater (SIW) and groundwater (SIG) before planting (BP) and after harvest (AH).

Irrigation Source	Depth (cm)	% of OM Content			CEC (meq/100 g)		
		Before Planting	After Harvest	*p* Values (BP×AH)	Before Planting	After Harvest	*p* Values (BP ×AH)
WW	0–20	0.8 ± 0.4	0.7 ± 0.2	0.82	7.5 ± 1.6	6.2 ± 1.3	0.01
	20–40	0.6 ± 0.3	0.8 ± 0.8	0.45	9.7 ± 3	7.6 ± 2.6	0.01
	40–60	0.8 ± 0.3	0.9 ± 0.9	0.68	8.6 ± 3.3	7.4 ± 1.7	0.22
GW	0–20	1.9 ± 0.3	2.3 ± 0.3	0.08	10.9 ± 1.2	10.7 ± 3.5	0.88
	20–40	1.5 ± 0.4	2.1 ± 0.4	0.02	12.1 ± 1.7	12.4 ± 1.5	0.47
	40–60	2.1 ± 0.9	2.0 ± 0.5	0.66	19.0 ± 11.4	20.7 ± 11.7	0.28
p values (SIW×SIG)							
	0–20	<0.00	<0.00		<0.00	0.00	
	20–40	<0.00	<0.00		0.07	<0.00	
	40–60	<0.00	0.01		0.37	0.02	

NO_3^-, NH_4^+ *and Total N Content in Soil*

The N concentration was measured in the forms of NO_3^-, NH_4^+ and total N (Figures 4.5–7). In general, the NO_3^- concentration in soil was higher in SIG than in SIW before planting, while after harvest this difference was observed only in the bottom layer (Figure 4.6). In both irrigation areas, the NO_3^- concentration was generally higher in the topsoil layers compared to the bottom soil layers. The concentration of NO_3^- increased after harvest in SIW, ranging from 14 to 33 mg/kg in the top layers.

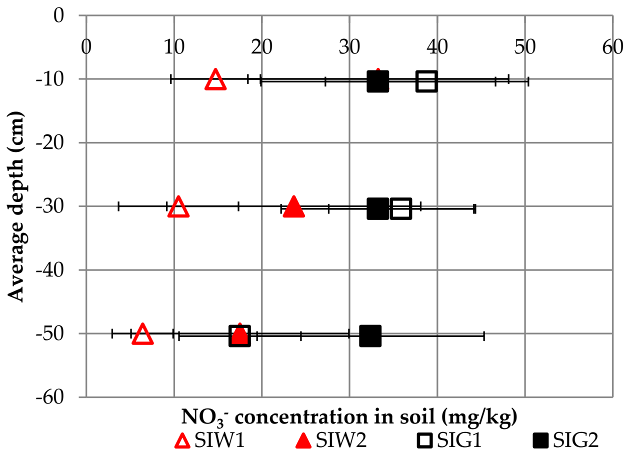

Figure 4.5. NO_3^- concentration (mg/kg) in soils irrigated with wastewater (SIW) and groundwater (SIG) before planting (1) and after harvest (2).

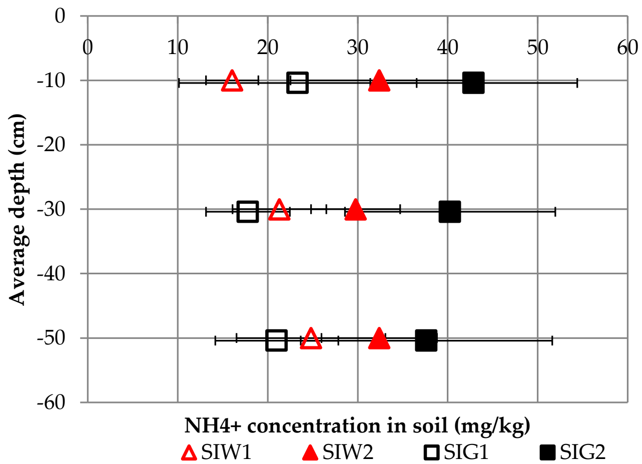

Figure 4.6. NH_4^+ concentration (mg/kg) in soils irrigated with wastewater (SIW) and groundwater (SIG) irrigated soil before planting (1) and after harvest (2).

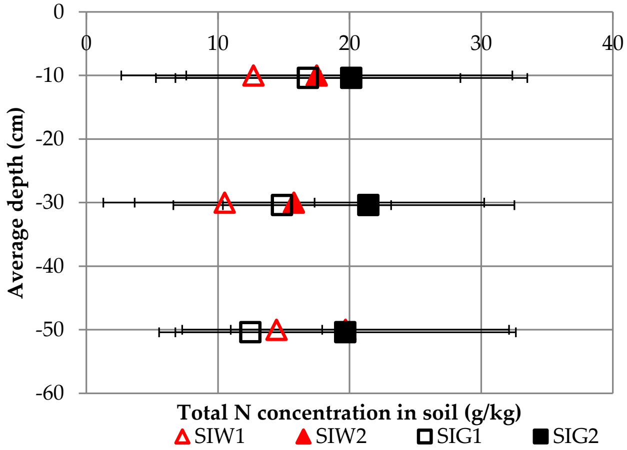

Figure 4.7: Total N concentration (g/kg) in soil irrigated with wastewater (SIW) and groundwater (SIG) before planting (1) and after harvest (2).

NH_4^+ concentration increased after harvest for both irrigation waters; SIW ranging from 16 to 32 mg/kg, and SIG ranging from 23 to 42 mg/kg. Similar NH_4^+ concentrations were found in both SIG and SIW (Figure 4.6). Considering the amounts of NH_4^+ present in wastewater it was likely that the concentration in SIW would rise higher than the SIG. This observation indicates the likelihood of ammonium (NH_4^+) losses occurring within the system, primarily in the wastewater (WW) site. Given the high concentrations of NH_4^+ in wastewater, it raises concerns about the fate of this nutrient in the context of irrigation and its potential environmental implications.

Total N increased in all soil layers for both SIW and SIG plots (Figure 4.7). In general, similar total N concentrations were found in both SIG and SIW.

Available P and Total P Content in Soil

P concentration (mg/kg) was measured as PO_4^{3-} and total P (Figures 4.8 and 4.9). In the soil profile, all forms of P showed highest concentrations in top layers and decreased with depth. In general, PO_4^{3-} in SIG was higher than in SIW before planting and after harvest the concentration of PO_4^{3-} decreased. After harvest, PO_4^{3-} concentration in SIG showed a sharper drop (about 52%) in the first two layers, while in the bottom layer the reduction was about 42%. In contrast, only a small PO_4^{3-} reduction after harvest was observed in the SIW soil layers where the drop was only up to 7% (Figure 4.8). The measured concentrations showed that wastewater contributed to conserve soil available P concentrations in SIW.

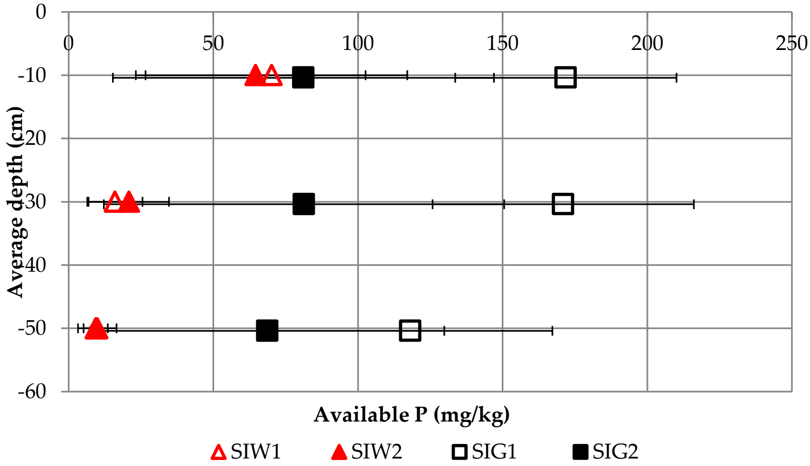

Figure 4.8. Available PO_4^{3-} concentration (mg/kg) in soil irrigated with wastewater (SIW) and groundwater (SIG), soil before planting (1) and after harvest (2).

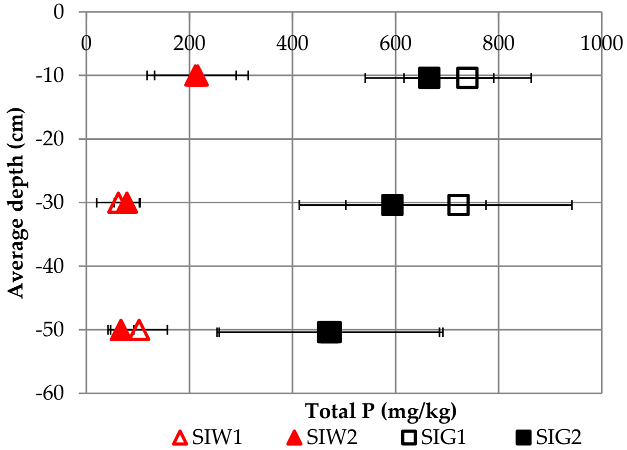

Figure 4.9. Total P (mg/kg) in soil irrigated with wastewater (SIW) and groundwater (SIG), before planting (1) and after harvest (2).

Total P concentration in SIG was higher than the SIW. The levels did not change during the experimental period (Figure 4.9).

Available K^+ and Total K Content

K concentrations (mg/kg) were measured as K^+ and total K (Figures 4.10 and 4.11). In general, SIG samples showed higher concentrations of available K than SIW (Figure 4.11). The amount of K^+available in SIW increased, i.e., from 50 mg/kg in the top layer before planting to 116 mg/kg after the harvest. The highest concentration of K^+ was found in the bottom layers (260 mg/kg). Similarly, for SIG, the K^+ available concentration increased after harvest to 627 mg/kg in bottom layer.

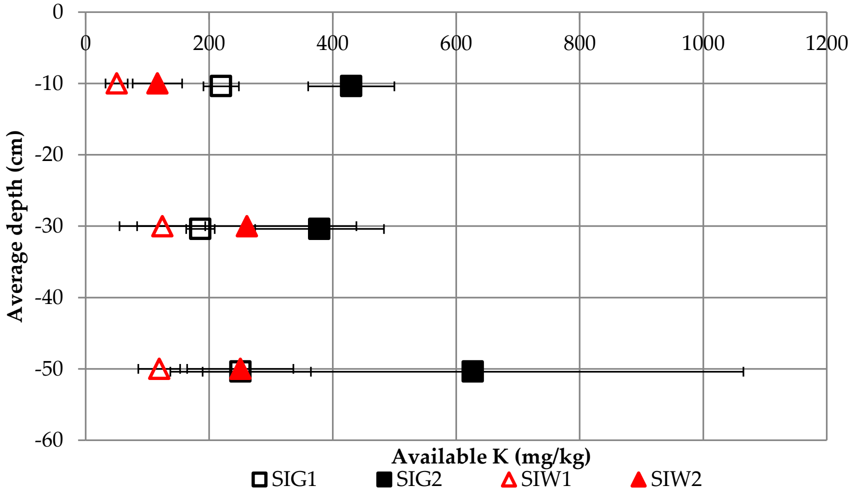

Figure 4.10. Available K concentration (mg/kg) in soil irrigated with wastewater (SIW) and groundwater (SIG) before planting (1) and after harvest (2).

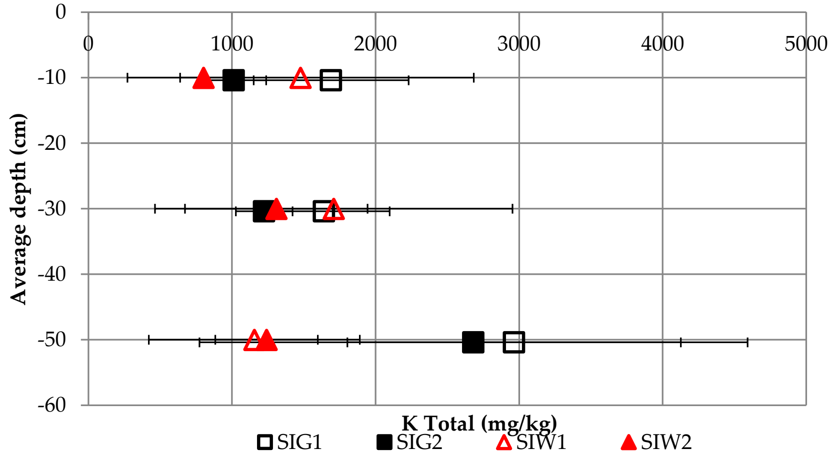

Figure 4.11. Total K concentration (mg/kg) in soil irrigated with wastewater (SIW) and groundwater (SIG) before planting (1) and after harvest (2).

The concentrations of total K for SIG and SIW were at same levels for the bottom layer before planting and after harvest, where the concentrations in SIG were higher than in SIW. For both SIG and SIW, the total K concentrations in the bottom soil layer remained unchanged during the experimental period. A drop was observed in the top layer of both SIW and SIG (Figure 4.11).

4.3.3. Manure Composition, Lettuce Yield and Nutrient Balances

The manure applied to the soils had a composition (g/kg) of N, P, and K in a ratio of 35.0:4.2:0.2 for wastewater-irrigated soils and 36.4:3.0:0.2 for groundwater-irrigated soils.

The lettuce yield (in tons/ha) in wastewater irrigated areas was higher, i.e., 43,8 ± 16 tons/ha, compared to the groundwater irrigated area, i.e., 35 ± 8 tons/ha. However, the variability in results was quite large and an independent T-test showed that there were no significant differences in produce yield found between the areas irrigated with groundwater and wastewater ($t(6) = 0.992$, $p > 0.05$).

The nutrient balances assessed in wastewater and groundwater irrigated areas revealed that the nutrient contents in wastewater were distinctly higher than those in groundwater (Table 4.5). Wastewater served as an essential nutrient source due to its nutrient content contribution during the cropping season and contributed for 88%, 96% and 97% of N, P and K to the total nutrient supply, respectively. While groundwater contributed for 23%, 76% and 75% of N, P and K supply, respectively. The remaining fraction of the nutrient supply was compensated by the farmers using manure as additional fertilizer (Table 4.5). Possibly, the supplied nutrients via irrigation water and manure might only be partly taken up by the plants, while the remainder leached to the underground. Nonetheless, the nutrient balances demonstrated that the soil nutrient content in the wastewater-irrigated areas, in most cases, was not depleted, in contrast to the groundwater-irrigated areas. The ratio nutrient input in relation to the 'required nutrient supply' was 0.3 and 2.3 for N, 1.3 and 11.4 for P, and 0.5 and 4.9 for K, for ground water and wastewater, respectively. Results presented in Table 4.5 showed that wastewater irrigated areas had positive nutrient balances, which may have influenced reduced nutrient depletion in the soils. In contrast, the groundwater irrigated areas exhibited accentuated decline in nutrient contents particularly for NO_3^-, available P, total P, and available K (Figures 4.5 and 4.8–10). Overall, negative balances were found for N, P, and K in groundwater irrigated areas. These findings suggest that wastewater irrigation contributed to nutrient supply, while groundwater irrigation without the application of manure, could lead to reduced nutrient content in the soil over time as this will lead to less pollution and flushing of nutrients underground. The amount of N uptake was higher than other nutrients, which was consistent with previous reports (Hawkesford et al., 2011; Jiaying et al., 2022) on N, P, and K uptake, showing nutrient contents of 1.5%, 0.2% and 1.0% in plants mass, respectively.

Table 4.5: Nutrient balances in wastewater (WW) and groundwater (GW) irrigated areas for lettuce production.

Irrigatio nSource	N_Inflow (kg/ha)		N_Uptake (kg/ha)	Ratio	Balance (kg/ha)
	Water	Manure			
GW	151.5	497	1973.6	0.3	−1324.4
WW	5086.0	714.1	2571.2	2.3	3229.6
	P_Inflow (kg/ha)		P_Uptake (kg/ha)	Ratio	Balance (kg/ha)
	Water	Manure			
GW	64.9	20.7	66.2	1.3	19.4
WW	981.6	43	90.0	11.4	934.6
	K_Inflow (kg/ha)		K_Uptake (kg/ha)	Ratio	Balance (kg/ha)
	Water	Manure			
GW	342.6	113.2	970.9	0.5	−515.1
WW	4910.6	163.2	1038.7	4.9	4035.1

4.4. Discussion

These results from our research showed that the crop yield in WW irrigated plots were somewhat higher than with GW irrigated plots. The observed differences between GW and WW were statistically insignificant. The average weight of lettuce in the wastewater site was consistently higher than in the groundwater site, providing evidence that better yields may be attainable when wastewater is used for irrigation. Nevertheless, it's important to consider that various other factors could have influenced the outcomes observed. The observed crop yield may be related to the pH and CEC, which was verified in both WW and GW irrigated plots. It was found that both GW and WW irrigation increased the soil pH profile, particularly in the top layer, a result consistent with previous work (Elmeddahi et al., 2016). This relatively high pH could have affected the negatively nutrient availability in both areas. Groundwater had a slightly higher pH than wastewater, with values ranging between 7.5–8.5 and 7–8, respectively. These values fall within the acceptable pH ranges of 6.5–8.5 for irrigation water (Elmeddahi et al., 2016). In addition, the EC values in irrigation water indicated slight to moderate salinity levels of 0.7–3 dS/m, as classified by Sainju et al. (Sainju, 2017). These soil salinity levels imply the possibility of salt accumulation in the soil on the long term, which may limit crop productivity (Ayers & Westcot, 1985). The relatively high pH may have affected the micronutrient availability, which was, however, not monitored in this study. It was also found that wastewater showed a higher nutrient content than groundwater, making wastewater a fertilizing agent of interest for these areas. The implication of a higher nutrient content in WW than GW is that soil stability in WW-irrigated crops will increase, making it more reliable for long term crop cultivation, while positively influencing the crop growth compared to GW irrigated areas. With the agricultural use of wastewater being part of appropriate nutrient management in the Infulene Valley, less nutrients would be lost to the environment, reducing environmental pollution such as eutrophication in the rivers and coastal marine areas. The observed values for pH, average nitrate and phosphate concentrations in wastewater were consistent with those found in previous studies in same area (Gulamussen et al., 2021). However, for ammonia the values differed, with higher averages in our study compared to previously reported (Gulamussen et al., 2021).

In this study, the soils irrigated with wastewater had a lower nutrients content than those irrigated with groundwater. The reason for this is that farmers in Infulene Valley use manure as a part of the nutrient supply, which also impacts the crop nutrient availability (Table 4.5). Therefore, the nutrient supply in this study was not solely from the irrigation water but also from manure. Comparisons of the amount of nutrients, i.e., nitrogen and phosphorous, applied from manure and irrigation water during the period of study of SIG was half the amount applied in SIW (Table 4.5), indicating variations in the nutrient supply in groundwater and wastewater irrigated plots. The manure composition used in these areas in the study was animal manure, which is often blended with other materials (Joshi et al., 2017; Khai et al., 2007). It can be argued that the long-term use of manure may increase the soil organic matter content and improve the soil quality, as observed in the groundwater irrigated soils.

Positive nutrient balances were found for wastewater irrigated areas regarding all evaluated nutrients and negative balances were found in groundwater irrigated areas for N, P, and K. These negative balances resulted from the difference between plant demand and the combined nutrient supply by irrigation water and manure. The balance revealed that the nutrient supply by water and manure might not satisfy the plant demand in groundwater irrigated areas on the long-term as demonstrated in Table 4.5. For SIW, there was a surplus of nutrient, which might have leached to the subsoil. The existing in-soil storage plays a role in explaining the changes after the harvest for both areas. Before planting, the SIG samples had higher nutrient content than SIW. However, nutrient reduction occurred after the harvest in the soil layers irrigated with groundwater (SIG), i.e., N, available P and available K. After harvest, nutrient concentration in SIW were lower than the SIG in some layers; i. e, for the bottom layer available P and total K, for the top layer of available K and for all layers total P.

Nonetheless, results showed an increase in nutrient content for NO_3^-, NH_4^+, total N, available K and total P in SIW. However, the nutrient content of available P remained unchanged, while the content of total K declined. The overall increase in nutrients content in the soil showed that the nutrient crop demand was not limited by nutrient supply in SIW. The positive nutrient balance in WW-irrigated sites is likely to have significant impact on both to the agricultural system productivity and the environment. On the long term, it may lead to reduced need for supplementary nutrient through manure or fertilizers. For instance, the OM in WW is expected to improve soil structure, and stability thereby enhancing crop production, promoting better crop growth, and increasing yields over time. WW irrigated areas require proper nutrient monitoring to reduce potential environmental pollution. The negative nutrient balance in GW irrigated areas will likely be detrimental to the soil, leading to soil nutrient depletion, negatively impacting crop production. Farmers will likely need the use more supplementary nutrients, such as manure or fertilizers, resulting in increased expenses, and potentially higher market prices. On the long run, this could affect the sustainability of the production in GW areas of the Infulene Valley.

To the extent of this study, the soil condition in terms of N, P, K concentration after harvest for SIW and SIG indicated the vital contribution of nutrients present in the wastewater in guaranteeing nutrient crop demand and soil nutrition in the area. In addition, it can be argued that the amount of nutrients present in manure, contributed to the crop yield and soil condition after harvest for both groundwater and wastewater irrigated areas. However, the amounts of nutrients present in the wastewater, compared to crop demand, indicated that the use of manure in wastewater-irrigated areas might not be necessary. It was found that the N, P and K content in the wastewater was 34, 15, and 14 times higher than in groundwater. These results clearly show that wastewater may be considered an additional source for crop nutrient supply, as previously suggested by other studies (Brito et al., 2014; Elmeddahi et al., 2016; Khai et al., 2007; Rezapour et al., 2021). Therefore, using wastewater for irrigation purposes offers interesting perspectives for replenishing nutrients removed during crop production. Hence, wastewater might be considered of interest for ferti-irrigation to benefit crop growth and reduce fertilizer dependency (Chauhan & Kumar, 2020).

Our findings corroborate with previous research (Khai et al., 2007; Qadir et al., 2020), highlighting the potential role of wastewater in nutrient supply in peri-urban areas, where wastewater is frequently used for irrigation, which is the case for areas in Infulene Valley. Moreover, in many parts of sub-Saharan Africa, lack of nutrient supply and fertilizers has been pointed as the cause for a low crop yield (Vitousek et al., 2009). Therefore, wastewater can be considered a reliable source of nutrients for crop production. However, concerns about the use of wastewater for irrigation due to the presence of heavy metals and microbial contaminations must be considered. Precautions should be taken to ensure the safe use of this irrigation water in agriculture, such as adequate treatment, implementation of safe practices in the field and during the irrigation and selling. Consumers should also take advanced measures in the cleaning of products irrigated with wastewater.

This study highlights the advantages associated with the use of wastewater for irrigation, particularly in the context of lettuce cultivation. One notable advantage is the nutrient supply provided by wastewater, which significantly benefits plant growth. However, it's crucial to acknowledge the impact of initial soil conditions on crop yield. Since, in this study the initial soil conditions in the wastewater site differed from those in the groundwater site, and this disparity likely played a role in achieving similar yields in both locations. Nevertheless, the wastewater site showed promising signs for better yields, as evidenced by the higher average weight of lettuce heads found there. To strengthen the validity of future studies and draw more conclusive results, its recommend standardizing soil conditions when comparing various irrigation methods. This practice will help researchers to better understand the true impact of nutrient-rich wastewater on crop production and ensure that their conclusions are based on more controlled and consistent variables.

In addition to the irrigation water, also the application of manure as organic fertilizer may have positively influenced the nutrient content in soil for both SIG and SIW. The balance calculations showed a potential disparity of nutrient supply and crop requirements when using wastewater for irrigation in Infulene Valley, which was also found by Boom et al. (Boom et al., 2008) in Jordan. Nevertheless, the results clearly demonstrated that the nutrient content in wastewater is sufficient to supply the crop nutrients demand likely leading to the observed better yields in WW irrigated crops. As found, with the weight of lettuce heads varied 0.33–0.5 kg/head and 0.2–0.36 kg/ha in wastewater and groundwater irrigated areas, respectively.

It should be noted that also manure played a role in nutrient accumulation in both SIG and SIW, while there is a surplus of nutrients supplied by wastewater, suggesting a possibility of nutrient accumulation in the soil. Results showed that initially (before planting) the analyzed soils (SIW) showed lower nutrient concentrations compared with the final soil condition (after harvest). Therefore, there is a need to properly manage the nutrient input from wastewater in Infulene peri-urban area to prevent nutrient losses, affecting the environment and groundwater resources. Previous studies indicated the potential risk of nutrient losses, resulting from wastewater irrigation (Werner et al., 2019), albeit wastewater irrigation may be considered a viable option for nutrient supplementation in lettuce production in Infulene Valley. Therefore, the implementation requires careful nutrient management to prevent environmental hazards resulting from excess nutrients dosing. A range of management options to prevent environmental problems and protect public health should be adopted. An example of such management option is combined source control with frequent water monitoring to aid decision making by managing the amount of nutrients supplied by irrigation water and manure (Qadir et al., 2010; Stewart et al., 2005). Additionally, measures can be taken at wastewater treatment works, which are appropriate for the region, such as wetlands or decentralized treatment.

4.5. Conclusions

The findings of our study suggest that wastewater can be considered a viable alternative for nutrient supply in Infulene Valley, Maputo. The analysis showed that wastewater contains higher amounts of essential nutrients (N, P, and K) compared to groundwater. Although soils irrigated with wastewater initially had lower nutrient content than those irrigated with groundwater, the wastewater-based nutrients compensated for the nutrient requirements for lettuce production and prevented nutrient depletion in the soils.

The relative contribution of groundwater and wastewater as nutrient sources varied significantly and the research has demonstrated substantial disparities in nutrient contributions between wastewater and groundwater as irrigation sources for meeting crop requirements. Wastewater emerged as a potent supplier of essential nutrients, with relative values of nutrient input versus output, 2.3 for Nitrogen (N), 11.4 for Phosphorus (P), and 4.9 for Potassium (K). In contrast, groundwater exhibited significantly lower nutrient contributions, with relative values of nutrient input versus output 0.3 for N, 1.3 for P, and 0.5 for K. These findings underscore the critical role of wastewater in enhancing nutrient supply for agricultural purposes.

These results highlight the potential of wastewater as an effective source for re-plenishing nutrients in agricultural systems. Utilizing wastewater for irrigation purposes not only helps to meet crop nutrient demands, but also reduces reliance on traditional fertilizers. However, careful nutrient management is crucial to avoid excessive nutrient dosing, which can lead to health and environmental hazards such as groundwater pollution, pollution of water ways and soil degradation. Implementing strategies such as combined source control, frequent water monitoring, and appropriate treatment options can help for ferti-irrigation in peri-urban areas like Infulene Valley.

Overall, this study provides valuable insights into the nutrient content of wastewater and impact on soil fertility and crop productivity. These findings have broader applications in various agricultural settings where wastewater is used for irrigation such as the importance of monitoring the amount of nutrient present in wastewater. To fully harness the benefits of wastewater irrigation while mitigating potential risks, further research on the long-term effects of wastewater irrigation and the implementation of appropriate nutrient management practices are essential. This research was conducted in real-world farmer field conditions to offer valuable insights into practical applications of water reclamation in Infulene Valley. It's important to acknowledge that these field conditions often involve less control over variables, which can introduce increased variability into the results. Nevertheless, this approach allowed us to bridge the gap between controlled experiments and real-world scenarios, providing a more comprehensive perspective on the subject.

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Chapter 5: Potential toxic elements in irrigated lettuce at Infulene valley;

Potential toxic elements in irrigated lettuce at Infulene valley;

Abstract

The aim of this study was to assess the presence and potential risks of potentially toxic elements contamination in lettuce irrigated with wastewater, groundwater and river water in the Infulene Valley. Irrigation water, soil, and lettuce samples were analysed with Inductively Coupled Plasma Optical Emission Spectroscopy (ICP OES) and X-ray fluorescence (XRF). The ICP OES measured the potentially toxic elements in water and plants and XRF in soils. The results showed potential contamination of manganese in water, and aluminium, iron, chromium and sodium in lettuce.

5.1. Introduction

The use of untreated or partially treated wastewater in agriculture could present risks to the environment and human health due to the presence of potentially toxic elements (PTE). PTE are heavy metals and other elements which may be toxic to soil and plants when present in quantities above certain thresholds (Pourret & Hursthouse, 2019). In Maputo, the capital of Mozambique, peri-urban agriculture is practiced in the Infulene Valley. The irrigation sources in use are untreated or partially treated wastewater, groundwater, and river water. Owning to the discharge of wastewater from local factories such as a paper manufacturing company and beer factory, the river water might be a source of pollution (Nhantumbo et al., 2023). Aluminium, petroleum, cement and chemical industries potentially release PTE such as lead (Pb), cadmium (Cd), chromium (Cr), manganese (Mn), nickel (Ni), and zinc (Zn) into the wastewater (Scarlet & Bandeira, 2014). Certain PTE, such as Cd and Pb, have known carcinogenic effects on humans (Hafeez et al., 2023).

Although the wastewater treatment plant (WWTP) in the Infulene Valley plays a crucial role in treating a portion of the generated wastewater from Maputo city, the effluent from this facility may still contain heavy metals and other pollutants (Scarlet & Bandeira, 2014). Consequently, the presence of PTE in irrigation water could pose risks of contamination to both crop production and human health, since, the consumption of contaminated crops may cause health problems (Orisakwe et al., 2012). Therefore, to assess the presence and potential risks of PTE contamination, we conducted a study on lettuce grown in the Infulene Valley, specifically focusing on lettuce irrigated with partially treated wastewater, river water, and groundwater. We examined the chemicals present in the irrigation water, soil, and lettuce, with a particular emphasis on evaluating their potential health impacts on consumers.

By studying the PTE, we aim to contribute to the understanding of the challenges posed by wastewater irrigation with partially treated wastewater in the Infulene Valley.

5.2. Methodology

5.2.1. Sampling procedure:

The study was conducted from July to November 2021 in the Infulene valley situated in Maputo city. The sampling period corresponds to two cropping seasons of lettuce production; the first cropping season from July to September, and the second cropping season from September to November. The sampling site and water sources in the area are described in (Niquice-Janeiro et al., 2024). Four study sites in the Infulene valley were used as sampling sites. Each study site had four replicates, to enhance the accuracy and reliability of the results. The study sites were selected based on their distinct qualities of irrigation water sources, i.e., river water, partially treated wastewater from the effluent of Infulene WWTP, and groundwater from two extreme points (stated as Groundwater A and B). At each location, soil, water, and plant samples were collected and taken to the Faculty of Agronomy and Forest Engineering (FAEF) of Eduardo Mondlane University (UEM) in Maputo for further preparation prior to the analysis.

Table 5.4: Sampling in Infulene valley

Type of Sample	Irrigation Water	Soil	Plant (root+shoot)
Nr Samples collected	120	192	16 sample shoot and 16 samples roots
Amount per sample	250 ml	0,5 kg	Three Lettuce heads with roots
Periodicity	Weekly collection (15 weeks)	Before Plant and after harvest	After harvest
Type of extra analyses	pH, Conductivity,	pH, Conductivity	
PTE tested	Aluminium (Al), Silicium (Si), chromium (Cr), Barium (Ba), Sodium (Na), strontium (SR), Sulphate (SO4), Phosphate (PO4), Arsenic (As), Calcium (Ca), Cadmium (Cd), Copper (Cu), Potassium (K), Iron (Fe), Lead (Pb), Magnesium (Mg), Manganese (Mn), Nickel (Ni), Phosphorus (P), Sulphur (S), and Zinc (Zn)		

We collected a total of 192 of soil samples in four layers (0-20 cm, 20-40 cm, 40-60 cm, and 60-80 cm) at each location to check the potential of lixiviation. Only for the first layer (0-20 cm), two samples were combined at each plot to create a composite sample to ensure representativeness of the sampling area. After the collection in the field, the samples were placed in plastic bags. Soil samples after collection were prepared at the FAEF, where they were air dried, then sieved to a size of less than 0.5 mm, and stored for further analysis. The samples were then shipped and analysed at the Micro2Macro lab of the Faculty of Civil Engineering and Geosciences at Delft University of Technology, the Netherlands.

In addition, a total of 120 irrigation water samples were collected weekly using the farmers' irrigating cans. These water samples were placed into sterile glass bottles of 250 ml, and stored in a cool box with ice packs for transportation until processing within 2-8 hours after collection. Water samples were prepared at the FAEF. After the collection of water samples, pH and electric conductivity were measured in the laboratory and then acidified with 2.5 ml of a solution of HNO_3 (65%), and stored in a refrigerator at a temperature of 5 ^{0}C to preserve the samples until analysis. Water analyses were conducted at the Waterlab at Delft University of Technology.

Furthermore, 32 lettuce samples (including roots) were collected to be tested for concentrations of heavy metals (see Table 5.4) . At each plot, three lettuce heads (including roots) were collected when ready for harvest, placed in plastic bags, and transported to the laboratory of FAEF. Samples were washed with tap water to remove soil and then air dried for 48 h to remove water excess. Following drying, the samples were chopped to separate the roots from the leaves. The samples were then packed in paper bags and placed in an oven at 60 ^{0}C, and removed after achieving a constant weight (Tariq, 2021). Next, the lettuce samples were milled to size less than 1 mm and stored until further analysis at Faculty of Mechanical Engineering at Delft University of Technology.

5.2.2. Laboratorial Analysis Procedure:

pH and electrical conductivity in water and soil

On arrival at the FAEF, the water and soil samples were measured for pH and electric conductivity. The water samples were then acidified. The pH and electric conductivity of the soil samples were measured in a soil-to-water suspension at a 1:2.5 ratio using a pH meter and electrical conductivity meter (Orion STAR A215, Thermo Fischer Scientific Inc., Kota Administrasi Jakarta Selatan, Indonesia).

Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) analysis of water and plant

Water and plant samples were analysed by means of Inductively Coupled Plasma Optical Emission Spectroscopy (SPECTRO ARCOS EOP, Spectro, Germany) at the process and energy laboratories at the Faculty of Mechanical Engineering at Delft University of Technology. The water samples prior to the analysis were filtered using a chromafil@Xtra PES-20/25. The samples were diluted to 1:100 using a 1% HNO_3 solution for ICP analysis.

Plant samples were digested (see supplementary material 1) prior to the analyses at the TU Delft Bioreactor laboratory at the Faculty of Mechanical Engineering, using the EPA Method 3052 (Da Silva et al.,2014). SRM spinach leaves 1570a (Becker, 1995) were used as reference material for quality assurance control certified by the National Institute of Standards and Technology (NIST). The digestion was performed in a Microwave where a volume of 9 ml of HNO_3 and 3 ml of HF were added to 0.5 g of well-mixed plant sample for a period of 40 minutes at a temperature of 180±5 ^{0}C. Following the digestion, samples were collected from the Microwave once the temperature was reduced to approximately 30 ^{0}C.

Preparation of soil pellets for analysis in XRF

Soil samples were analysed with X- ray fluorescence (XRF) for heavy metal content, determining the elemental composition of materials. Samples were milled until reaching particle a size ≤ ±50 μm for pellet making. The pellets were prepared using two binders: BOREOX ® to produce a coating layer and COREOX®, to ensure homogeneity during the compression. The preparation of 32 mm (weighing 8-10 g) pellets consisted in compressing 2.5 grams of BOREOX , then add for further compressing process, a mixture of 0.5 grams of COREOX and 2 grams of the soil samples. The soil XRF analysis was conducted at the laboratory of the Faculty of Mechanical Engineering of the Delft University of Technology.

5.2.3. Data Analysis

Principal component analysis (PCA) was used to cluster and characterize the data in the three matrices of water, soil, and plant to establish a common pattern considering the used irrigation sources and their respective location.

Further, PTE uptake was determined as the product of heavy metals in plant tissue (M) and plant biomass (W).

$$PTE\ uptake = M * W \qquad (1)$$

The Translocation Factor (TF) was used to measure if the PTE translocated from roots to shoots. When TF > 1 , the plant translocate PTE effectively from roots to shoots

$$TF = \frac{Concentration\ of\ PTE\ in\ Leaves_{shoots}}{Concentration\ of\ PTE\ in_{Roots}} \qquad (2)$$

PCA was performed to reduce the dimensionality for water, soil, and plant data . The analysis was conducted in R version 4.0.3 (2020-10-10) .

5.3. Results

5.3.1. Water and soil characteristics

pH and electrical conductivity in irrigation water

In the Infulene valley, three irrigation water sources were used to irrigate lettuce, namely groundwater (two locations), river water, and partially treated wastewater. In both cropping seasons, the partially treated wastewater consistently displayed a pH that was, approximately, one unit lower compared to those of other the irrigation sources (Figure 5.1). Additionally, all irrigation water sources exhibited elevated electrical conductivity levels surpassing 0.75 dS/cm, indicating a high salinity, observed in all water sources regardless of their origin. However, partially treated wastewater and river water irrigation demonstrated higher electrical conductivity values compared to those of groundwater irrigation sources across both seasons. The pH and electrical conductivity values were consistent with those previously found in the study area for groundwater (7.92 ± 0.25 and 1.95 ± 0.69 dS/m), partially treated wastewater (7.40 ± 0.29 and 1.84 ± 0.24 dS/m), and river water (7.07 ± 0.05 and 1.22 ± 0.41 dS/m) (Nhantumbo et al., 2023; Niquice-Janeiro et al., 2023). A previous study has reported an interface of fresh/salty water, located 500m from the Maputo coast (Cendón et al., 2020). Another study has demonstrated that high salinity such as inland brackish/salt groundwater is caused by mixing freshwater with seawater trapped within clay layers, and that brackish/salt surface waters result from seepage of brackish groundwater into rivers and wetlands, followed by evaporation (Nogueira et al., 2019). These findings underscore the specific challenges associated with partially treated wastewater irrigation, including low pH levels and high salinity, which could potentially impact agricultural practices and crop health.

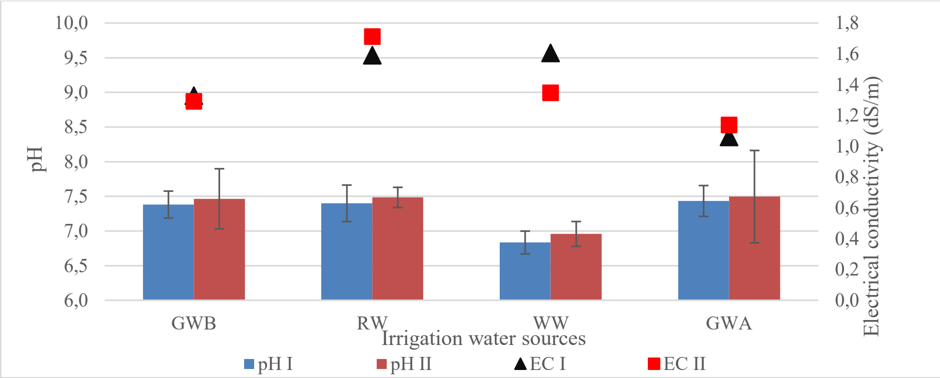


Figure 5.1. pH and electrical conductivity of irrigation water sources (Groundwater A and B, wastewater and river water) in cropping season I and II.

pH and electrical conductivity in soil

The pH patterns observed in soils irrigated with different water sources varied . For example, pH of the soil irrigated with partially treated wastewater ranged from 8.5 to 9.2 and increased with depth (Figure 5.2 D). Conversely, the pH of soil irrigated with river water, ranged from 7.7 to 8.5 and decreased with depth (Figure 5.2 C). Soils irrigated with groundwater did not exhibit a consistent pattern as the pH ranged from 7.5 to 9 across different depths (Figure 5.2 A and B). In addition, the difference in pH values of soil irrigated with groundwater may be influenced by the location of the fields where the samples were taken. In addition, the farmers usually bring soil from other locations to prepare their field beds, which may affect the pH characteristics of the soil.

The electrical conductivity values of the soil did not demonstrate a distinct pattern with depth for most of the study areas, except for the study area using partially treated wastewater as a source, which showed an increase in electrical conductivity with depth (Figure 5.2 D). Groundwater irrigated soils (Figure 5.2 A and B) showed a lower electrical conductivity compared to both river irrigated soils (Figure 5.2 C) and treated wastewater irrigated soils.

Overall, the pH and electrical conductivity values were consistent with ranges reported in a previous study on the use of the partially treated wastewater for irrigation (Niquice-Janeiro et al., 2023). However, in the present study lower electrical conductivity values with groundwater were found. Specifically, the pH and electrical conductivity ranges in the current study were 8.0 to 8.4 and 0.3 to 0.65 dS/m for treated wastewater, and 8.2 to 9.0 and 0.4 to 0.8 dS/m for groundwater, respectively.

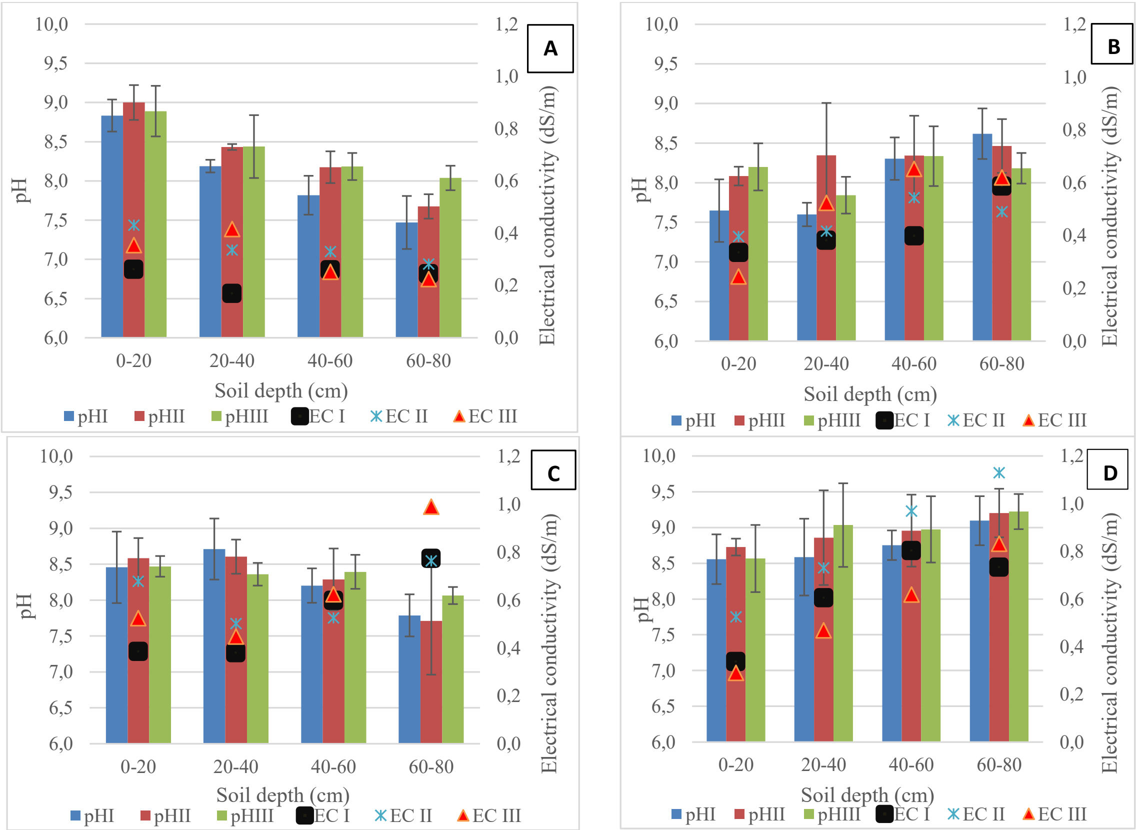


Figure 5.2: Soil pH and EC at different depth in soils irrigated with different water sources in sampling I, II and III. Panel A, B, C and D corresponds to soil irrigated with groundwater A, groundwater B, river water and wastewater, respectively (suplementary material table 2.1-2. 3).

5.3.2. PTE concentrations in water, soil and lettuce

PTE in irrigation water

PCA was applied to evaluate the similarities in the presence of PTE in irrigation water, with PC1 and PC2 accounting for 33.3% and 23.3% of the dataset's variance, respectively, together explaining 56.6% of the total variance. Through the PCA biplot, four major groups can be identified. The PCA biplot represents observations from different water sources relative to the measurement of the 109 water samples by ICP-OES (Figure 5.3).

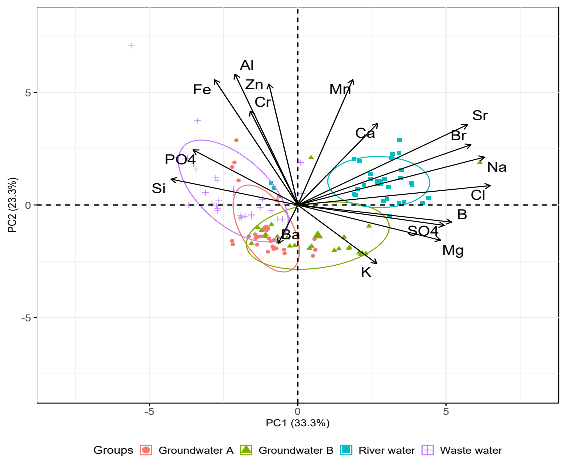


Figure 5.3. Principal component analysis PTE (Al, Fe, Si, Mn, Zn, Cr, Ca, Mg, Ba, K, Na, Sr, Br, Cl, SO4, PO4) in irrigation water(Groundwater A, Groundwater B, River water and Wastewater) as affected by source of water of 109 water samples from Infulene Valley. Arrows represent variables that contribute to the principal components (PC1 and PC2). Individuals (Groundwater A, Groundwater B, River water and Wastewater) close to each other have similar concentration of chemical elements, whereas individuals far apart differ.

Overall, groundwater A shared similarities with groundwater B, but displayed a lower content of most of the chemical elements. The chemical composition of the river water differed from that of the other water sources, and presented a high content of Na, Sr, Br , Mn and Cl, and a low content of Si, PO_4 as explained by PC1. The treated wastewater contained high concentrations of

Fe, Al, Zn, Cr, PO_4 and Si as explained by PC2. Strong and positive correlations were found among elements described by PC 1 such as, Sr, Br, Na, Cl, as well as among elements described by PC2 such as Fe, Al, Zn and Cr. However, no correlation was observed between the groups of elements described by PC1 and PC2. In addition, strong and negative correlation were found between SO_4 and PO_4 in PC1. In PC2, the elements Fe and K exhibited a negative correlation as well as Mn and Ba, respectively. Some of these elements are essential for plant growth such as Fe, K, Mn, Zn while others are harmful for crop development, such as, Sr, Br, Ba and Cr. Since river water is also used for irrigation and exhibted high Sr levels, it could result in the contamination of irrigated crops, considering that Sr is a non-essential element for crops, and its mobility in plants can cause harmful effects to humans. However, the level of Sr contamination also depends on the abiotic and biotic factors such as chemical soil composition and pH, temperature, and agricultural soil cultivation (Burger & Lichtscheidl, 2019).

The PTE concentration in irrigation water differed from season 1 to season 2 in groundwater A and groundwater B, whereas for river water and treated wastewater some similarities in concentrations of some PTE were found, as shown in Figure 5.4.

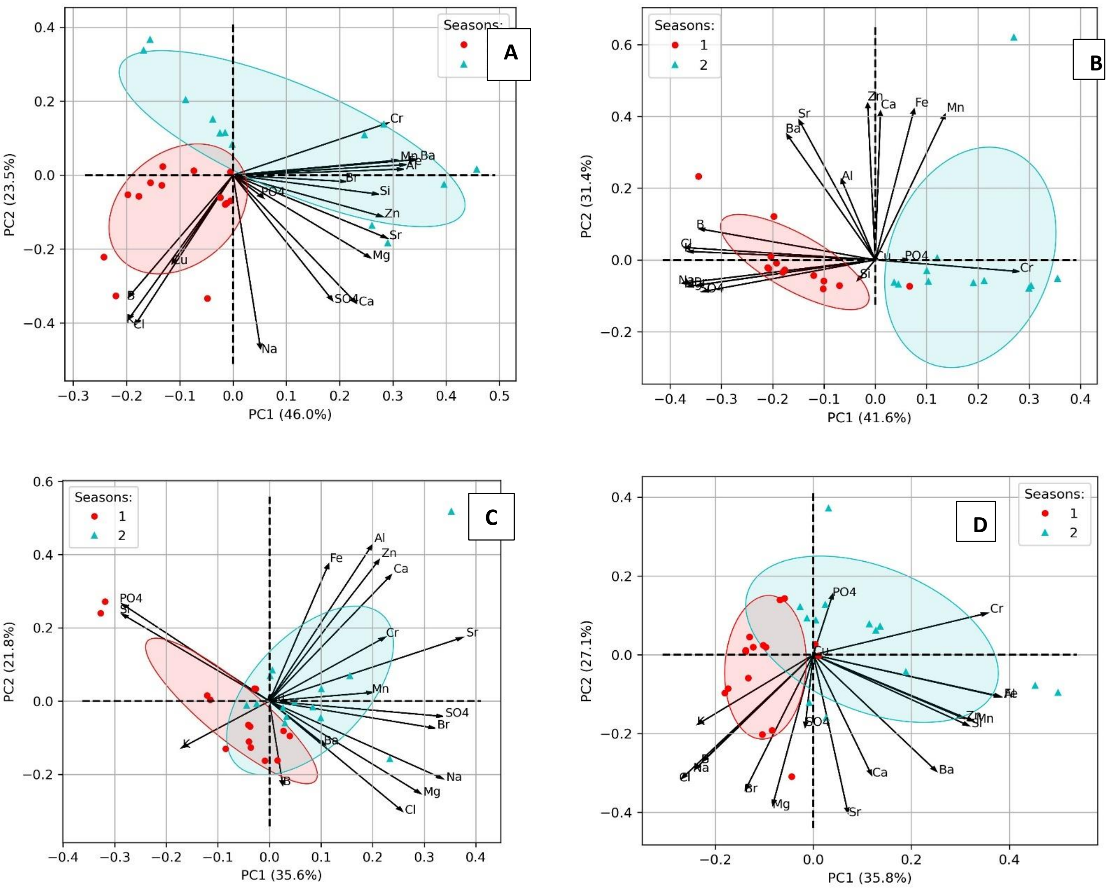


Figure 5.4: Principal component analysis of PTE (Al, Fe, Si, Mn, Zn, Cr, Ca, Mg, Ba, K, Na, Sr, Br, Cl, SO4, PO4) in groundwater A, groundwater B, river water and wastewater from Infulene Valley represented in Panel A, B, C and D, respectively

The mean concentrations of chemicals found in groundwater, river water, and partially treated wastewater sources of the Infulene valley are presented in Figure S4.2 panel A to C (Supplementary materials) based on cropping seasons I and II. Among the different chemicals found, B and Zn are essential micronutrients for plant growth and their concentrations were below the limits for plant toxicity. Cr is not an essential nutrient, and in all the irrigation sources the concentrations were below the limits. Mn stands out as a particular concern, especially for irrigation with river water in both cropping seasons, where it surpasses the threshold limits of 0.2 mg/l. Additionally, in partially treated wastewater an increasing trend of Mn occurrence was observed. However, the concentrations of Mn in groundwater A and B, respectively, remained below acceptable limits.

Al, Fe, Si, PO_4 and K, essential nutrients for crop development, showed concentrations within 4 to 40 mg/l. SO_4, Cl, Na, Mg and Ca were found in concentrations exceeding 40 mg/l, and in particular, Na presented concentrations above 100 mg/l for all irrigation sources in both cropping seasons, but all elements were below the limits for plant toxicity.

All irrigation water sources presented medium sodium adsorption rate (SAR), (see Table 5.5), although the SAR of river water was outside the ranges of 0-15 meq/l, which is considered to be adequate for irrigation of suitable crops and soil types according to FAO (Ayers and Westcot, 1985).

Table 5.5: Sodium adsorption rate (SAR) in meq/l of the Infulene valley irrigation water sources for the I and II cropping season

Irrigation water sources	SAR I	SAR II	Irrigation water sources	SAR I	SAR II
Groundwater A	9,35	8,55	River Water	17,1	19,29
Groundwater B	12,6	9,8	Partially treated wastewater	10,29	7,26

PTE in soil

The PC1 and PC2 accounted for 31.2 % and 14.2% of the variance of the dataset, respectively, explaining a total of 45.4 % of the variance of 187 soil samples measured by XRF. The results thereof are represented in the PCA biplot (Figure 5.5). Overall, no differences were found in the PTE concentrations of soils irrigated with Groundwater A and B, which presented high concentrations of Zr, P, K, Cu, Ba and Zn, as explained by PC2. The concentrations of most PTEs found in soils irrigated with river water was lower, whereas soils irrigated with treated wastewater displayed higher concentrations of Na, Fe, Al, Mn, Rb, Mg, Sr, Ca, S and Cl, as explained by PC1 and PC2.

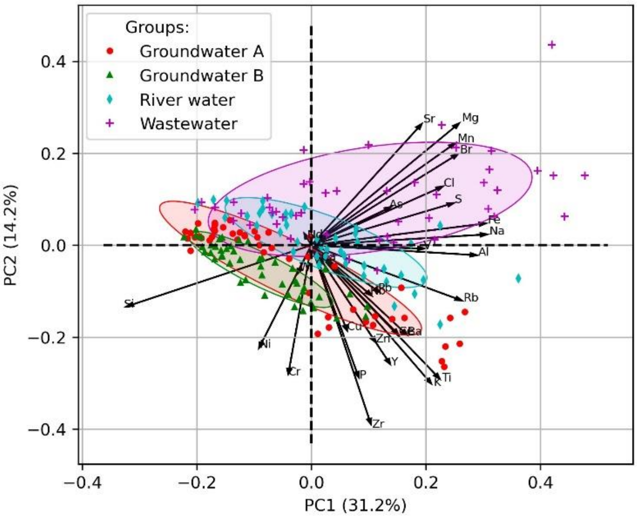


Figure 5.5. Principal component analysis of PTE (Al, Fe, Mn, Zn, Cu, Cr, Ca, Ni, Zr, Mg, Ba, Ti, Rb, K, Na, Sr, Br, Cl, P, S) in soil as affected by different water source of 187 samples from the Infulene Valley. Arrows represent variables that contribute to the principal components (PC1 and PC2). Individuals (Groundwater A, Groundwater B, River water and wastewater) close to each other have similar concentration of chemical elements, whereas individuals far apart differ.

Strong and positive correlations were found between Mg, Sr, Mn and Cl, with no correlation between these and Zr, P, Cu, Zn, Ba, K, Ba and Ti, explained by PC2. In addition, strong and positive correlations were found between Al, Na, Fe, S, and Rb as explained by PC1 (Figure 5.5).

The soil samples were also compared within the stage sampling before cropping and after harvest. Therefore, samples were collected before and after the first and second cropping season identified as sampling 1, 2 and 3 from soils irrigated with groundwater A, groundwater B, river water and partially treated wastewater (Figure 5.6 A to D). The PCA showed no difference between sampling 1 and 2 in all analysed soils, suggesting that the PTE concentrations in the soil remained relatively constant regardless of the irrigation source (Figure 5.6). However, especially for the groundwater sources differences were noted in the PTE concentration of the soil for sampling 3, indicating that the soil chemistry changed in cropping season II, compared to the first cropping season.

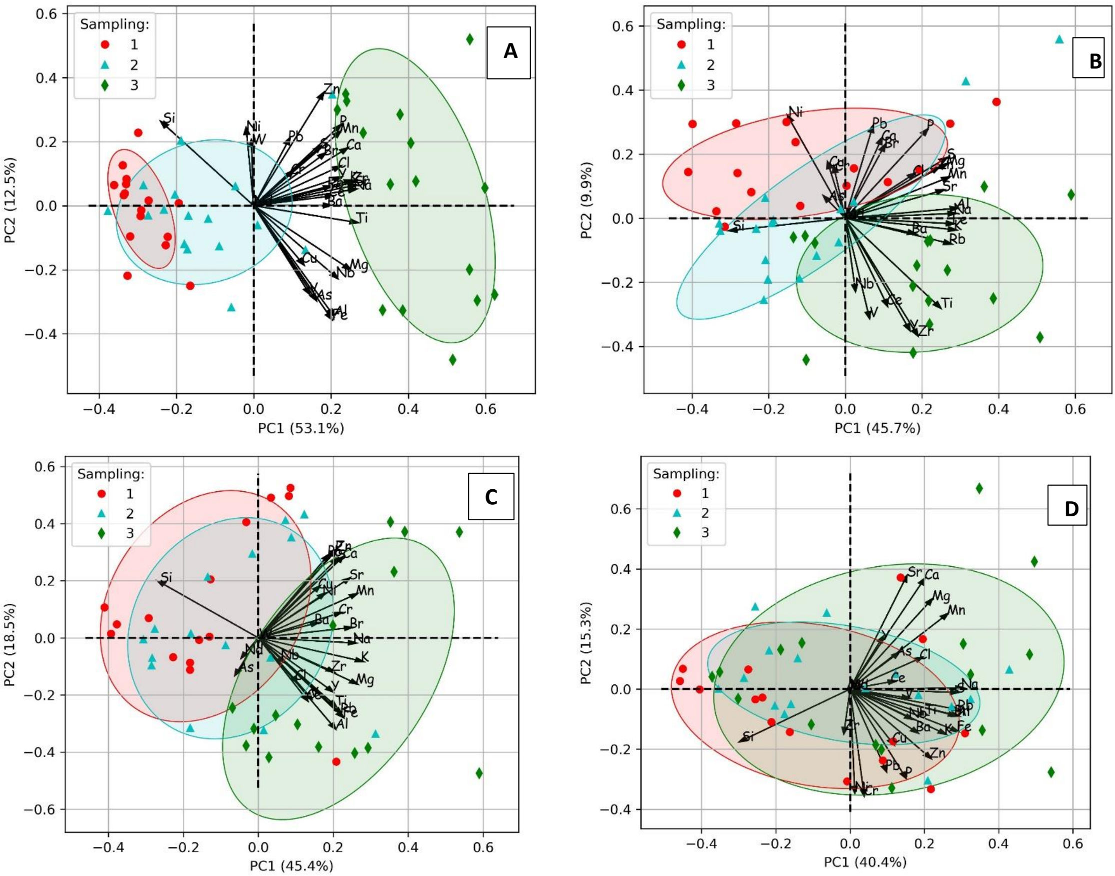


Figure 5.6. Principal component analysis of PTE (Al, Fe, Mn, Zn, Cu, Cr, Ca, Ni, Zr, Mg, Ba, Ti, Rb K, Na, Sr, Br, Cl, P, S) in soil from Infulene Valley irrigated groundwater A, groundwater B, river water and wastewater represented in Panel A, B, C and D, respectively. Arrows represent variables that contribute to the principal components (PC1 and PC2). Individuals (Sampling 1, Sampling 2 and Sampling 3) close to each other have similar concentration of chemical elements, whereas individuals far apart differ.

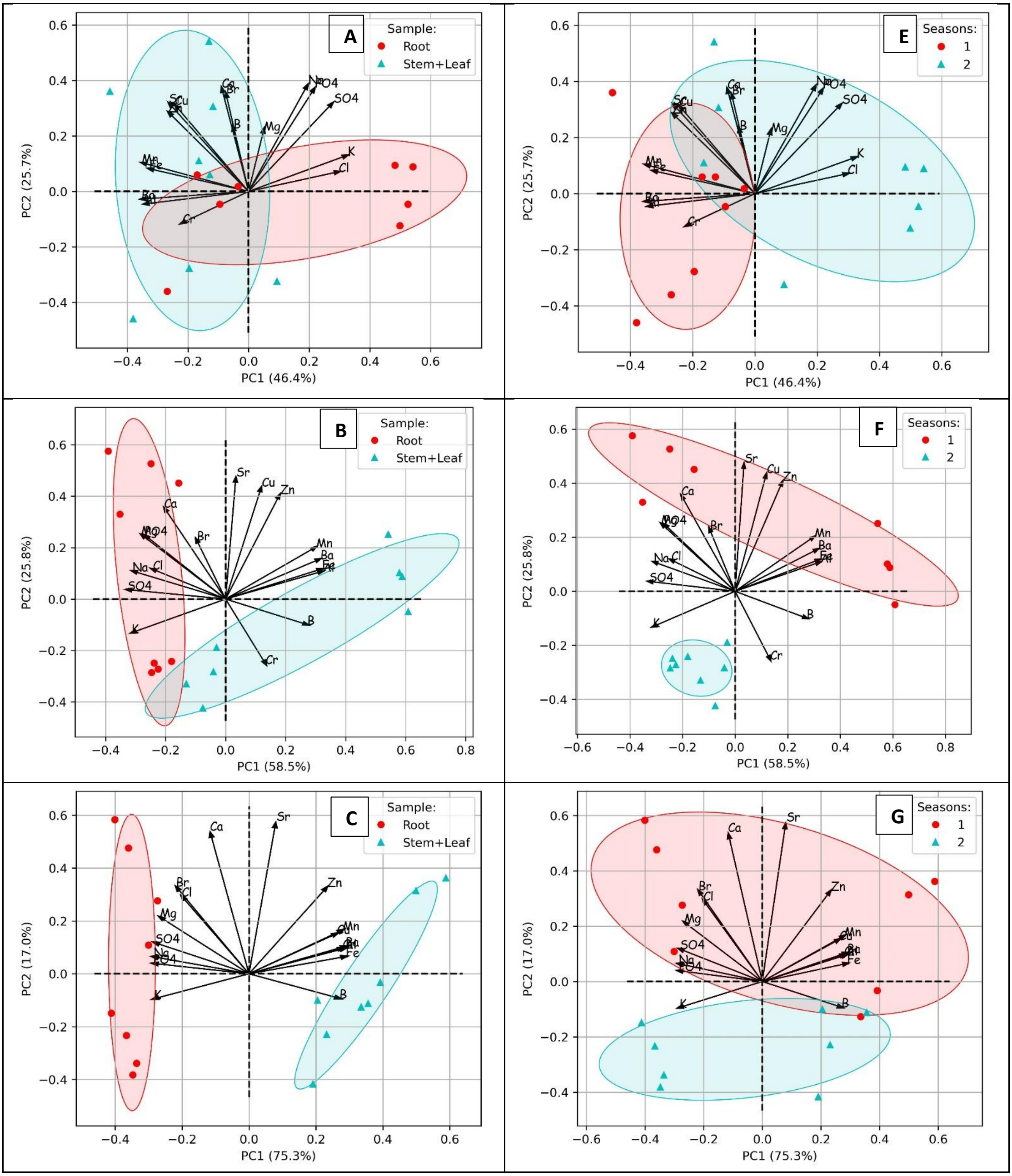
PTE in lettuce

Lettuce irrigated with partially treated wastewater, groundwater and river water presented concentrations of Ca, Sr, Cu, Zn, Mn, Al, Cr, Ba, Fe, K, SO4, Cl, Na, PO_4 and Mg. The elements Ca, Cu, Zn, Mn, Fe, K, SO_4, Cl, Na, PO_4 and Mg are essential for crop development, while others, such as Ba, Sr, Cr, Al and Br, are not.

Results from PCA, PC1 and PC2 account for 16.1% and 58.3% of the variance of the dataset, respectively, explaining a total of 74.4% of the datasets variance (Figure S5.1 supplementary materials). We did not find differences in PTE concentrations in lettuce among the different studied irrigation water sources. Lettuce irrigated with river water and partially treated wastewater presented the highest concentrations of the elements Al, Sr, Cu, Mn, Ba, Fe and Cr.

Moreover elements Sr, Cu, Mn, Zn, Al, Ba, Fe, and Cr tended to be more concentrated in the roots, whereas Mg, PO4, Na, Cl, SO4, and K tended to be more concentrated in the leaves. This differentiation in chemical composition between roots and leaves highlights the dynamic uptake and transport processes the lettuce.

Figure 5.7 panel A to D shows differences in concentrations of the PTE between the roots and leaves of lettuce produced in the Infulene valley, by irrigation source. Groundwater A and B presents overlaps of some of PTE present in roots and leaves. This observation applies for both essential and non-essential PTEs across two cropping seasons (Figure 5.7 panel E to H). Specifically, an overlap in chemical parameters appears to exist between season 1 and 2 for lettuce irrigated by groundwater A and by river water, indicating distinct chemical compositions based on the irrigation source.


A
Sample:
Root
Stem+Leaf
PC1 (46.4%)
PC2 (25.7%)
E
Seasons:
1
2
B
PC1 (58.5%)
PC2 (25.8%)
F
C
PC1 (75.3%)
PC2 (17.0%)
G

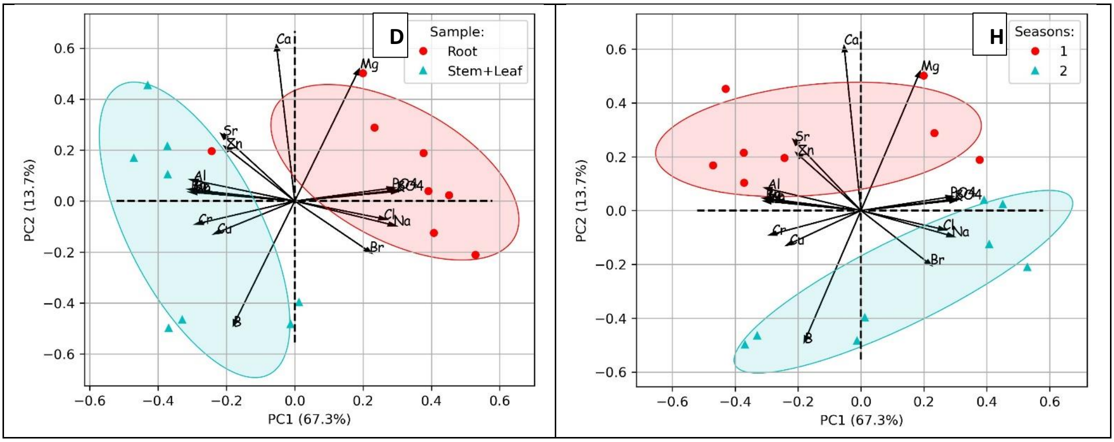


Figure 5.7. Principal component analysis of PTE (K, S, Cl, Na, P, Mg, Ca, Sr, Cu, Zn, Mn, Al, Fe, Ba, Cr) in lettuce irrigated with groundwater A, groundwater B, river water and wastewater from Infulene Valley in Left: respective to of lettuce root and Leaf panel A, B, C and D and Right: respective to lettuce cropping seasons panel E, F, G and H. Arrows represent variables that contribute to the principal components (PC1 and PC2). Arrows represent variables that contribute to the principal components (PC1 and PC2).

Figure 5.8 to Figure 5.11 present concentrations of PTEs found in lettuce, which varied with the type of irrigation source. B, an essential nutrient for the crops, was only present in lettuce irrigated with partially treated wastewater. Cu was present in lettuce irrigated with groundwater in concentrations below the recommended values (1-5 mg/kg) for at least one season (Figure 5.8), whereas for river water and treated wastewater the concentrations were within the acceptable levels (Figure 5.10).

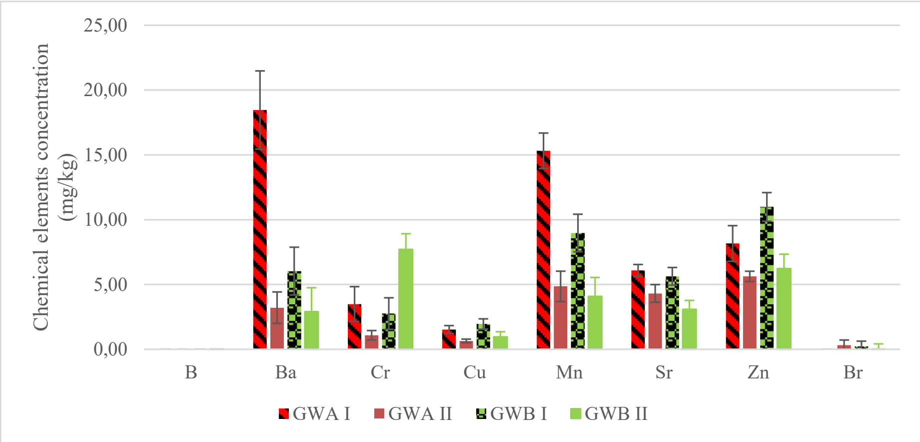


Figure 5.8. PTE concentration (mg/kg) in lettuce irrigated with groundwater (GWA and GWB) in Infulene, in cropping season I and II in Valley, Maputo, Mozambique.

Concentration of Mn was highly variable among the irrigation sources. Groundwater A (Figure 5.8) and partially treated wastewater (Figure 5.10) presented sufficient concentrations in at least one season, although Mn might become deficient in the following seasons.

Zn, another essential element, presented concentrations within the limits for river water, whereas for other irrigation sources the concentration was below the recommended levels. In contrast, concentrations of Fe tended to be in toxicity levels for lettuce irrigated with partially treated wastewater (Figure 5.11).

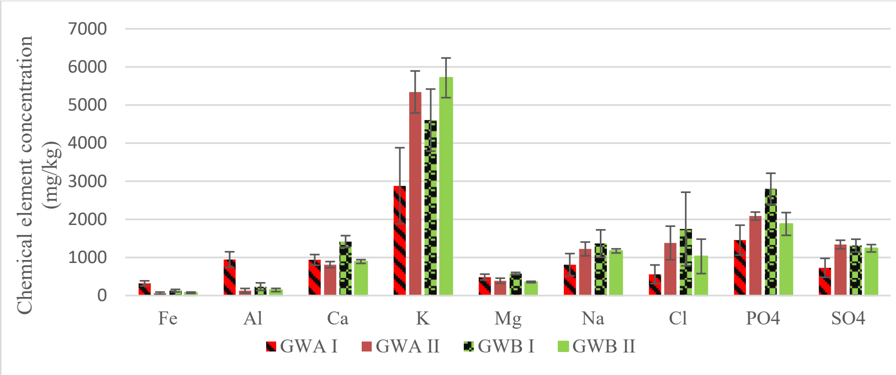


Figure 5.9: PTE concentration (mg/kg) in lettuce irrigated with groundwater A and B in cropping season I and II in Infulene, Valley, Maputo, Mozambique.

Concentrations of Ca, Cl and K were found to be within the limits for all irrigation sources. However, concentrations of Mg in lettuce were below the recommended limits, showing deficiency for this essential nutrient (Figure 5.9 and Figure 5.11).

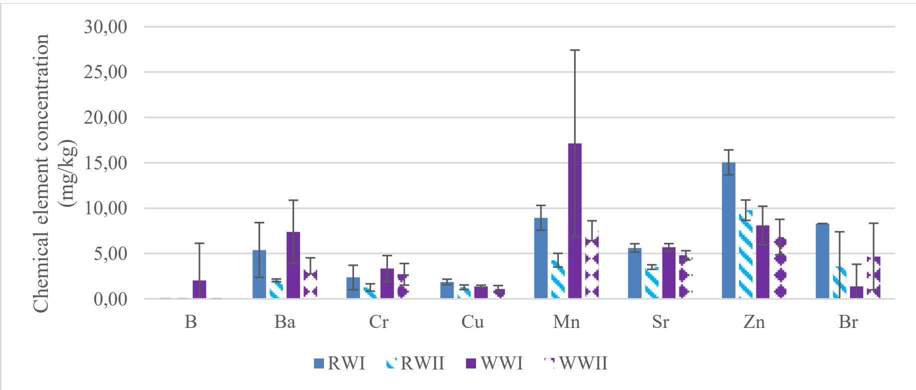


Figure 5.10: PTE concentration (mg/kg) in lettuce irrigated with river water(RW) and wastewater(WW) in cropping season I and II in Infulene, Valley, Maputo, Mozambique.

Furthermore, concentrations of Cr and Al were found at toxicity levels across all irrigation sources (Figure 5.8 and Figure 5.10). Despite being a beneficial nutrient in lettuce, the concentration of Na were also at toxicity levels for river water and treated wastewater, almost reaching 2000 mg/kg (Figure 5.11).

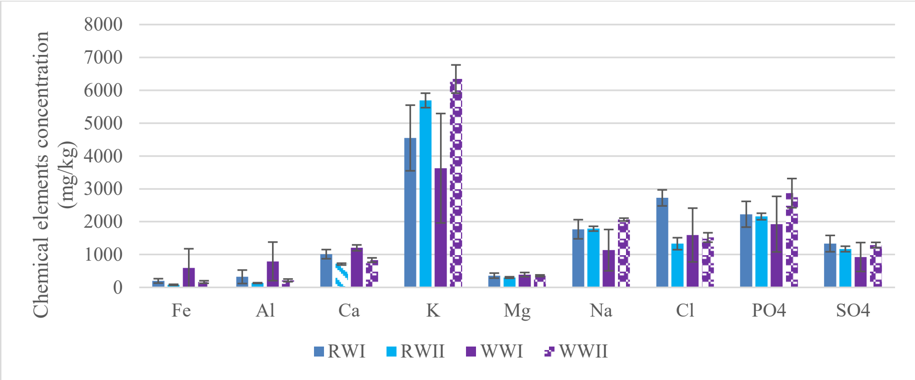


Figure 5.11: PTE concentration (mg/kg) in lettuce irrigated with river water(RW) and wastewater(WW) in cropping season I and II in Infulene, Valley, Maputo, Mozambique.

The presence of Mn, Ba and Zn is also a concern with concentrations above 5 mg/kg for the treated wastewater and river water irrigated lettuce (Figure 5.10). Long exposure to these elements can cause harm to human health.

Table 5.6: Average concentration (mg/kg) of PTE of concern in irrigated lettuce valley

Irrigation sources	PTE concentration (mg/kg) in lettuce in 1st and 2nd cropping season							
	Cr		Fe		Al		Na	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Groundwater A	3.5	1.08	318.9	63.0	944.1	127.0		
Groundwater B	2.8	7.7			233.3	145.4		
River water	2.4	1.26			322.6	132.8	1770.1	1787.1
Wastewater	3.4	2.771	589.4	164.5	792.8	213.9	1133.7	2064.4
Limits	1-2		>500		40-200		2000-5000	

Translocation factor (TF)

TF exhibited a large variability across different irrigation water sources (Figure 5.12 A to D). Na, Al, Cr and Fe presented the possibility of being translocated to leaves and consequently being a concern for consumers. Cr also exhibited a TF higher than 1 in one cropping season for lettuce irrigated with groundwater, indicating effective translocation to the leaves. This contrasted with treated wastewater and river water irrigation, where TF values for Cr remained below 1 in both seasons. Al only presented TF value greater than 1 in groundwater A.

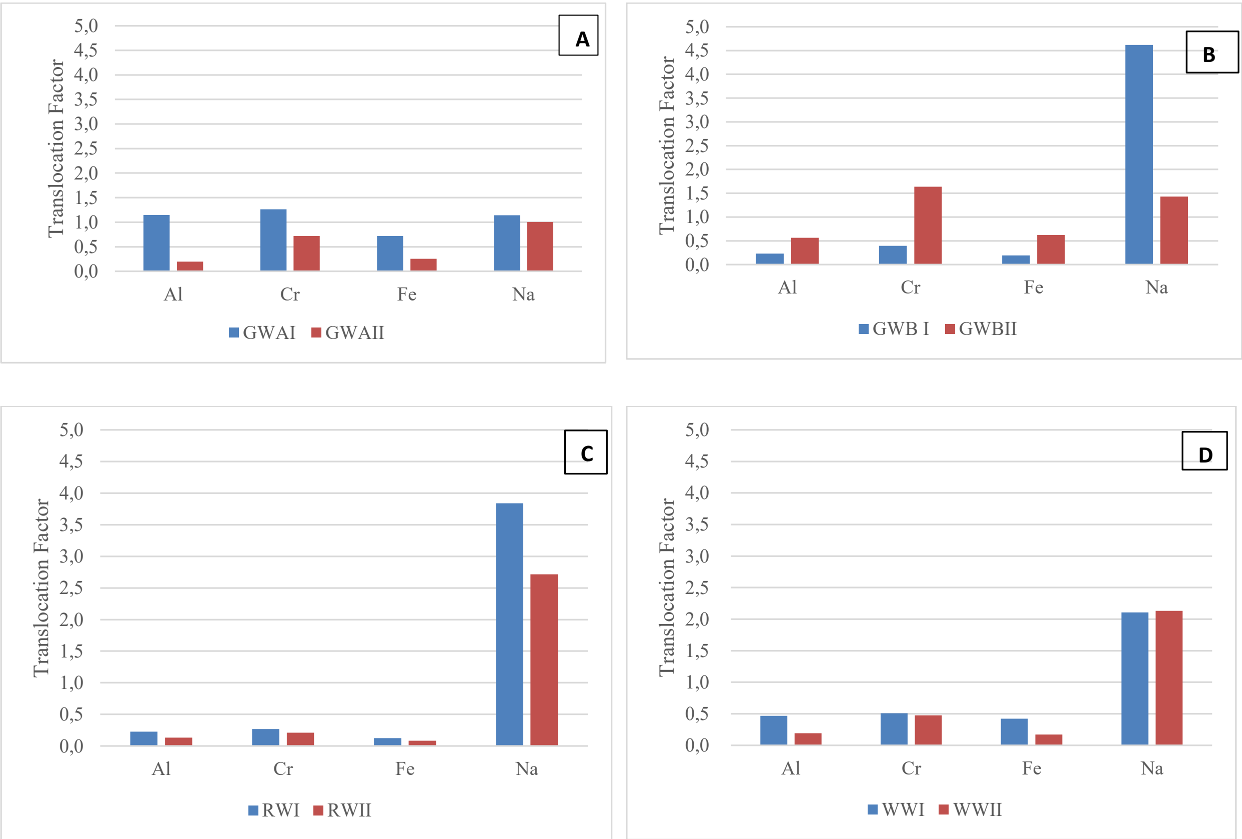


Figure 5.12: Translocation factor for lettuce irrigated with groundwater A, B, river water and wastewater in cropping season I and II in Infulene valley. Panel A, B, C and D represents the lettuce irrigated by groundwater A, B, river water and wastewater

5.4. Discussion

In this study, we analysed the soil, plants, and water to detect PTEs content, which include both essential and non-essential elements. Heavy metals, being part of PTE, have a potential to adversely affect plant health and soil structure, in accordance with findings from Hussain et al. (2002).

Electrical conductivity was measured in soil and water samples across different cropping seasons and irrigation sources and consistently exceeded the recommended limits set by the FAO (Bauder et al., 2007; Ayers and Westcot, 1985). The elevated salinity levels is also evident in the Na concentrations, surpassing permissible limits with risk of soil degradation and possible challenges for agricultural productivity (Khalid et al., 2018). In addition, the elevated sodium adsorption ratio (SAR) levels observed in river water points to potential consequences for soil and crop health, necessitating careful monitoring in irrigation strategies. The differences in chemical composition highlight the impact of different irrigation sources on soil chemistry, especially over multiple cropping seasons, to ensure sustainable agricultural practices and soil health.

Interestingly, Cr and Al concentrations exceeded recommended limits in some lettuce samples while, the presence of Cr and Al was not attributed to irrigation water sources. Cr occurs in the environment as a result of fossil fuels burning fertilizer use (Jaishankar et al., 2014). When Cr in plants exceeds the toxicity limits, it affects plant growth, leaf chlorosis and germination, due to phytotoxicity (Jaishankar et al., 2014). Al toxicity is affected by the water pH and organic matter content. The Al toxicity increases when the water pH is low and the of organic matter is high (Jaishankar et al., 2014).

Fe was found in high concentrations in the soil, lettuce and partially treated wastewater samples. Children are likely to be more affected by Fe than adults when they are exposed to products contaminated with Fe (Jaishankar et al., 2014).

Overall, the irrigation water presented high values of electrical conductivity. PTE found in lettuce is not attributable to the irrigation water rather the anthropogenic activities and environment.

5.5. Conclusions

Irrigation water may have impact on the soil chemistry which changes over time. PTE elements were found in low concentrations in the analysed water matrices. However, chromium, aluminium, iron and sodium exceeded the recommended levels in plants, suggesting sources unrelated to irrigation water. Additionally, elevated SAR and electrical conductivity levels across irrigation sources emphasize the need for cautious use of all sources in the Infulene valley, including partially treated wastewater for irrigation.

The high concentration of certain PTE when using river water and partially treated wastewater revealed the need for monitoring and understanding the elemental composition of crops, especially when different irrigation sources are used. Therefore, careful management practices are essential to sustainably manage cropping systems amidst potential contaminant risks.

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ANNEXES (Supplementary material)

1. **Digestion Method and Water analysis**

Lettuce Microwave digestion procedure

APPARATUS

Microwave digestion apparatus

Teflon tubes (45 ml) capable of withstanding pressures of at least 30 atm (30 bar or 435 psi)

Volumetric ware, volumetric flasks, and graduated cylinders, 50 and 100 mL capacity

Filter paper, qualitative or equivalent

Filter funnel, polypropylene, polyethylene or equivalent.

Analytical balance, of appropriate capacity, with a ± 0.0001 g

REAGENTS : HNO3 +HF

PROCEDURE

Prepare acid blanks for each digestion performed + Prepare reference samples

1. Weigh 0.5 g of a well-mixed sample (For blanks =no sample)
2. Add 9 ± 0.1 mL concentrated nitric acid(65%) and 3 ± 0.1 mL concentrated hydrofluoric acid to the vessel in a fume hood
3. Weigh the mixture before digestion and record the value
4. Insert the vessel into the Microwave: The total digestion time is 15 minutes which; The temperature of each sample should rise to 180 ± 5 ºC in approximately 5.5 minutes and remain at 180 ± 5 ºC for 9.5 minutes.
5. At the end of the Microwave program, allow the vessels to cool for a minimum of 5 minutes before removing them from the Microwave system. When the vessels have cooled to near room temperature, determine if the Microwave vessels have maintained a seal throughout the digestion. Due to the wide variability of vessel designs, a single procedure is not appropriate: If the weight loss of sample exceeds 1% of the weight of the sample and reagents, then the sample is considered compromised.
6. Complete the preparation of the sample by carefully uncapping and venting each vessel in a fume hood.
7. Transfer the sample to an acid-cleaned bottle. If the digested sample contains particulates which may clog nebulizers or interfere with injection of the sample into the instrument, the sample may be centrifuged, allowed to settle, or filtered. (refer to procedure for appropriate agitation and filtration recommendation)
8. Transfer or decant the sample into volumetric ware and dilute the digest to a known volume (50 ml when 0.5 g of sample used)
9. Calculations: The concentrations determined are to be reported on the basis of the actual weight of the original sample.

Water analysis

At collection, acidify entire sample with 5 mL conc HNO3/L sample. To prepare sample, mix well, transfer 100 mL to a beaker or flask, and add 5 mL 1 + 1 high-purity HCl. Heat 15 min on a steam bath. Filter through a membrane filter (preconditioned as in Section 3030B) and carefully transfer filtrate to a tared volumetric flask. Adjust volume to 100 mL with metal-free water, mix, and analyze. If volume is greater than 100 mL, determine volume to nearest 0.1 mL by weight, analyze, and correct final concentration measurement by multiplying by the dilution factor (final volume ÷ 100).

2. pH in soils

Table2.1:Soil pH before the first crop season in soils irrigated with different irrigation water.

Group 1	Water sources			
Depth(cm)	GW B	RW	WW	GW A
0-20	7.65 ± 0.11	8.46 ± 0.50	8.56 ± 0.35	8.83 ± 0.20
20-40	7.60 ± 0.27	8.71 ± 0.43	8.59 ± 0.54	8.19 ± 0.08
40-60	8.30 ± 0.15	8.20 ± 0.24	8.75 ± 0.21	7.82 ± 0.25
60-80	8.62 ± 0.34	7.79 ± 0.29	9.09 ± 0.34	7.47 ± 0.34

Table 2.2: Soil pH after the first crop season in soils irrigated with different irrigation water. This data also are equivalent to before second crop season.

Group 2	Water sources			
Depth(cm)	GW (B)	RW	WW	GW A
0-20	8.08 ± 0.39	8.58 ± 0.28	8.73 ± 0.12	9,00 ± 0.22
20-40	8.35 ± 0.15	8.61 ± 0.23	8.86 ± 0.66	8.43 ± 0.04
40-60	8.34 ± 0.27	8.29 ± 0.24	8.96 ± 0.50	8.18 ± 0.20
60-80	8.46 ± 0.32	7.71 ± 0.74	9.20 ± 0.34	7.68 ± 0.16

Table 2.3: Soil pH after the second crop season in soils irrigated with different irrigation water.

Group 3	Water sources			
Depth(cm)	GW (B)	RW	WW	GW (A)
0-20	8.20 ± 0.30	8.47 ± 0.14	8.57 ± 0.47	8.89 ± 0.32
20-40	7.84 ± 0.23	8.36 ± 0.16	9.03 ± 0.58	8.44 ± 0.40
40-60	8.34 ± 0.38	8.39 ± 0.24	8.97 ± 0.46	8.18 ± 0.17
60-80	8.18 ± 0.19	8.06 ± 0.12	9.22 ± 0.25	8.04 ± 0.16

3. PTE in soils irrigated with wastewater, groundwater A, groundwater B and River water. Measurements from four soil layers (0-20 cm), (20-40 cm), (40-60 cm) and (60-80 cm).

Table 3.1: PTE in soil irrigated with wastewater(WW) in Infulene valley, Maputo, Mozambique. Three measurements of soil before and after first crop season and before and after the second cropping season. After first crop season and before first cropping season is the same parameter.

WW		Si	Fe	Al	K	Ni	Ca	Ti	Na	P	Cr	Mg	Cl	Mn	Zr	S	Ba	Zn	Cu	Rb	Sr
1_0-20 (p	Average	8093,23	700,28	522,43	154,55	53,98	220,60	68,35	30,90	35,23	10,60	54,20	11,08	10,68	7,53	11,55	4,80	3,03	1,83	1,23	2,10
	STDV	50,28	32,60	16,89	7,55	7,72	45,34	10,73	4,98	9,51	0,55	3,39	2,03	1,09	0,70	1,81	3,61	1,01	0,30	0,05	0,32
1_20-40 (	Average	7260,90	1147,80	705,58	177,40	103,33	273,35	91,30	47,03	29,20	14,48	76,45	17,38	14,50	7,93	14,73	3,33	2,88	2,35	1,83	2,50
	STDV	982,59	455,49	227,78	35,91	31,03	180,65	24,79	21,56	16,07	2,40	39,39	7,97	7,82	1,21	10,20	0,65	1,82	0,67	0,57	1,02
1_40-60 (	Average	7422,33	995,40	655,00	161,08	81,70	378,10	79,93	47,50	20,00	13,03	74,48	20,13	14,48	7,15	14,63	3,95	2,75	1,50	1,55	2,85
	STDV	1342,96	498,08	257,48	34,90	33,44	351,70	22,08	31,60	10,22	4,59	59,46	16,14	11,92	0,96	12,08	0,49	2,04	0,28	0,66	2,02
1_60-80 (	Average	6090,77	893,90	685,67	159,23	47,00	1679,90	85,43	53,67	20,13	8,23	167,73	29,27	27,17	7,07	24,33	0,00	1,87	3,00	1,57	9,23
	STDV	1642,44	210,14	168,72	24,01	13,58	1163,23	22,90	20,02	6,07	2,20	88,09	17,26	15,08	0,23	13,97	0,00	0,71	0,14	0,45	5,64
2_0-20 (p	Average	7965,18	780,53	531,90	156,48	57,10	244,73	70,65	32,85	34,85	10,18	60,58	11,88	12,18	8,15	11,80	0,00	3,40	1,53	1,28	2,28
	STDV	266,08	92,40	55,99	12,27	5,11	70,26	13,43	6,07	8,76	0,85	10,28	1,64	2,39	1,96	3,22	0,00	1,19	0,42	0,19	0,65
2_20-40 (	Average	6409,03	1233,23	711,83	167,35	77,38	980,73	93,70	47,85	37,28	12,20	133,53	16,55	30,33	9,08	20,18	3,73	2,75	2,83	1,80	6,38
	STDV	649,97	388,49	115,02	14,48	56,77	345,21	12,84	12,16	12,71	4,91	27,62	4,93	7,43	2,83	8,28	0,23	1,58	1,11	0,36	1,33
2_40-60 (	Average	6854,53	1088,58	696,03	165,33	50,88	762,20	90,00	49,00	27,15	9,38	109,65	20,05	26,58	8,95	21,80	4,25	2,83	2,35	1,78	5,45
	STDV	1106,85	416,29	198,02	25,24	7,59	457,17	6,16	22,48	13,70	0,34	50,33	8,19	17,20	1,75	16,85	1,59	1,82	0,07	0,50	3,07
2_60-80 (	Average	6297,98	1144,08	802,35	184,08	39,78	1091,93	85,40	58,08	17,85	8,65	161,78	34,65	26,15	8,40	18,18	2,87	2,75	1,57	2,08	9,05
	STDV	1110,01	421,53	298,51	52,87	22,39	463,21	24,97	23,11	6,76	4,35	62,14	12,84	9,17	1,15	5,64	1,63	0,96	0,23	0,87	3,92
3_0-20 (p	Average	7125,28	981,73	797,90	206,83	55,43	421,50	132,55	42,33	44,75	11,58	96,75	12,15	17,15	17,78	17,10	3,90	4,13	2,03	1,78	3,48
	STDV	329,41	112,96	87,77	12,29	11,85	93,11	15,24	4,82	10,73	2,32	12,31	1,52	2,42	2,29	4,25	0,55	1,29	0,47	0,15	0,39
3_20-40 (	Average	6131,90	1193,28	839,73	202,75	36,55	1159,05	106,43	44,70	27,43	7,28	155,88	11,85	30,60	10,90	16,15	4,45	3,00	1,88	2,08	7,35
	STDV	1801,52	505,58	242,36	45,07	14,17	1191,52	10,13	24,23	11,22	1,81	79,95	6,65	24,37	3,17	11,29	0,21	2,09	0,29	0,90	5,48
3_40-60 (	Average	6366,90	1262,15	910,55	209,18	33,43	794,05	116,63	48,50	24,05	7,70	127,98	15,55	25,40	11,08	18,93	5,10	2,38	2,57	2,23	5,70
	STDV	1720,45	619,91	391,02	46,76	8,09	670,78	19,56	30,37	17,15	2,38	77,88	10,77	18,68	2,25	18,46	0,14	1,54	1,19	1,20	3,59
3_60-80 (	Average	5553,68	1027,28	803,38	183,10	39,10	1832,10	106,53	58,65	20,60	8,53	242,55	22,75	40,60	9,58	21,23	3,43	2,58	2,13	1,93	15,33
	STDV	1857,34	369,91	265,21	33,75	10,81	1397,89	17,19	26,87	7,06	1,63	172,54	9,97	26,16	3,17	10,94	0,82	1,22	0,71	0,72	15,71

Table 3.2: PTE s in soil irrigated with River water in Infulene valley, Maputo, Mozambique. Three measurements of soil before and after first crop season and before and after the second cropping season. After first crop season and before first cropping season is the same parameter.

RW		Si	Fe	Al	K	Ni	Ca	Ti	Na	P	Cr	Mg	Cl	Mn	Zr	S	Ba	Zn	Cu	Rb	Sr
1_0-20 (	Average	7992,00	694,83	572,48	208,38	58,95	195,65	71,70	52,60	34,68	11,10	41,50	12,10	8,88	8,43	15,58	4,28	7,18	2,98	1,50	2,38
	STDV	133,59	42,60	38,51	5,49	14,97	32,66	14,15	2,88	5,54	2,04	2,08	3,01	1,34	0,56	2,68	0,57	1,96	0,78	0,08	0,38
1_20-40	Average	8245,15	687,73	586,83	178,20	51,10	57,13	71,68	33,88	14,20	8,35	30,78	8,73	4,88	6,88	5,23	2,85	1,95	1,73	1,35	1,28
	STDV	247,89	80,53	78,68	28,22	5,01	28,32	7,51	13,43	4,32	0,70	12,63	2,50	1,26	0,87	2,77	0,21	1,14	0,35	0,31	0,45
1_40-60	Average	8154,48	722,65	650,30	179,55	42,95	42,78	80,40	39,50	7,35	8,00	34,10	14,60	4,23	7,58	4,15	3,10	1,03	1,53	1,55	1,15
	STDV	320,03	111,58	113,22	29,27	4,21	21,49	11,54	18,60	2,34	0,92	15,56	5,93	0,64	1,15	1,59	0,57	0,39	0,17	0,45	0,34
1_60-80	Average	7864,27	848,23	722,70	200,70	47,17	59,13	87,77	50,07	7,47	7,93	45,90	24,60	4,97	8,43	6,30	3,90	1,67	1,65	1,77	1,30
	STDV	790,45	301,81	266,54	59,96	6,07	43,92	26,95	29,49	4,80	2,19	34,48	2,21	2,61	1,27	2,86	1,51	1,00	0,07	0,72	0,56
2_0-20 (	Average	7888,13	766,45	583,43	219,50	51,65	187,28	85,18	56,78	35,65	9,00	44,40	16,75	9,55	9,60	16,20	3,90	7,23	2,05	1,63	2,55
	STDV	123,18	41,36	46,65	7,99	16,75	24,57	14,86	3,99	4,72	2,16	3,15	4,00	1,43	0,38	2,26	0,55	1,80	0,64	0,21	0,17
2_20-40	Average	8089,23	759,78	614,08	188,95	39,85	80,20	79,93	39,93	20,08	6,98	34,80	10,93	7,43	9,15	6,55	3,30	3,15	1,63	1,60	1,37
	STDV	121,97	68,00	72,36	18,59	5,80	37,52	12,86	12,69	8,17	1,13	8,54	4,78	1,75	0,61	3,92	0,99	1,73	0,65	0,16	0,40
2_40-60	Average	8051,33	764,20	662,10	194,50	38,43	59,27	92,70	35,70	13,90	7,03	32,93	16,23	5,13	9,73	5,07	3,43	2,17	1,47	1,50	1,27
	STDV	391,68	141,27	106,71	30,72	12,62	53,54	16,90	18,30	4,23	2,48	20,47	7,73	1,63	1,90	2,54	0,12	1,08	0,15	0,44	0,46
2_60-80	Average	7537,45	1029,05	795,30	215,85	41,08	76,73	102,03	58,63	12,08	8,38	56,48	27,43	6,60	8,83	10,20	3,27	1,88	1,50	2,05	1,58
	STDV	645,59	262,54	198,31	41,88	14,84	38,88	17,37	23,34	5,57	2,85	27,95	22,57	3,76	0,79	5,88	0,61	1,02	0,57	0,60	0,61
3_0-20 (	Average	7177,28	968,83	822,58	256,70	66,08	281,30	132,85	66,78	51,53	12,18	66,33	11,85	13,55	16,73	22,73	4,30	10,90	2,50	1,95	3,63
	STDV	83,20	22,97	24,98	3,47	10,94	45,88	7,65	0,89	5,44	2,44	3,41	0,47	1,53	0,95	1,11	1,11	1,66	0,48	0,13	0,41
3_20-40	Average	7337,27	994,30	954,40	228,43	53,80	101,43	128,90	47,37	23,83	10,27	59,93	9,20	8,63	14,70	7,90	3,35	4,03	1,73	1,97	1,93
	STDV	83,42	18,41	15,89	11,96	3,12	37,63	11,76	11,34	8,80	0,32	10,31	2,09	2,80	1,06	2,93	0,07	2,58	0,50	0,12	0,45
3_40-60	Average	7208,50	1081,15	1011,88	234,03	47,83	76,55	134,75	51,53	15,10	9,78	65,93	13,33	7,13	14,80	6,30	3,85	2,33	2,40	2,20	1,65
	STDV	228,26	98,53	67,85	15,17	5,04	16,06	7,23	9,17	3,81	0,58	16,30	2,63	2,55	0,47	1,53	0,99	0,47	0,80	0,22	0,17
3_60-80	Average	7097,40	1122,43	1040,35	241,88	47,63	85,28	139,55	54,90	16,30	9,10	64,33	23,60	7,78	15,23	8,90	3,68	3,00	2,18	2,33	1,83
	STDV	783,90	340,90	243,76	37,86	9,16	58,59	7,42	26,69	9,20	2,03	42,01	7,35	3,30	2,40	4,18	0,60	1,94	0,99	0,64	0,62

Table 3.3: PTE in soil irrigated with Groundwater B in Infulene valley, Maputo, Mozambique. Three measurements of soil before and after first crop season and before and after the second cropping season. After first crop season and before first cropping season is the same parameter

Groundwater SE		Si	Fe	Al	K	Ni	Ca	Ti	Na	P	Cr	Mg	Cl	Mn	Zr	S	Ba	Zn	Cu	Rb	Sr
1_0-20 (p	Average	8724,75	506,68	242,33	136,20	97,28	121,03	50,68	19,20	29,25	15,88	14,90	9,35	6,80	7,50	5,33	2,70	3,43	6,08	0,93	1,40
	STDV	86,50	30,44	25,61	17,56	6,48	16,40	10,64	2,64	6,50	1,33	1,85	4,57	1,05	1,21	1,43	#DIV/0!	0,64	8,56	0,13	0,18
1_20-40 (p	Average	8516,63	560,05	297,65	157,40	96,48	157,60	60,75	21,45	48,63	15,95	18,33	8,88	8,30	9,53	8,28	3,23	4,83	3,18	1,00	1,68
	STDV	55,01	15,56	43,82	14,45	11,29	10,84	12,74	2,81	3,40	2,04	1,04	1,03	1,33	2,45	1,94	0,55	0,66	2,12	0,29	0,10
1_40-60 (p	Average	8261,00	602,40	403,78	195,30	88,43	180,05	93,35	26,10	50,30	15,20	26,45	8,55	9,85	12,53	11,05	3,73	5,15	2,43	1,40	1,78
	STDV	342,20	62,24	116,32	40,05	4,76	66,77	20,03	7,24	23,66	1,61	13,18	2,29	2,12	1,15	5,43	0,54	2,03	0,61	0,37	0,68
1_60-80 (p	Average	8186,05	651,63	453,15	201,08	79,90	162,68	90,90	27,08	43,80	12,53	31,50	10,20	9,58	12,18	13,95	3,37	4,53	2,33	1,40	1,78
	STDV	398,48	103,91	140,10	41,91	9,67	64,26	16,93	9,29	16,38	0,65	15,63	4,81	1,85	2,26	7,23	0,21	1,78	0,50	0,22	0,62
2_0-20 (p	Average	8644,10	577,30	252,08	139,48	81,53	122,78	62,10	20,75	31,95	13,70	15,25	8,23	6,68	9,60	6,28	2,70	3,38	1,83	0,90	1,35
	STDV	72,57	27,24	20,48	8,02	2,72	8,60	8,07	1,53	5,27	0,63	2,27	2,34	0,32	0,55	0,74	0,14	0,72	0,47	0,08	0,13
2_20-40 (p	Average	8445,25	606,20	322,70	175,65	82,08	143,43	72,93	24,08	42,13	13,08	19,33	10,18	8,65	12,55	7,58	3,07	4,05	2,53	1,00	1,68
	STDV	143,33	26,42	56,95	25,99	4,72	13,74	15,23	2,68	6,97	1,65	3,47	0,69	1,58	2,70	2,28	0,15	0,51	0,30	0,14	0,22
2_40-60 (p	Average	8314,45	614,83	379,28	194,30	82,20	156,58	83,50	25,93	51,95	13,20	26,45	8,83	8,98	14,53	12,53	3,05	4,65	2,23	1,30	1,63
	STDV	353,00	57,45	97,68	31,57	2,75	95,40	12,65	6,41	32,32	1,29	14,67	1,27	3,30	1,24	8,68	0,78	2,57	0,42	0,14	0,50
2_60-80 (p	Average	8224,98	702,80	421,58	189,40	67,90	59477,08	89,10	24,90	44,08	10,95	29,73	9,68	10,05	13,45	13,00	3,47	3,83	2,00	1,28	1,55
	STDV	465,85	147,42	140,48	42,33	7,15	118748,62	10,00	8,85	25,56	1,76	14,55	3,33	4,06	0,60	9,57	0,35	2,38	0,61	0,30	0,59
3_0-20 (p	Average	8350,53	648,60	325,18	170,10	86,05	148,13	112,13	24,95	39,15	15,88	20,00	8,50	8,70	20,20	7,10	3,67	4,75	2,05	1,13	1,80
	STDV	130,48	36,89	34,59	9,94	11,83	21,74	14,95	3,50	9,80	1,71	2,17	3,71	1,83	1,62	1,75	0,42	0,97	0,69	0,10	0,18
3_20-40 (p	Average	8155,50	683,90	401,10	203,48	73,10	181,88	114,35	29,43	47,85	14,25	25,48	11,23	9,70	17,95	11,25	3,40	5,03	2,60	1,43	1,95
	STDV	198,28	42,58	63,15	41,94	2,89	44,86	24,97	5,00	13,71	1,72	5,00	3,19	1,04	4,37	3,81	0,70	1,33	0,41	0,34	0,48
3_40-60 (p	Average	7892,50	729,80	504,70	256,18	77,38	207,20	123,13	34,75	51,30	15,08	31,08	10,08	10,18	19,73	15,48	3,80	6,33	2,75	1,65	2,48
	STDV	122,09	42,32	47,65	22,67	3,25	29,64	9,13	5,62	11,91	1,84	7,28	1,67	1,36	3,96	0,85	0,70	0,87	0,48	0,17	0,46
3_60-80 (p	Average	7843,80	754,18	552,75	247,10	71,08	176,35	138,75	33,73	51,20	13,40	37,05	11,43	11,98	22,03	14,70	3,73	5,53	2,30	1,78	2,05
	STDV	348,21	106,13	134,98	45,36	7,54	26,37	12,82	6,51	8,99	2,52	10,86	1,65	1,32	2,42	5,67	0,69	1,11	0,85	0,26	0,34

Table 3.4: PTE in soil irrigated with Groundwater A in Infulene valley, Maputo, Mozambique. Three measurements of soil before and after first crop season and before and after the second cropping season. After first crop season and before first cropping season is the same parameter

Groundwater 1A		Si	Fe	Al	K	Ni	Ca	Ti	Na	P	Cr	Mg	Cl	Mn	Zr	S	Ba	Zn	Cu	Rb	Sr
1_0-20 (p	Average	8886,33	424,80	225,95	170,08	96,43	70,58	27,70	22,00	19,63	14,20	12,50	7,70	5,48	4,40	3,00	2,80	1,65	2,05	0,95	1,20
	STDV	42,99	23,37	22,32	13,72	7,05	10,98	5,40	2,19	2,15	1,31	2,18	0,77	1,35	0,60	0,22	0,42	0,31	0,47	0,13	0,26
1_20-40 (p	Average	8747,03	468,43	316,15	186,75	84,85	55,10	43,53	23,48	19,78	13,10	14,43	6,58	5,25	5,48	2,95	2,95	1,58	1,60	1,23	1,28
	STDV	90,65	22,76	51,72	8,61	11,47	9,60	4,32	1,82	3,52	1,80	2,50	1,72	1,72	0,57	0,79	0,49	0,25	0,14	0,05	0,17
1_40-60 (p	Average	8481,43	557,38	484,03	186,20	67,73	57,63	58,33	24,68	18,90	11,65	22,08	7,55	4,20	7,40	2,70		1,38	1,35	1,3	1,275
	STDV	115,72	37,40	78,04	4,23	6,01	1,94	3,97	1,13	2,04	0,59	3,42	0,47	0,65	0,80	0,39		0,40	0,29	0,14	0,10
1_60-80 (p	Average	8207,23	665,58	623,68	191,25	60,43	63,13	74,88	26,85	18,73	9,93	27,05	7,15	3,98	8,98	2,75	3,40	1,33	1,80	1,43	1,33
	STDV	187,04	81,56	95,95	3,39	5,53	14,05	9,36	1,64	5,85	0,84	3,82	0,58	0,66	0,65	0,75	0,70	0,40	0,17	0,13	0,29
2_0-20 (p	Average	8531,50	516,98	307,43	196,98	75,10	134,58	81,35	32,00	36,35	12,00	24,40	11,30	8,78	13,80	5,85	3,47	2,63	2,15	1,18	1,75
	STDV	280,78	48,99	65,51	44,83	15,56	54,41	37,95	8,83	11,42	2,37	7,63	2,29	2,79	5,38	2,20	0,50	0,98	0,21	0,30	0,47
2_20-40 (p	Average	8625,03	571,00	338,65	180,33	62,53	58,33	57,08	26,10	20,13	10,03	16,45	9,13	6,63	8,78	2,95	3,28	1,53	1,67	1,23	1,35
	STDV	129,63	37,91	55,72	7,13	3,95	12,64	15,30	2,86	4,08	0,79	3,60	1,45	1,47	1,90	0,21	0,59	0,33	0,15	0,17	0,21
2_40-60 (p	Average	8184,10	724,25	563,65	188,30	53,58	72,45	81,00	28,88	25,95	9,35	26,33	9,37	7,00	10,98	3,35	4,23	1,55	1,83	1,45	1,55
	STDV	68,53	28,24	63,12	6,02	3,27	7,35	12,89	1,80	3,73	1,94	1,51	0,64	1,28	0,36	0,72	0,46	0,35	0,48	0,13	0,19
2_60-80 (p	Average	7644,05	896,85	843,53	207,95	59,35	90,90	102,25	34,05	22,65	10,63	37,23	9,30	6,93	13,40	3,55	3,98	1,40	1,90	1,85	1,78
	STDV	181,44	115,07	84,24	15,11	17,76	30,00	14,99	1,84	8,63	2,45	5,21	2,02	1,47	2,84	1,08	0,75	0,29	0,26	0,26	0,19
3_0-20 (p	Average	8016,58	598,60	456,83	251,48	77,28	179,78	171,78	48,10	51,05	13,45	36,23	16,40	11,83	33,63	7,78	4,53	4,18	3,08	3,10	2,43
	STDV	120,45	12,69	63,42	28,04	9,21	20,68	11,89	11,10	8,60	1,06	3,64	5,70	2,89	4,36	1,22	0,49	0,42	0,39	2,87	0,15
3_20-40 (p	Average	7670,90	758,30	681,93	254,95	71,28	140,15	176,13	49,08	47,70	12,33	41,35	17,08	13,20	32,28	10,50	5,35	3,83	4,40	2,10	2,40
	STDV	181,65	61,11	72,97	20,42	4,76	14,64	24,84	2,65	11,29	0,47	5,17	3,79	3,14	6,12	7,87	0,85	0,83	3,90	0,55	0,24
3_40-60 (p	Average	6762,78	1150,08	1117,80	252,40	70,85	164,28	199,88	50,03	52,75	13,80	61,08	15,60	11,20	30,48	8,48	6,50	3,00	8,75	2,55	2,78
	STDV	397,73	215,75	156,18	27,30	5,85	31,67	23,37	7,05	9,72	1,68	9,34	5,22	1,41	6,90	3,99	0,41	0,74	12,45	0,19	0,29
3_60-80 (p	Average	6447,33	1371,53	1264,45	251,33	69,85	142,78	200,13	47,68	30,35	13,95	68,20	14,35	9,15	29,95	5,28	5,90	2,43	10,33	2,75	2,38
	STDV	150,23	95,18	51,81	6,36	5,17	28,98	14,60	6,46	7,08	1,38	3,98	5,32	1,34	3,82	1,40	1,65	0,81	12,06	0,06	0,29

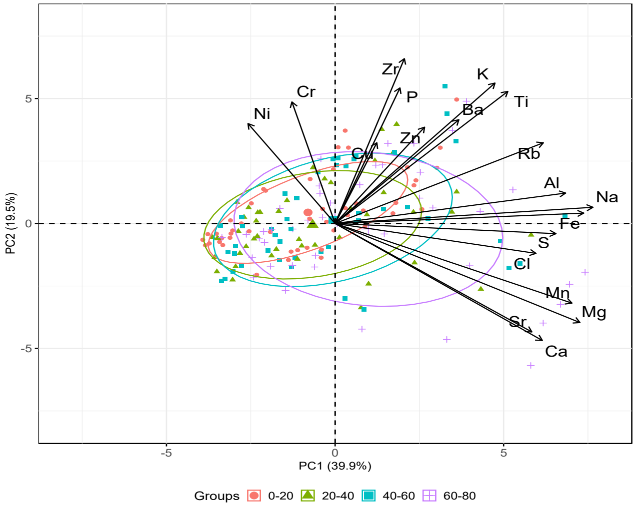

Figure 3.1: Principal component analysis of PTE (Al, Fe, Mn, Zn, Cu, Cr, Ca, Ni, Zr, Mg, Ba, Ti, Rb K, Na, Sr, Br, Cl, P, S) in soil as affected by different soil depth of 187 samples from Infulene Valley. Arrows represent variables that contribute to the principal components (PC1 and PC2). Individuals (0-20 cm, 20-40 cm, 40-80 cm, and 60-80 cm) close to each other have similar concentration of chemical elements, whereas individuals far apart differ.

4. Chemicals concentration in irrigation water

Table 4.1: PTE concentration(mg/l) in irrigation water for 1st and second season irrigated with groundwater (GWA, GWB), River water, Wastewater) in Infulene valley, Maputo, Mozambique.

		SO4	Si	Cl	PO4	Na	K	Mg	Ca
GWA I	Average	95,96	25,10	119,63	6,23	117,27	16,59	45,44	59,69
	STDV	3,16	1,06	38,81	5,14	6,42	4,77	2,50	4,81
GWA II	Average	92,66	25,77	51,08	4,52	106,57	7,73	46,34	59,96
	STDV	9,59	2,81	12,87	0,77	9,14	1,39	3,59	8,99
GWB I	Average	120,55	22,42	159,26	6,37	146,51	32,91	49,61	74,81
	STDV	5,43	2,82	45,67	5,56	6,66	6,00	2,33	6,71
GWB II	Average	105,30	22,70	53,61	4,29	118,40	18,39	42,87	74,27
	STDV	8,75	2,46	20,52	1,21	10,48	2,05	3,94	30,20
River water	Average	89,12	21,10	250,64	16,32	204,49	21,75	44,96	73,98
	STDV	28,75	1,73	67,05	13,46	33,47	3,67	5,25	6,00
River water II	Average	126,00	20,28	233,81	6,49	215,16	11,71	47,45	95,39
	STDV	40,65	0,94	40,22	1,96	19,35	2,26	3,49	50,15
WW	Average	27,92	22,85	127,50	38,27	138,14	21,38	33,29	62,61
	STDV	24,88	0,66	49,78	14,23	15,31	6,02	3,38	9,32
WW II	Average	35,33	24,00	25,77	31,08	98,91	8,86	30,89	63,19
	STDV	26,46	5,37	28,46	12,87	16,91	4,25	7,56	10,79

Table 4.2 Conversion of chemical irrigation parameters from mg/l to meq/l

		Mg	Ca	Na	Cl	SO4	B	K	Mg	Ca	Na	Cl	SO4	B	K
GWA I	**Average**	45,44	59,69	117,27	119,63	95,96	0,06	16,59	3,74	2,98	5,09	2,71	2,00	0,02	0,42
	STDV	2,50	4,81	6,42	38,81	3,16	0,05	4,77							
GWA II	**Average**	46,34	59,96	106,57	51,08	92,66	0,00	7,73	3,81	2,99	4,63	2,62	1,93	0,00	0,20
	STDV	3,59	8,99	9,14	12,87	9,59	0,00	1,39							
GWB I	**Average**	49,61	74,81	146,51	159,26	120,55	0,08	32,91	4,08	3,74	6,36	3,41	2,51	0,02	0,84
	STDV	2,33	6,71	6,66	45,67	5,43	0,04	6,00							
GWB II	**Average**	42,87	74,27	118,40	53,61	105,30	0,01	18,39	3,52	3,71	5,14	2,97	2,19	0,00	0,47
	STDV	3,94	30,20	10,48	20,52	8,75	0,01	2,05							
RW I	**Average**	44,96	73,98	204,49	250,64	89,12	0,09	21,75	3,70	3,69	8,89	2,52	1,86	0,02	0,56
	STDV	5,25	6,00	33,47	67,05	28,75	0,04	3,67							
RW II	**Average**	47,45	95,39	215,16	233,81	126,00	0,07	11,71	3,90	4,76	9,35	3,56	2,62	0,02	0,30
	STDV	3,49	50,15	19,35	40,22	40,65	0,03	2,26							
WW I	**Average**	33,29	62,61	138,14	127,50	27,92	0,04	21,38	2,74	3,13	6,01	0,79	0,58	0,01	0,55
	STDV	3,38	9,32	15,31	49,78	24,88	0,03	6,02							
WW II	**Average**	30,89	63,19	98,91	25,77	35,33	0,00	8,86	2,54	3,16	4,30	1,00	0,74	0,00	0,23
	STDV	7,56	10,79	16,91	28,46	26,46	0,00	4,25							

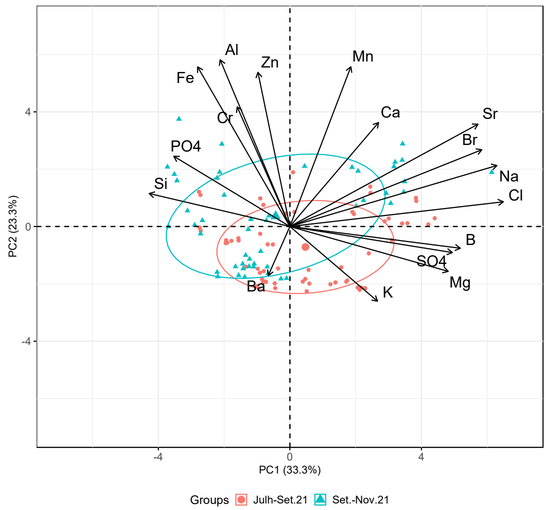

Figure 4.1: Principal component analysis of PTE (Al, Fe, Si, Mn, Zn, Cr, Ca, Mg, Ba, K, Na, Sr, Br, Cl, SO4, PO4) in irrigation water as affected by different seasons of water sampling of 109 samples from Infulene Valley. Arrows represent variables that contribute to the principal components (PC1 and PC2). Individuals (July-September 2021 and September – November 2021) close to each other have similar concentration of chemical elements, whereas individuals far apart differ.

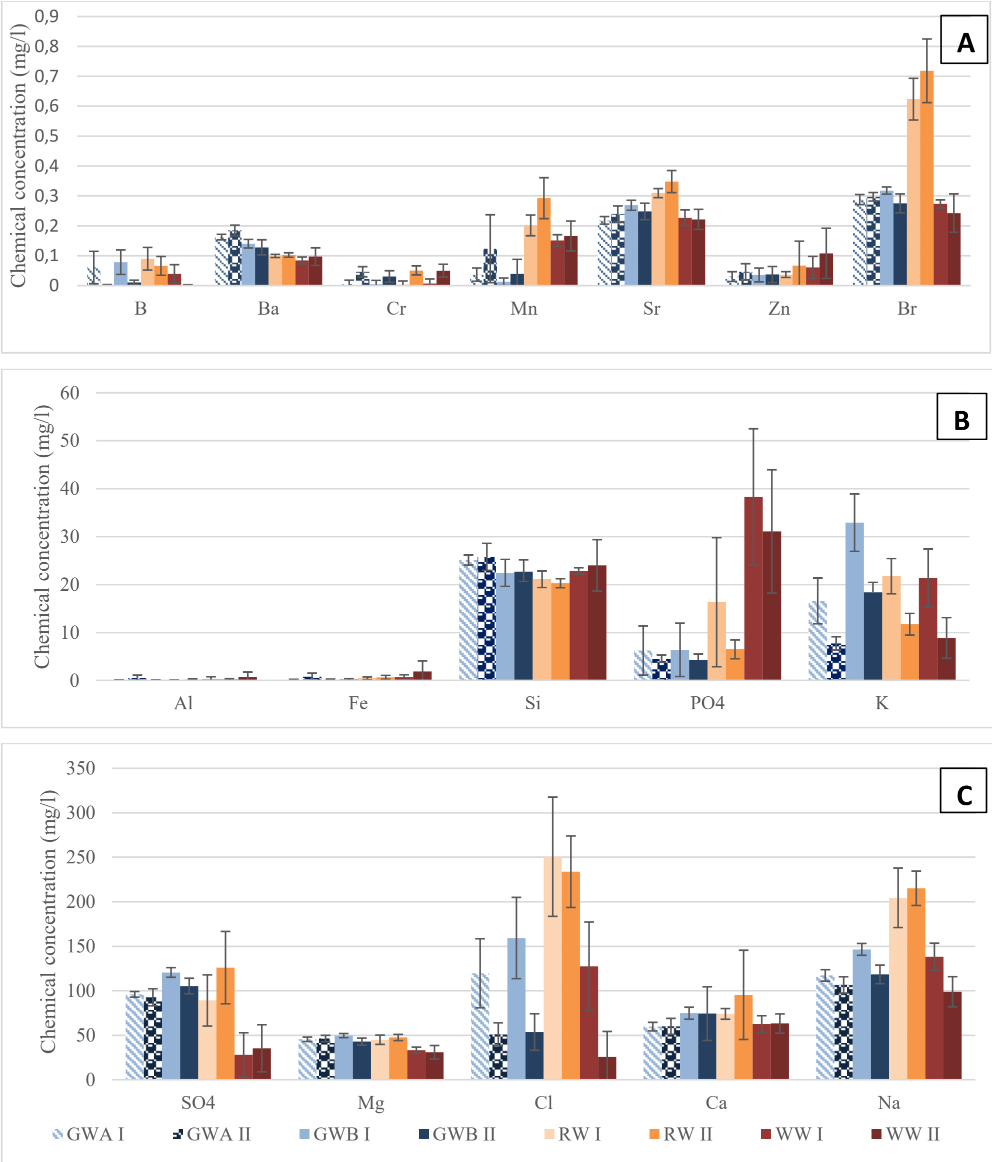

Figure 4.2: PTE concentrations in irrigation water in sampling I,II and III. Sampling I before cropping season I. Sampling II represents after cropping season I and also before cropping season II. Sampling III, Panel A represents (B, Ba, Cr, Mn, Sr, Zn and Br) below 1 mg/l. Panel B represents (Al, Fe, Si, PO_4 and K) with concentration 4-40 mg/l, Panel C represents (SO_4, Cl, Na, Mg, Ca) with concentrations above 40 mg/l.

Table 4.3: Elements concentration limits in irrigation water (mg/l)

Nutrient in water	Concentration limits	Source
Aluminium (mg/l)	5 (Maleki et al., 2014)	(Bouwer, 1987)
Arsenic (mg/l)	0.1 (Maleki et al., 2014)	
Boron (mg/l)	1	
Cadmium (mg/l)	0.01 (Maleki et al., 2014)	
Chromium (mg/l)	0.1 (Maleki et al., 2014)	
Cobalt (mg/l)	0.05 (Maleki et al., 2014)	
Copper (mg/l)	0.2 (Maleki et al., 2014)	
Fluoride (mg/l)	1	
Iron (mg/l)	5	
Lead (mg/l)	5 (Maleki et al., 2014)	
Manganese (mg/l)	0.2	
Molybdenum (mg/l)	0.01	
Selenium (mg/l)	0.02	
Zinc(mg/l)	2 (Maleki et al., 2014)	
Strontium (mg/l)		
Nickel (mg/l)	0.2	(Maleki et al., 2014)
pH	6.5-8.5	(Orosun, 2023)
pH (wastewater irrigation water)	6.5-8	(Ayers and Westcot, 1985)
Sulphate (mg/l)	250-300 mg/l in irrigation water 500-1000 mg/l in discharging water	(Moreno et al., 2009)
SAR (limits Mg, Ca, Na) $(mmol/l)^{0.5}$	Low: <10	
	Medium: 10-18	
	High: 18-26	
	Very high: >26	
SAR (meq/l) Restriction for use for irrigation	No restriction :<3	(Ayers and Westcot, 1985)
	Slight to moderate 3-9	
	Severe: >9	
Chloride (meq/l) Restriction for use for irrigation	None <4	(Ayers and Westcot, 1985)
	Slight to moderate: 4-10	
	Severe: 10	
Boron Restriction for use for irrigation	None: <0.7	
	Moderate: 0.7-3.0	
	Severe: >3	
Salinity of irrigation water EC (μS/cm)	Low: 100-250	
	Medium: 250-750	
	High: 750-2250	
	Very high > 2250	

Table 4.4. Irrigation water quality parameters (Ayers and Westcot, 1985)

Water parameter	Usual range in irrigation water	Units	Units in mg/l
Cations and anions			
Calcium (Ca^{2+})	0-20	meq/l	400.80
Magnesium (Mg^{2+})	0-5	meq/l	60.83
Sodium (Na^{+})	0-40	meq/l	919.600
Chloride	0-30	meq/l	
Sulphate	0-20	meq/l	960.600
Nutrients			
Phosphate-Phosphorus(PO_4-P)	0-2	mg/l	
Potassium (K)	0-2	mg/l	
Miscellaneous			
Boron (B)	0-2	mg/l	
Sodium Adsorption Ratio (SAR)	0-15	meq/l	
pH			

5. Chemicals found in Lettuce (mg/kg) for 1st and second season irrigated with groundwater (GWA, GWB), River water, Wastewater) in Infulene valley, Maputo Mozambique.

Table 5.1. Chemicals concentrations (mg/kg) in lettuce irrigated with groundwater (GWI , GWII) in Infulene valley, Maputo, Mozambique.

	GWA I		GWA II		GWB I		GWB II	
	Average	STDV	Average	STDV	Average	STDV	Average	STDV
B	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Ba	18,46	3,02	3,21	1,21	6,03	1,84	2,90	0,86
Cr	3,49	1,34	1,08	0,36	2,76	1,22	7,70	1,41
Cu	1,52	0,30	0,65	0,14	1,95	0,40	0,96	0,15
Mn	15,31	1,37	4,86	1,17	8,97	1,45	4,09	0,63
Sr	6,08	0,46	4,31	0,68	5,63	0,68	3,09	0,32
Zn	8,16	1,38	5,63	0,40	10,98	1,10	6,23	0,83
Br	0,00	0,00	0,33	0,39	0,21	0,42	0,00	0,00
Fe	318,98	67,28	63,02	29,13	128,27	33,85	74,70	18,10
Al	944,06	204,72	127,01	59,06	233,32	99,87	145,42	42,79
Ca	936,09	139,57	810,65	80,70	1417,16	155,13	892,84	49,19
K	2880,71	998,98	5343,44	550,90	4605,00	814,68	5714,25	520,84
Mg	485,50	76,46	388,00	67,31	579,24	29,01	355,69	19,05
Na	809,72	291,64	1223,16	180,97	1364,65	359,31	1170,79	54,36
Cl	558,29	244,22	1380,85	440,87	1746,12	966,02	1028,58	452,29
PO4	1455,10	391,87	2086,48	104,43	2803,38	406,76	1879,26	298,54
SO4	727,97	248,61	1338,79	112,86	1310,49	168,76	1240,31	97,24

Table 5.2: Chemicals concentrations in lettuce irrigated with wastewater and river water (mg/kg), in Infulene valley, Maputo, Mozambique.

	RW I		RW II		WW I		WW II	
	Average	STDV	Average	STDV	Average	STDV	Average	STDV
B	0,00	0,00	0,00	0,00	2,04	4,09	0,00	0,00
Ba	5,39	1,27	2,05	0,15	7,40	3,48	3,65	0,88
Cr	2,37	0,64	1,26	0,40	3,35	1,43	2,71	1,19
Cu	1,87	0,40	1,29	0,25	1,38	0,14	1,10	0,37
Mn	8,94	1,05	4,27	0,75	17,14	10,28	7,52	1,09
Sr	5,62	0,78	3,51	0,25	5,68	0,41	4,80	0,51
Zn	15,05	0,35	9,78	1,12	8,10	2,11	6,82	1,95
Br	8,31	1,58	3,57	3,83	1,37	2,45	4,67	3,67
Fe	198,37	51,90	79,59	15,96	589,40	587,30	164,53	38,87
Al	322,61	122,97	132,79	10,86	792,82	586,73	213,94	41,22
Ca	1011,95	115,91	708,53	28,02	1204,21	89,79	832,36	66,85
K	4547,63	399,95	5690,88	220,43	3627,48	1664,94	6342,19	429,53
Mg	358,42	52,46	300,53	24,30	389,95	64,17	354,46	25,83
Na	1770,06	322,35	1787,09	72,76	1133,67	629,04	2064,43	43,35
Cl	2724,86	1388,43	1330,38	182,56	1593,86	818,59	1518,90	144,01
PO4	2226,56	276,27	2157,64	99,52	1925,34	845,30	2869,12	444,06
SO4	1333,66	158,92	1169,85	83,14	925,06	440,13	1289,22	81,41

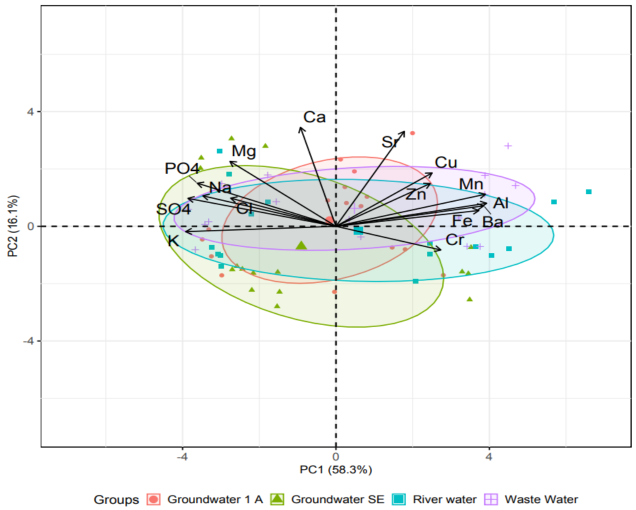

Figure 5.1: Principal component analysis of chemical parameters (K, S, Cl, Na, P, Mg, Ca, Sr, Cu, Zn, Mn, Al, Fe, Ba, Cr) of lettuce from Infulene Valley. Arrows represent variables that contribute to the principal components (PC1 and PC2).

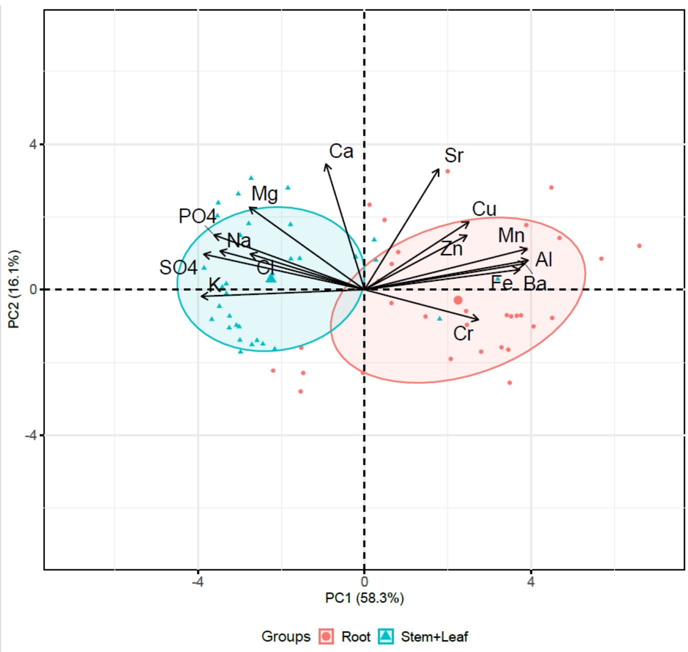

Figure 5.2: Root and stem PTE composition

	Matrix	Recommended limit for the selected PTMs					
		As	Cd	Cr	Pb	EC (μS cm^{-1})	pH
WHO	Irrigation water	0.1	0.01	0.1	5.0	400–600	6.5–8.5
WHO	Soil	–	0.48	11.0	2.0	–	–
WHO	Vegetables	–	0.2	2.3	0.3	–	–
FAO	Irrigation water	–	–	–	–	400–600	6.5–8.4

Table 3. Recommended limit for selected PTMs in irrigation water, and soil for agriculture. [51–53].

Table 5.3: Critical limits concentration in leaf (White & Brown, 2010)

Element	Critical leaf concentrations (mg/kg)		Element	Critical leaf concentrations (mg/kg)
	Sufficiency	Toxicity		Toxicity
Potassium (K)	5000- 40000	>50000	Sodium (Na)	2000-5000
Phosphorous (P)	2000-5000	>10000	Selenium (Se)	10-100
Calcium (Ca)	500-10000	>100000	Cobalt (Co)	10-20
Magnesium (Mg)	1500-3500	>15000	Iodine (I)	1-20
Sulphur (S)	1000-5000		Fluorine (F)	100
Chlorine (Cl)	100-6000	4000-7000	Lithium (Li)	10-200
Boron (B)	5-100	100-1000	Lead (Pb)	10-20
Iron (Fe)	50-150	>500	Arsenic (As)	1-20
Manganese (Mn)	10-20	200-530	Vanadium (V)	1-10
Copper (Cu)	1-5	15-30	Chromium (Cr)	1-2
Zinc (Zn)	15-30	100-300	Aluminium (Al)	40-200
Nickel (Ni)	0.1	20-30	Cadmium (Cd)	5-10
Molybdenum (Mo)	0.1-1	1000	Mercury (Hg)	2-5

Chapter 6: Conclusions and Outlook.

6.1. Overview of research results

From the previous chapters in this thesis, it can be concluded that reclaimed wastewater represents an alternative water source for peri-urban irrigation in most Sub-Saharan African (SSA) countries. Reclaiming wastewater promotes i) freshwater savings, reducing the impacts of persistent droughts in regions with water scarcity; ii) environmental protection from noncontrolled wastewater disposal because of anthropogenic activities from population growth and sprawling; and iii) the possible use of wastewater-based nutrients for agricultural crop production. In fact, chemicals-based nutrients can be saved when the crops are irrigated with (treated) wastewater, closing the nutrient gap for crop development and ensuring a high crop yield in peri urban areas. At present, many countries face the increase in costs of chemical fertilizers. Therefore, reclaiming wastewater and using its nutrients could provide a viable and cost-effective alternative to the required nutrient supply. However, water reclamation occurring in many SSA countries is still informal and is lacking adequate treatment facilities, while conducted formal urban planning regarding wastewater conveyance and treatment, does not consider the collected wastewater for reclamation. In many cases, urban wastewater is discharged into the environment and in peri urban agriculture informal reclamation exists to produce crops. The current reclamation process does not sufficiently monitor faecal contamination, nor does it consider other sources of contamination such potential toxic elements (PTE).

The conducted research in the context of this thesis also concludes that the value chain from farm to market has several points of contamination that should all be considered and monitored. Wastewater is being reclaimed as irrigation water for agricultural production in the Maputo peri urban areas, supplying Matola and nearby areas as its markets. However, in these areas, reclaimed wastewater is not the only potential source of contamination of the agricultural products. Other sources of contamination can be found at the farmlands in the Infulene valley, such as the use of manure and farming activities from planting to harvesting. In addition, inadequate transportation and preservation practices, and unhygienic handling and processing practices, such as the washing process and inadequate vegetable display in the markets, occur. Our results showed that markets contributed most to faecal contamination therefore the risks associated with faecal contamination should be addressed throughout the entire value chain and not only during irrigation with reclaimed wastewater.

The research found that wastewater contributed to nutrient supply although it also showed the existence of PTE in wastewater and other irrigation sources in the Infulene valley. Results showed that also other PTE were found in the crops (e.g. Cr and Al) of which the origin was not clear; samples from neither soil nor irrigation water showed its presence. Contaminated air, fertilizers and pesticides/ herbicides also could be potential sources of PTE (Thompson & Darwish, 2019). Nonetheless, by adopting formal water reclamation practices, applying restrictive guidelines, the potential contamination with PTE in irrigation water, can be minimized.

6.2. Challenges for water reclamation in SSA countries

The main challenges in reclaiming wastewater for agricultural production in SSA are adopting the suggested interventions to mitigate contamination along the value chain, implementing these solutions, and changing the stakeholders' behaviour. In peri-urban areas, the limited water availability usually affects the agricultural production, being an incentive for the implementation of water reclamation, as in such situations wastewater is the only available water source for irrigation. Consequently, the use of treated, partly treated or even non-treated wastewater has been widely adopted by farmers with plots near the nearby the wastewater treatment facilities, such as pond systems, also benefiting from the nutrients present in the water.

Thus, water reclamation for agricultural production is a viable option to be implemented and will contribute towards alleviating food security in most SSA countries, since urban water demands have been predicted to increase as a result of urban growth and development, possibly leading to water scarcity (He et al., 2021). In addition, it reduces the effects of increasing periods of droughts resulting from climate change.

In the Infulene wastewater treatment plant the farmers have free access to (partially) treated wastewater. As the practice of peri-urban agriculture is associated with health risks, linked to the use of polluted water (Cofie et al., 2003; Reyes Tejada et al., 2024), formalised reclamation of wastewater will minimise the use of polluted water in peri-urban areas, however, with associated treatment costs. In formalised applications, water reclamation should be continuously monitored to properly manage water safety risks, and to guarantee water safety and cost efficiency. This will also ensure an appropriate and balanced nutrient supply in the agricultural areas. The continuous monitoring can supply decision makers with information that can be used to protect the crops grown and the consumers' health. Ideally, a collaborative monitoring program involves farmers, academic researchers and other stakeholders. The associated treatment costs to comply with the reuse requirements are transport and storage which may require financial support, since, without incentives, the costs will be transferred to the farmers, negatively affecting their income (Ofori et al., 2021). We advise to share information and success stories about water reclamation for agricultural practices within the local communities and disseminate this information to other areas and regions in order to be able to further expand the use of water reclamation for agricultural purposes.

In addition, SSA governments should include water reclamation in their governance plans and policies, and enforce its implementation with guidelines for agricultural water reclamation, which both considers the social and technical aspects for safe and affordable reclamation. The ideas and concepts, albeit based on "western" solutions, should be designed and tweaked locally and made to fit the local context, expertise, expectations, historical background, local customs and practices. Moreover, consideration of different uses, inclusion of all stakeholders of the value chain (farmers to end consumers), and remediation of the potentially negative effects, is needed. For such remediation, every stakeholder from policy maker to end consumer should be involved to reduce risks. Water reclamation initiatives should be coupled with initiatives that guarantee its sustainability such as the climate ecosystems services activities in peri-urban areas (Mngumi, 2020), which aim to improve resilient measures for climate change, enable the communities to adapt to their local environment, and improve sustainable practices for food security in urban areas.

Growing peri-urban areas require a food production chain that matches the growing demands. Agriculture plays an important role in this production chain but relies on access to secure irrigation sources. Water reclamation is one of the most important enablers of food provision in many urban areas in SSA countries, because it increases water availability and thus promotes farming. At an individual level, this additional access to water also improves farmers' livelihoods. Aside feeding their own region, peri-urban agriculture is also responsible for a considerable share in the food supply to urban areas. This role is, however, often neglected because of peri-urban agriculture's association with sources of disease, or with contaminated food. Therefore, each peri-urban area should consider which crop to grow, and the risks associated with each individual crop grown under the conditions where reclaimed wastewater is used.

Water reclamation for application in peri-urban agriculture faces similar challenges as peri-urban agriculture at large (Cofie et al., 2003), such as limited recognition from authorities, and problems arising in relation to land tenure, affecting the availability of land for agricultural practices. These challenges are strikingly similar to the difficulties faced when securing land for the installation of wastewater treatment plants. Therefore, there is a need to focus on sensitizing authorities, policy makers and planners about safe water reclamation.

6.3. Perspectives

To further promote water reclamation in SSA countries, research would benefit from a holistic approach to water treatment in the agricultural value chain that includes its users (farms), crop handlers, market vendors, and end consumers. Furthermore, to reduce contamination, planners should consider the 'farm-to-market-consumer' chain to implement local safety measures that mitigate risks. Moreover, consumers' social behaviour towards reclaimed wastewater is steered by their attitudes and misconceptions about it, which should be addressed before behaviour can be changed. At policy level persistent behaviours should likewise be changed to facilitate revisiting infrastructures, as well as policies for reclaiming wastewater. In addition to including all stakeholders, initiatives for reclamation should consider combining reclamation for, among others, agricultural and industrial use, and imbedding opportunities for a circular economy for a positive impact on farmers, society, and the environment.

6.3.1 Decentralised (post-)treatment for water reclamation

Wastewater treatment technologies are generally selected on the basis of treatment functionalities, investments costs and operational costs (Kalbar et al., 2012). With regard to water reclamation, the pathogen removal capacity is deemed particularly important (Jiménez et al., 2009). Under conditions prevailing in Mozambique, low-cost and compact technologies are preferable. However, proper management is crucial for its operationalization to fit the local context, expertise, expectations, historical background, local customs and practices. Recently, Maputo's Infulene wastewater treatment plant was upgraded from a capacity of 90.000 to 128.000 inhabitant equivalent. This capacity does not cover the total amount of wastewater produced in Maputo, and land availability might pose a limitation for expansion, given that the current location of the municipal wastewater treatment plant is in a peri-urban area which is pressed by urban expansion. Therefore, when considering water reclamation for irrigation purposes, small-scale decentralised (post-)treatment should be considered at the point of use (Capodaglio et al., 2017). The implementation of such decentralised systems could e.g. be applied in the form of private, independent freshwater providers, characteristic for peri-urban areas in Maputo. In India, e.g., decentralised treatment has been adopted as a result of growing urbanization and the difficulty to link the existing sewer to the centralised distant WWTP (Geetha Varma et al., 2022). The characteristics of peri-urban areas in most SSA countries, and the need to improve sewage collections in newer and peri-urban areas, suggest that decentralized wastewater treatment could be an attractive option of treatment in this context.

6.3.2. Risk control points and social awareness

To prevent the contamination of crops, throughout the value chain, from farmland to market (where consumers usually buy their produce), crops should be managed with greater care to avoid contamination, damage, and deterioration. During handling at the farmlands, farmers should avoid placing crops near manure and potential contaminants. During transportation, crops should be kept separated from other food products and materials with a potential contamination risk. At the market, vendors should use clean containers while washing and frequently change the water during washing. Moreover, there is a need to include quality risk assessments at each point along the agricultural value chain into policies to facilitate water reclamation for irrigated agriculture.

To change set behaviours in the ways crops are handled and processed, towards behaviours that facilitate a reduced risk of crop contamination, a collaboration among different stakeholders is needed. Awareness campaigns, demonstrations, trainings and information exchange should be provided to stakeholders (farmers, vendors, and consumers). On the one hand, these actions may affect and possibly improve their practices of production, storage and washing at the market. On the other hand, the stakeholders will be made aware of the potential risks that arise in their activities. In addition, these practices should also be included in training programs and sensitisation programs as part of the promotion of water reclamation for agricultural use. Education institutions such as Eduardo Mondlane University, Polytechnic Institutes, and agricultural schools should also integrate these practices in their training programs.

6.3.3 Water reclamation in combined sectors and use of its byproducts.

The combination of agricultural and industrial reuse can become a potential option for implementation of water reclamation in Mozambique. Previous research reported studies on water reclamation for industries (Gulamussen et al., 2019). Those users could team up with agriculture for effective and efficient water reclamation, while minimizing non-controlled discharges of wastewater into the environment.

Promoting water reclamation also creates the possibility for the use of treatment by-products and energy recovery. Some experiences of the use of byproducts for soil amendment include biosolids from the wastewater treatment to improve the soil quality, instead of being landfilled (Basta, 2000). In addition, the options for energy recovery can also be explored (Solon et al., 2019), e.g. by using anaerobic treatment technologies for the collected sewage (Van Lier & Huibers, 2004; Van Lier et al., 2020; Van Lier, 2004). For the condition of Mozambique and other SSA countries this poses good opportunities.

6.3.4 Monitoring and policy enablers of water reclamation

Monitoring the amount of reclaimed water will help in future to balance the available water from various sources and can also help in its sustainable use (Vardon et al., 2023). For example, although limited amounts of reclaimed wastewater are available in Mozambique, there is a need to include the amount of the treated wastewater in the urban water balances for making informed decisions at management level. Such activities should be combined with the monitoring of nutrients and contaminants in those systems. The accounting of reclaimed wastewater and its inclusion into policy will promote reclamation and will visualize its contribution in closing the water shortage gap. This measure can also support decision and policy makers to ensure its implementation.

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Curriculum Vitae

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As a lecturer at Eduardo Mondlane University and the Higher Polytechnic Institute of Gaza (ISPG), she lectured subjects such as water management and hydrology, and provided technical assistance in fieldwork and research projects.

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List of Publications

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