

A Work Project, presented as part of the requirements for the Award of a Master's degree in
Management from the Nova School of Business and Economics.

OPPORTUNITIES AND CHALLENGES OF CIRCULAR ECONOMY STRATEGIES
FOR WATER MANAGEMENT IN THE AGRICULTURAL SECTOR

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27/01/2025

Abstract

The thesis explores the integration of circular economy (CE) principles in agricultural water management, identifying key opportunities and challenges. CE strategies, such as wastewater reuse and nutrient recovery, provide economic opportunities by reducing costs and improving resource efficiency, while creating revenue streams through biogas and biofertilizers. Environmental opportunities include conserving freshwater resources, improving soil health, reducing pollution, and supporting ecosystem restoration. Social opportunities, such as equitable access to water and community development, highlight the potential of CE to strengthen agricultural resilience. However, barriers such as technology costs, financial constraints, regulatory challenges, and cultural resistance highlight the need for context-specific solutions.

Keywords

Sustainability, Water Management, Sustainable Water Management, Circular Economy, Circular Economy of Water, Agriculture, Water Governance

This work used infrastructure and resources funded by Fundação para a Ciência e a Tecnologia (UID/ECO/00124/2013, UID/ECO/00124/2019 and Social Sciences DataLab, Project 22209), POR Lisboa (LISBOA-01-0145-FEDER-007722 and Social Sciences DataLab, Project 22209) and POR Norte (Social Sciences DataLab, Project 22209)

Table of Contents

1. Introduction.....	2
1.1 <i>Background and Motivation</i>	2
1.2 <i>Objectives and Research Questions</i>	3
1.3 <i>Thesis Structure</i>	3
2. Literature Review	4
2.1 <i>Circular Economy Principles in Water Management</i>	4
2.1.1 Core Principles of a Circular Economy	4
2.1.2 Application of Circular Economy Principles to the Water Sector	6
2.2 <i>Opportunities of a Circular Economy in Agricultural Water Management.....</i>	8
2.2.1 Environmental Opportunities	8
2.2.2 Economic Opportunities	9
2.2.3 Social Opportunities.....	11
2.3 <i>Risks and Challenges of a Circular Economy in Agricultural Water Management .</i>	11
2.3.1 Technological and Financial Challenges	11
2.3.2 Regulatory and Environmental Challenges	12
2.3.3 Operational and Practical Limitations	13
3. Methodology	13
3.1 <i>Research Design</i>	14
3.2 <i>Stakeholder Groups</i>	14
3.3 <i>Data Analysis.....</i>	15
4. Results and Discussion.....	16
4.1 <i>Opportunities identified through Interviews.....</i>	16
4.1.1 Environmental Opportunities	16
4.1.2 Economic Opportunities	17
4.1.3 Social Opportunities.....	18
4.2 <i>Risks and Challenges identified through Interviews</i>	18
4.2.1 Technological and Financial Challenges	18
4.2.2 Regulatory and Environmental Challenges	19
4.2.3 Operational and Practical Limitations	20
4.3 <i>Case Examples and Best Practices in Circular Economy Water Management</i>	20
4.4 <i>Comparative Analysis with Literature Review</i>	21
5. Conclusion	23
5.1 <i>Summary of Key Findings.....</i>	23
5.2 <i>Limitations of the Thesis and Future Research Directions</i>	24
6. References	26
7. Appendix.....	33

1. Introduction

This section highlights the urgency of sustainable water management in agriculture, with a focus on water scarcity and circular economy strategies. It outlines the motivation, thesis objectives, research questions, and structure of the thesis. A list of abbreviations is provided in [Appendix 1](#).

1.1 Background and Motivation

The current water crisis is one of the greatest challenges we face today (World Bank Group 2024), as water is an essential resource under increasing pressure due to rising global demand, climate change impacts, population growth, urban and agricultural expansion, and regional water scarcity (Liu et al. 2016). In this context, agriculture is emerging as the largest consumer, using about 70% of the world's freshwater (see [Appendix 2](#)) - significantly more than industry and domestic use, which account for nearly 20% and 12%, respectively (UNESCO 2024). With agriculture occupying approximately 40% of the Earth's land surface, its practices, particularly irrigation, have a profound impact on global water cycles, often leading to river depletion and ecological disruption (Foley et al. 2005). As the demand for food production continues to grow, agriculture is under increasing pressure to adapt by balancing productivity with sustainable water management. This balance is essential not only to ensure food security, but also to protect the ecosystems that support human life. (WWF International 2022) Achieving this requires innovative strategies that align agricultural practices with responsible water use.

As a result, the concept of the circular economy has gained prominence as a promising alternative to the unsustainable linear model of "take, make, consume and waste" (World Bank Group 2024). By maximizing resource efficiency and retaining value within systems, circular economy models have the potential to make agricultural systems more sustainable and improve ecosystem outcomes while minimizing waste (Morseletto, Mooren and Munaretto 2022). These frameworks are aligned with sustainable management principles at different scales and

governance levels, addressing immediate water management challenges while contributing to broader Sustainable Development Goals (SDGs), particularly SDG 6 ("Clean water and sanitation"), SDG 9 ("Industry, innovation and infrastructure") and SDG 12 ("Ensure sustainable consumption and production patterns") (United Nations 2024).

1.2 Objectives and Research Questions

The primary research question guiding this thesis is: *How can a circular economy approach create key opportunities and address challenges in promoting sustainable water management in the agricultural sector?* To address this, the thesis explores several secondary questions that aim to deepen our understanding of the potential opportunities and challenges of CE strategies in this context.

Among the secondary research questions, this thesis examines the *primary opportunities of adopting circular water management practices*, particularly in terms of water efficiency and cost savings for agricultural stakeholders. It also explores *key challenges and risks*—such as technological, financial, regulatory, and environmental barriers—that may hinder the adoption of circular water management practices. In addition, the thesis also aims to identify *best practices and innovations* that have been successfully implemented to mitigate risks associated with circular water management.

1.3 Thesis Structure

This thesis first presents a literature review to examine core CE principles relevant to water management, with a focus on opportunities in agriculture, such as economic and social opportunities, and environmental sustainability. It also addresses the risks and challenges of implementing CE practices, including technological, financial, regulatory, and operational constraints.

Next, the methodology section outlines the qualitative research design, detailing the different stakeholder groups and explaining the data collection method. The results and discussion

section then presents the findings from these interviews, identifying both opportunities and challenges in CE water management, supported by real-world case examples and best practices. This section includes a comparative analysis with the literature and examines the implications for sustainable agricultural practices.

The thesis concludes by summarizing key findings from the expert interviews and literature review, offering practical recommendations for stakeholders, and identifying areas for future research. References and an appendix of supplementary materials support the thesis' comprehensive exploration of CE strategies for agricultural water management.

2. Literature Review

This section explores key CE principles in agricultural water management, highlighting opportunities such as economic and social gains and environmental sustainability, while addressing challenges such as technological, financial, and regulatory barriers to provide a balanced perspective.

2.1 Circular Economy Principles in Water Management

2.1.1 Core Principles of a Circular Economy

The concept of the circular economy emerged in the 1960s and 1970s from a range of disciplines and ecological systems literature aimed at minimizing resource extraction and waste generation, which eventually coalesced into what is now known as the circular economy (Velenturf and Purnell 2020). This framework has been defined in numerous ways, reflecting the different perspectives of researchers and practitioners, as illustrated by Kirchherr, Reike, and Hekkert (2017). Despite these variations, the common goal of all definitions is to optimize resource use, although the interpretation of what constitutes "better" resource use remains controversial (Velenturf and Purnell 2020). In recent years, the circular economy concept has gained traction, particularly through the efforts of the Ellen MacArthur Foundation, which has integrated it into the "green growth" narrative, arguing that resource use and emissions can be

decoupled from GDP growth, thereby justifying continued economic expansion (Parrique 2019).

The Ellen MacArthur Foundation defines a circular economy as being founded on three fundamental principles. The first principle is to eliminate waste and pollution, moving away from the linear "take-make-waste" model (see [Appendix 3](#)) that depletes finite resources (Ellen MacArthur Foundation 2022a). The second principle seeks to keep products and materials in use for as long as possible, thereby maximizing their value and minimizing waste (Ellen MacArthur Foundation 2022b). The third principle promotes the regeneration of natural systems, supporting ecosystems and biodiversity for sustainable growth (Ellen MacArthur Foundation 2022c).

While these principles represent the overarching goals of a CE, many authors share a type of framework that goes beyond different aspects of CE, known as "R" frameworks: the 3Rs (Ranta, Aarikka-Stenroos, and Mäkinen 2018), the 4Rs, the 6Rs, the 9Rs (Al 2021), or even the 10Rs (Kirchherr, Reike, and Hekkert 2017). Each framework is based on different principles - Reuse, Repair, Reduce, Recycle, Refuse, Rethink, Refurbish, Remanufacture, Repurpose, and Recover - that scholars combine in different ways according to their research and discussions (Salvioni et al. 2015).

The circular economy holds immense promise, with projected global economic benefits of up to \$4.5 trillion by 2030, as well as potential reductions in material costs, resource dependency, and greenhouse gas emissions (Lacy and Rutqvist 2016; Circle Economy 2018). Social benefits include job creation and improved quality of life. However, critics point to challenges such as "industrial symbiosis" that can reinforce unsustainable systems, and waste-to-energy practices that generate emissions and reduce recyclability (Desrochers and Leppala 2010; Farmer et al. 2015). Overall, while the circular economy offers remarkable benefits, its success depends on carefully addressing these complexities.

2.1.2 Application of Circular Economy Principles to the Water Sector

The concept of a circular economy is increasingly applied to water—a vital resource essential for life and a pillar of global economic systems. As noted above, the Ellen MacArthur Foundation's circular economy framework, tailored to sustainable water management, outlines three principles: design out waste, keep resources in use, and regenerate natural systems (Ellen MacArthur Foundation 2022a). Designing out waste emphasizes reducing energy and chemical use, optimizing water coordination across sectors, and using waterless technologies. Keeping resources in use prioritizes water reuse, energy recovery, and recycling. Restoring natural systems focuses on securing environmental flows, protecting ecosystems, and reducing human impacts (Ellen MacArthur Foundation, ARUP, and antea group 2018). Building on these principles, Smol, Adam, and Preisner (2020) propose a comprehensive circular economy model that aligns with the waste hierarchy (see [Appendix 4](#)) by prioritizing sustainable practices that minimize resource consumption and maximize resource recovery. It presents a structured framework with six core strategies: Reduce, Reclaim (Remove), Reuse, Recycle, Recover and Rethink. (Smol, Adam and Preisner 2020)

Reduce is the first and most impactful option presented in the concept. This approach emphasizes the importance of preventing wastewater generation at its source by reducing water use and pollution through improved planning and design (Smol, Adam, and Preisner 2020). In agriculture, this principle is exemplified by precision irrigation, which uses sensor data to deliver water precisely based on the specific needs of crops, significantly increasing efficiency, and minimizing waste (Smith & Baillie 2009). Enabled by advances in the Internet of Things (IoT)¹ and data analytics, precision irrigation involves a dynamic process of data collection, control, and evaluation. This allows irrigation systems to adapt in real time, conserving water while optimizing crop yields. (Bitella et al. 2014)

Reclamation, the second option in the waste hierarchy, focuses on treating wastewater to

¹ refers to devices with sensors, software, and processing capabilities that connect and share data with other systems via the Internet or communication networks (Yasar and Gillis 2024)

remove contaminants and make it suitable for non-potable uses such as irrigation (Smol, Adam, and Preisner 2020). In agricultural water management, this process is particularly important in water-scarce regions, providing an alternative source that reduces reliance on freshwater supplies (Kowalewski, Neverova-Dziopak, and Preisner 2016). Wastewater treatment typically includes primary, secondary, and tertiary stages, each of which targets specific contaminants such as pathogens, nutrients, and organic compounds to meet safety standards for reuse, thereby minimizing risks to human health and ecosystems (Gupta et al. 2012).

Reuse, the third option in the framework, involves the direct use of treated wastewater for non-potable agricultural applications, particularly irrigation (Haberkamp et al. 2019). Unlike reclamation, which requires extensive treatment for potable or high-standard reuse, reuse utilizes wastewater treated to basic or moderate levels to meet agricultural safety requirements (Smol, Adam, and Preisner 2020). This approach retains beneficial nutrients like nitrogen and phosphorus, enriching soil and minimizing reliance on synthetic fertilizers. Treatment processes such as biological filtration² and membrane technologies³ effectively remove pathogens while maintaining crop-suitable nutrient levels (Vymazal 2010).

Recycling, the fourth option in the framework, focuses on reclaiming wastewater to produce high-quality, potable water for reintroduction into the supply system (Kizinievič et al. 2017). This resource-intensive process relies on advanced technologies such as nanofiltration⁴, reverse osmosis⁵, or forward osmosis⁶ to achieve high contaminant removal suitable for drinking or industrial use. While recycling conserves water resources, it requires significant economic and environmental investments, making it a last-resort option when reduction, reuse, or reclamation are not viable. (Smol, Adam, and Preisner 2020)

The fifth strategy, recovery, focuses on extracting valuable nutrients from wastewater to support

² Filtration process using porous media, such as sand or activated carbon, colonized by microbes that play a key role in the treatment functions (Hammes et al. 2011); ³ Use of semipermeable membranes to improve water management, resource efficiency, and sustainable farming by allowing specific substances to pass while blocking others (Kadadou et al. 2023); ⁴ Membrane filtration process with pore sizes of 1–10 nanometers (Kadadou et al. 2023); ⁵ Water purification process using a semipermeable membrane to separate water from dissolved substances (Malaeb and Ayoub 2010); ⁶ Water separation process that uses a semipermeable membrane and osmotic pressure to separate water from dissolved solutes (Cath, Childress, and Elimelech 2006)

Opportunities of a Circular Economy in Agricultural Water Management

sustainable agriculture. Key nutrients such as phosphorus and nitrogen can replace conventional fertilizers, reducing reliance on phosphate rock, a finite resource. (Smol, Adam, & Preisner 2020) In addition, composted biosolids can serve as a nutrient-rich agricultural input if properly treated for safety (Smol et al. 2018). By closing nutrient cycles, recovery is in line with EU goals to reduce fertilizer imports and promote resource independence (Official Journal of the European Union 2012).

Rethink, the final strategy in the circular economy model, focuses on systemic changes throughout the water and wastewater value chain. In contrast to the specific actions outlined earlier, it advocates a shift from the traditional linear "take-make-waste" model to a circular system that emphasizes resource reduction, reuse, and recovery. (Smol, Adam, & Preisner 2020) For agriculture, this requires integrating water management with energy, spatial planning, and environmental protection, and fostering cross-sector collaboration and holistic solutions (Smol et al. 2018).

2.2 Opportunities of a Circular Economy in Agricultural Water Management

2.2.1 Environmental Opportunities

Applying circular economy principles to water management in the agricultural sector offers significant environmental opportunities by reducing resource consumption, mitigating pollution, and increasing resilience (Brears 2019). First, circular water systems focus on reducing water use through advanced technologies such as precision irrigation, which delivers precise amounts of water to crops based on their specific needs (Smith and Baillie 2009). Supported by IoT sensors and data analytics, this approach prevents over-irrigation and evaporation losses, significantly improving water efficiency by up to 50% in water-scarce regions without compromising yields (Rodias et al. 2020). By reducing withdrawals from natural sources such as aquifers, these practices preserve essential water reserves for future generations while increasing climate resilience. Therefore, reliable water supplies during

droughts and extreme weather events serve as a buffer against the impacts of climate change (Fernandes and Marques 2023).

Second, the reuse of treated wastewater reduces pollution and recovers valuable resources. Removing pollutants, nutrients, and pathogens from wastewater prevents harmful substances from entering aquatic ecosystems, mitigating problems such as eutrophication and protecting biodiversity (Kakwani and Kalbar 2020). Treated wastewater also contains nutrients such as nitrogen, phosphorus, and potassium, which can be repurposed as natural fertilizers, decreasing dependence on synthetic alternatives and mitigating the environmental impacts of their production and transportation (Rodias et al. 2020).

Third, the implementation of circular systems has the potential to reduce energy intensity of water management. The reuse of water at the local level has been demonstrated to reduce energy consumption for pumping, treatment, and distribution, as well as associated greenhouse gas emissions (Ghafourian et al. 2021). In addition, anaerobic digestion⁷ of wastewater enables the recovery of biogas, a renewable energy source that can power agricultural operations or local grids (Nguyen et al. 2020).

Finally, circular practices contribute to ecosystem restoration by reducing human impacts such as over-extraction and pollution, which helps preserve environmental water flows essential for maintaining wetlands, rivers, and biodiversity (Kakwani and Kalbar 2020). Reclaimed water for irrigation further reduces stress on freshwater ecosystems, promoting recovery and enhancing biodiversity (Fernandes and Marques 2023).

2.2.2 Economic Opportunities

In addition to environmental benefits, agricultural water management offers significant economic benefits, including increased efficiency, cost savings and the potential to generate new revenue streams. First, circular water systems reduce operating costs across the board. Precision irrigation applies water exactly where and when crops need it, conserving water while

⁷ Process whereby bacteria decompose organic matter, including animal manure, wastewater biosolids, and food waste, in the absence of oxygen (Chen, Cheng, and Creamer 2007)

significantly reducing irrigation costs. For example, farmers can save thousands of dollars per acre annually by reducing the costs associated with water collection and distribution. (Adeyemi et al. 2017) Similarly, treated wastewater, which is rich in nutrients such as nitrogen, phosphorus, and potassium, can replace synthetic fertilizers, reducing input costs and lowering overall production costs. In Morocco, wastewater reuse reduced fertilizer costs by 45% for wheat and 94% for alfalfa⁸, directly increasing farm profitability (Lahlou, Mackey, and Al-Ansari 2021). In addition, using locally treated wastewater for irrigation minimizes energy costs for groundwater pumping and water transport, as seen at the Ferrara wastewater treatment plant in Italy, where a 60% reduction in pumping distances saved 200,000 euros annually (Colella et al. 2021).

Second, circular systems create new revenue opportunities by recovering valuable by-products. Anaerobic digestion of wastewater produces biogas that can be used to power farms or local grids, offsetting energy costs and potentially generating additional revenue. Nutrient recovery technologies provide additional financial benefits by enabling the sale or reuse of recovered fertilizers to reduce operating costs. (Zarei 2020)

Finally, circular water management promotes long-term financial sustainability by reducing hidden costs that are often overlooked in traditional systems. For example, local reuse of treated wastewater reduces the burden on centralized water treatment facilities, saving on energy-intensive infrastructure and reducing maintenance costs. Studies show that these indirect savings-such as reduced water treatment and infrastructure maintenance-can exceed €0.31 per cubic meter of treated wastewater. (Fernandes and Marques 2023)

2.2.3 Social Opportunities

Implementing circular water management systems in agriculture creates significant social opportunities by promoting equity, empowering communities, and improving livelihoods. First, these systems improve access to water for smallholder farmers by ensuring that treated

⁸ Perennial herbaceous plant in the Fabaceae (legume) family, cultivated worldwide as a vital forage crop for grazing, hay, silage, and green manure or cover cropping (Veronesi, Brummer, and Huyghe 2009)

Risks and Challenges of a Circular Economy in Agricultural Water Management

wastewater or reclaimed water is distributed equitably. This is particularly important in water-scarce regions, where equitable access can reduce disparities between larger, well-resourced farms and smaller, vulnerable ones. By enabling farmers to benefit from the same water resource, circular systems improve the resilience and productivity of marginalized farming communities. (Hagenvoort et al. 2019)

Second, circular water management systems generate create local employment opportunities through the development and maintenance of infrastructure such as wastewater treatment plants and precision irrigation systems. These jobs not only support local economies, but also provide training and skills development opportunities for rural workers, increasing their economic mobility. For example, projects involving decentralized water reuse systems often lead to the creation of jobs in engineering, maintenance, and system monitoring, which can significantly improve the livelihoods of those involved. (Sartal, Ozcelik, and Rodríguez 2020)

2.3 Risks and Challenges of a Circular Economy in Agricultural Water Management

2.3.1 Technological and Financial Challenges

The adoption of circular water management practices in agriculture faces significant technological and financial challenges, particularly when farmers manage decentralized wastewater treatment systems. Implementing and maintaining small-scale on-farm wastewater treatment systems requires significant upfront investments in infrastructure, including treatment facilities, pipelines, and storage systems. (Magwaza et al. 2019) These costs are further increased by the need to meet stringent reuse standards for agricultural irrigation and to guarantee the treated water's safety and reliability. For example, advanced treatment processes can cost between €0.13 and €0.23 per cubic meter, as seen in Murcia, Spain, placing a significant burden on farm budgets. (Ofori et al. 2020)

Farmers managing their own systems face additional challenges, such as the costs of maintenance, monitoring, and compliance with regulations. Without sufficient financial

incentives, such as subsidies or preferential pricing for treated water, the economic burden may undermine the adoption of circular practices. (Wilderer and Schreff 2000) Furthermore, the need to upgrade existing irrigation infrastructure to accommodate treated water can add to the financial strain (Ezatollah Karami, Keshavarz, and Maleksaeidi 2019).

2.3.2 Regulatory and Environmental Challenges

First, the implementation of circular economy practices in agricultural water management is significantly hindered by regulatory and environmental risks. Inadequate treatment standards for wastewater reuse can lead to the introduction of harmful contaminants, including pathogens, heavy metals, and residual organic compounds, into soils and crops, thereby endangering environmental sustainability and human health. (Toze 2005) These risks are exacerbated by inconsistent regulatory frameworks across regions. The lack of uniform standards and enforcement mechanisms creates significant barriers to the widespread adoption of circular water technologies (Jaramillo and Restrepo 2017).

Second, repeated use of reclaimed water in arid regions often leads to soil salinization, which negatively impacts soil fertility and long-term agricultural productivity. Over time, high salt concentrations in reclaimed water disrupt plant growth and soil structure, especially in poorly drained areas (Andrews et al. 2016). Additionally, nutrient imbalances in reclaimed water or agricultural runoff can exacerbate soil degradation, hindering the sustainability of agricultural practices (Alcon et al. 2010).

Third, public acceptance is a critical societal challenge. Many stakeholders resist wastewater reuse because of perceived health and safety concerns, even when the water has been treated to meet established standards. Building trust through public awareness campaigns that emphasize the safety, benefits, and economic advantages of wastewater reuse is essential to overcoming this barrier. (Smith et al. 2017)

2.3.3 Operational and Practical Limitations

The adoption of circular economy practices in agricultural water management is constrained by several operational and practical barriers that impede their scalability and equitable implementation. First, certain biological and industrial processes require a minimum water input to function effectively, limiting the extent to which water use can be reduced without compromising productivity (Morseletto, Mooren, and Munaretto 2022). This poses a challenge to achieving the efficiency goals central to circular economy principles.

Second, precision irrigation systems and other advanced water-saving technologies remain inaccessible to many smallholder farmers due to their high cost and the technical expertise required to operate them. These disparities in access impede the broader adoption of circular practices, particularly in areas where resource limitations and knowledge gaps are significant. (Adeyemi et al. 2017)

Third, the monitoring tools that are essential for effective water management face their own practical challenges. For example, in-situ sensors, while critical for tracking soil and water conditions, are expensive, require regular maintenance, and often need seasonal reinstallation, increasing labor requirements and operational complexity (Diamond, Relyea, and McCaul 2023). Remote sensing technologies, such as satellite imagery, provide extensive coverage but lack the spatial resolution and real-time capabilities needed for on-the-ground decision-making (Entekhabi et al. 2010).

3. Methodology

This chapter outlines the research design, data collection methods, stakeholder selection, and data analysis approach. Any limitations associated with the thesis are discussed in [Chapter 5](#).

3.1 Research Design

This thesis uses a qualitative research approach to explore the opportunities and challenges of integrating circular economy principles into agricultural water management. Data collection

Methodology

was conducted through semi-structured interviews with three key stakeholder groups, complemented by an extensive literature review on CE principles in agricultural water management, as detailed in [Chapter 2](#). The combination of interviews and literature review has provided a robust basis for exploring both theoretical frameworks and practical insights from diverse global contexts.

Interviews were conducted via Microsoft Teams and email to account for participant availability and geographic diversity. The semi-structured format allowed for detailed, context-specific responses while maintaining consistency across key themes. Interview questions covered implementation of CE principles, observed opportunities, challenges, impact measurement, government incentives, environmental risks, and best practices. The complete interview guide is available in [Appendix 5](#).

3.2 Stakeholder Groups

To fully explore the opportunities and challenges of integrating circular economy principles into agricultural water management, this thesis engaged three key stakeholder groups: experts from water management organizations, farmers, and research and innovation experts. Two participants from each group were interviewed, providing balanced insights into their roles in designing, implementing, and promoting circular practices. Contact details and further information on the participants are provided in [Appendix 6](#).

The first group, experts from water management organizations, was included because of their macro-level involvement in governance, policymaking, and technological innovation. These stakeholders offer critical insights into systemic enablers and barriers, such as regulatory frameworks, infrastructure development, and financial incentives. Participants include Antonio Ventura, Vice President of Águas de Portugal, a leading organization managing water and sanitation services throughout Portugal, and Alex Grumbley, Water Sector Leader at SNV Mozambique, an organization focused on sustainable development through agriculture and

water and sanitation to improve livelihoods and reduce poverty.

The second group, farmers, provides on-the-ground perspectives on the operational realities, practical challenges, and economic feasibility of circular economy practices. These participants offer a first-hand understanding of sustainable water management techniques in agricultural settings. Participants include Daniel Gutierrez, an agricultural engineer and farmer from Colombia who manages 72 hectares of greenhouse rose production, and Boris Wortmann, founder of Happy Food Forest in Denmark, a regenerative farm that integrates agroecological principles with innovative water reuse practices. Their experiences highlight both the opportunities for improved resource efficiency and the practical and financial challenges of implementing CE strategies.

The third group, research and innovation experts, bridges the gap between theory and practice. Veena Srinivasan, a transdisciplinary researcher at IFMR, Krea University in India, works at the intersection of water science, policy, and practice, while also serving on the Board of Governors of the International Water Management Institute. Marisa Rio, Director of Fraunhofer Portugal AWAM (Water and Environmental Technologies), brings expertise from an institute focused on sustainable technologies for water management and environmental protection. Both experts provide cutting-edge insights into agricultural water management and sustainability based on their academic and applied research experience.

3.3 Data Analysis

A thematic analysis was conducted on the data in order to identify any recurring patterns or themes relevant to the research questions. The process was conducted in accordance with the steps outlined below: 1) Familiarization: Responses were reviewed and transcribed to fully understand the data set. 2) Coding: Key observations and recurring concepts were systematically identified and coded. 3) Theme development: Coded elements were organized into broader themes reflecting opportunities, challenges, and best practices, enriched with

stakeholder perspectives. 4) Comparative analysis: Themes were compared with the literature review to highlight convergence and divergence, and to ensure that findings were contextualized within theoretical frameworks.

4. Results and Discussion

This chapter explores the insights from stakeholder interviews and the literature review, focusing on the opportunities, challenges, and best practices for integrating CE principles into agricultural water management.

4.1 Opportunities identified through Interviews

4.1.1 Environmental Opportunities

Farmers highlighted the broad environmental opportunities of circular economy practices in water management, particularly in addressing agricultural challenges and conserving natural resources. As Boris Wortmann⁹, a regenerative farmer from Denmark, explained in an interview, "Building living soil through circular economy practices is about more than just water management; it relates to the nutritional value of our food and even our health." By strengthening the microbiome in the soil, these practices improve water infiltration and holding capacity while addressing broader agricultural issues such as carbon sequestration, nutrient cycling, and natural pest control through increased soil biodiversity. In addition, Daniel Gutierrez¹⁰, an agricultural engineer and farmer from Colombia, noted, "Reducing reliance on well water helps conserve natural aquifers, while reusing treated wastewater prevents contamination of natural waterways and ensures clean water for public use."

Experts from water management organizations emphasized the role of wastewater reuse in providing essential nutrients to agriculture. Antonio Ventura¹¹ stated, "Wastewater is rich in nutrients such as nitrogen and phosphorus, which reduces the reliance on synthetic fertilizers and supports sustainable agricultural practices." Beyond nutrient provision, the reuse of treated wastewater alleviates pressure on potable water supplies, reserving these resources for essential

⁹ Boris Wortmann, interviewed by author, Lisbon, November 29, 2024; ¹⁰ Daniel Gutierrez, interviewed by author, Lisbon, November 27, 2024; ¹¹ Antonio Ventura, interviewed by author, Lisbon, November 26, 2024

uses. Ventura further highlighted the environmental benefits, stating, "Our work ensures that improved water quality is returned to natural ecosystems, fostering a healthier and more resilient environment."

4.1.2 Economic Opportunities

Farmers emphasized the significant economic opportunities of reusing water to reduce their dependence on well water. Daniel Gutierrez explained, "In Colombia, the use of well water usually involves a fee paid to environmental institutions. By minimizing the use of well water, farmers can avoid these fees". Similarly, Boris Wortmann emphasized the cost-effectiveness of wastewater reuse, noting that "the cost of treating and reusing wastewater is often significantly lower than paying for traditional public water services". Beyond cost savings, these advances have opened new avenues for economic diversification, such as ecotourism, which can promote regional development and income stability.

Experts from water management organizations highlighted the potential of circular economy practices to create value from waste through innovative approaches. Antonio Ventura highlighted how rethinking waste can turn by-products into valuable resources: "By rethinking waste, we not only reduce costs but also create new revenue streams," he explained, citing the production of biofertilizers from wastewater by-products and their integration into agricultural value chains. Ventura also shared examples of wastewater treatment plants reusing treated wastewater for innovative applications, such as breweries using it for beer production, demonstrating the many ways in which resources can be reused. Alex Grumbley¹² expanded on this by highlighting the socio-economic benefits, including job creation during the construction of such facilities and sustainable employment opportunities during their operation.

Research and innovation experts highlighted the role of treated wastewater in reducing costs for farms in difficult geographical locations. Veena Srinivasan¹³ noted that farms at high altitudes face significant costs in importing and pumping water up steep slopes. By using locally

¹² Alex Grumbley, interviewed by author, Lisbon, November 26, 2024; ¹³ Veena Srinivasan, interviewed by author, Lisbon, November 19, 2024

treated wastewater, these farms can achieve significant cost savings while improving resource efficiency.

4.1.3 Social Opportunities

Veena Srinivasan was the only participant to emphasize the social opportunities of sustainable water management, particularly the often-overlooked aspect of equity. She explained that efforts to reduce water use go beyond conserving the resource; they aim to enable more efficient use and ensure that farmers have broader access to limited water supplies. "It is not just about saving water and leaving it in the environment," she said, "it is about making sure that more farmers can benefit from the same water sources." By emphasizing equity, Veena underscored the potential of sustainable practices to promote fairness, inclusivity, and a stronger social fabric within farming communities.

4.2 Risks and Challenges identified through Interviews

4.2.1 Technological and Financial Challenges

Farmers face significant technological and financial challenges in adopting advanced closed-loop water management practices. Daniel Gutierrez explained, "In remote areas, implementing live monitoring systems is particularly difficult due to limited access to reliable internet and appropriate equipment. Even when such systems are available, farmers often face challenges in training workers to effectively use interfaces, interpret data, and manage alerts. Highlighting the need for simpler solutions, Boris Wortmann said, "Affordable and rapid testing tools could significantly improve the learning curve and help navigate the complexities of these systems."

On the financial side, the high cost of transitioning to systems such as hydroponics¹⁴ is a major barrier. Wortmann noted, "The investment required for specialized structures, machinery and high-quality substrates tailored to production goals is often prohibitive. In addition, ongoing costs for testing and expert advice further strain financial resources, making it difficult for many growers to sustain or scale these practices." These challenges underscore the need for accessible

¹⁴ Method of cultivating plants in a nutrient-rich water solution instead of using soil (U.S. Department of Agriculture n.d.)

technological solutions and financial support mechanisms to enable wider adoption of circular water management systems.

4.2.2 Regulatory and Environmental Challenges

Farmers highlighted major regulatory and environmental challenges to adopting circular water management practices. Daniel Gutierrez noted that while incentives for sustainable practices exist in Colombia, "accessing these benefits requires navigating a complex and bureaucratic process," which discourages adoption. Farmers also face the risk of soil and crop contamination when wastewater treatment facilities fail to adequately treat industrial wastewater mixed with domestic wastewater, a problem that is particularly pronounced in regions with underdeveloped infrastructure. In Denmark, Boris Wortmann highlighted other challenges, including a lack of funding for essential testing. He also noted that frequent changes in subsidy policies and punitive measures against those who have already implemented sustainable changes have caused hesitation among farmers. "This uncertainty," he noted, "has increased the number of people holding back until rules and regulations are clarified."

Water management organizations emphasized the critical role of public acceptance in overcoming regulatory barriers. Ventura and Grumbley stressed, "You have to start with the mindset of the people," highlighting the need for cultural and educational efforts to address resistance to initiatives such as wastewater reuse. Such resistance, often rooted in misconceptions about safety, remains a major obstacle to progress.

Research and innovation experts drew attention to regional differences in regulatory frameworks. Veena Srinivasan noted that in India, "political instability and unclear guidelines create significant obstacles, even for large government projects." She also cited social challenges such as the "yuck factor," exacerbated by cultural stigmas and the caste system¹⁵, that hinder the acceptance of treated wastewater for agricultural or construction use. In contrast, Marisa Rio¹⁶ pointed out that European countries benefit from robust frameworks such as the

¹⁵ Typical example of classification organized around caste hierarchies in India (Hoff 2016); ¹⁶ Marisa Rio, interviewed by author, Lisbon, December 9, 2024

European Green Deal¹⁷ and the Circular Economy Action Plan¹⁸. She explained, "In Europe, legislation does not just support progress, it forces it," citing Portugal's strategy as an example of clear and consistent policy driving adoption.

4.2.3 Operational and Practical Limitations

Farmers and researchers highlighted the challenges of adopting circular water practices for soil health. Farmers like Boris Wortmann pointed to the lack of reliable, data-driven advice and the high cost of soil testing in Europe. He noted that timing and equipment issues further complicate nutrient application, emphasizing the need for better tools and coordination within circular water systems.

Researchers, including Veena Srinivasan, raised concerns about the risks of inadequately treated wastewater. In India, secondary treated water with high nutrient levels has damaged soil health, leading to complaints from farmers. These observations underscore the importance of improving water treatment and developing practical tools to support sustainable practices.

4.3 Case Examples and Best Practices in Circular Economy Water Management

Farmers demonstrated innovative water reuse practices vital to integrating circular economy principles into agricultural water management. Gutierrez emphasized that regular monitoring systems, operator training and awareness of system functions are essential to optimize water reuse processes. "Operator training and awareness are critical steps for success," he said, emphasizing the need for proper system management to fully leverage the advantages of reusing treated water for irrigation. Boris Wortmann emphasized the importance of crop-specific strategies, noting, "Each crop requires its own practice development," which is essential to tailor water reuse approaches to effectively meet varying water and nutrient needs.

Ventura presented the case study of Portugal's Alentejo vineyards, where a wastewater treatment plant was built specifically to pre-treat winery effluent and recharge irrigation reservoirs. This initiative is an example of water recycling in action, where treated wastewater

¹⁷ Transformative green agenda aimed at reaching climate neutrality in the European Union by 2050 (IEEP AISBL 2024); ¹⁸ Legislation 20 aimed to shift Europe from a linear to a circular economy (Ellen MacArthur Foundation 2022d)

is reused to ensure water availability during the critical summer months, ensuring uninterrupted grape production. Antonio Ventura remarked, "Without this system, grape production for wine would not be possible during the summer," underscoring the essential role of water recycling in sustaining agricultural production. In addition, he gave insights into the Atotonilco de Tula project in Mexico, where advanced wastewater treatment can tackle challenges in water reuse. In a region where only 6% of wastewater is treated, untreated water is often used by farmers, posing health risks from pathogens and toxins. The project treats 60% of wastewater, improving irrigation quality while generating biogas for energy. By combining tailored treatment processes, it exemplifies efficient resource recycling. Despite high initial costs, biogas utilization and economies of scale have lowered operating expenses, resulting in affordable tariffs, and showcasing how water recycling can turn waste into a valuable resource.

Emerging technologies are poised to improve the safety and efficiency of water reuse. Veena Srinivasan pointed to affordable handheld heavy metal testing devices that could revolutionize water quality assessments. "These tools could help determine safe uses for treated water, such as designating contaminated water for non-consumptive crops," she explained. Such advances align with circular economy goals by ensuring safe and efficient reuse of treated water, while protecting human and environmental health.

4.4 Comparative Analysis with Literature Review

The alignment between the literature and interviews is evident in their shared emphasis on the economic and environmental opportunities of water reuse and resource efficiency. The literature generally highlights potential cost savings, nutrient recovery, and environmental benefits such as reduced water withdrawals and pollution (Smol, Adam, and Preisner 2020; Fernandes and Marques 2023). Antonio Ventura's example of the Alentejo vineyard project in Portugal, which demonstrates how water recycling supports agricultural productivity, reflects these themes. Farmers like Daniel Gutierrez underscored these economic opportunities by

Results and Discussion

emphasizing the cost savings from reduced reliance on well water. However, Boris Wortmann's focus on tailored cropping strategies and the operational adjustments required for specific crops points to a practical dimension largely overlooked in the literature, revealing a gap in real-world applicability.

A comparison of challenges exposes notable differences in emphasis and specificity. Both sources recognize technological, financial, and regulatory barriers, but the literature frames these as systemic issues, such as inconsistent regulations and public skepticism about wastewater reuse (Toze 2005; Jaramillo and Restrepo 2017). Interviews, on the other hand, bring these barriers into sharper focus. Veena Srinivasan's concerns about the high cost and limited availability of heavy metal testing tools in India add precision to the literature's broader discussion of technical obstacles. Similarly, Daniel Gutierrez highlighted bureaucratic hurdles in accessing incentives in Colombia, an issue underexplored in the literature. These examples reveal how the literature's abstraction sometimes misses the operational and regional intricacies highlighted in stakeholder interviews.

When discussing best practices, the literature emphasizes broad principles such as the “reduce, reuse, recycle” hierarchy and systemic innovations like integrating wastewater treatment with energy recovery (Smol, Adam, and Preisner 2020). While interviews validate these principles through concrete examples, such as the Atotonilco de Tula project in Mexico, they also highlight practical challenges. Wortmann, for example, pointed to the prohibitive costs of soil and sap testing in Europe, which hinder nutrient recycling efforts. In addition, Srinivasan's emphasis on emerging technologies like handheld testing devices for heavy metals provides a forward-looking view that the literature only indirectly addresses.

Finally, the literature provides a system-level perspective, focusing on theoretical potential and long-term sustainability goals. In contrast, the interviews ground these ideas in operational realities, revealing gaps in the literature's applicability to different contexts. While the literature

Conclusion

positions circular economy principles as universally transformative, interviews underscore the importance of localized strategies, tailored solutions, and practical problem solving. This divergence highlights the need for academic discourse to engage more critically with on-the-ground realities to close the gap between theoretical frameworks and practical implementation.

5. Conclusion

This chapter concludes the thesis by summarizing the key findings from the literature review and interviews, while addressing the limitations of the thesis and providing recommendations for future research to advance sustainable water practices in agriculture.

5.1 Summary of Key Findings

Overall, this thesis found that CE principles in agricultural water management offer significant economic, environmental, and social opportunities, while facing significant technological, financial, regulatory, and operational challenges.

Economic opportunities include significant **cost savings** and **resource efficiency**. Farmers can reduce dependence on expensive water sources, as seen in Colombia, where reuse of treated water avoids environmental fees. CE practices such as wastewater reuse and nutrient recovery lower input costs by reducing reliance on synthetic fertilizers and enable value creation through biogas and biofertilizer production. Projects such as the Atotonilco de Tula wastewater treatment plant in Mexico illustrate how integrated CE systems combine cost-effective operations with renewable energy production.

Environmental opportunities focus on **conservation** and **ecosystem restoration**. Reuse of treated wastewater improves soil health by promoting water retention, carbon sequestration, and nutrient cycling while reducing pollution. The Alentejo vineyard project in Portugal highlights the role of CE in ensuring sustainable irrigation and reducing dependence on freshwater sources. In addition, wastewater reuse minimizes environmental damage by reducing pollutants entering natural ecosystems, while energy recovery through biogas

Conclusion

production reduces greenhouse gas emissions.

Social opportunities, emphasized more in interviews than in the literature, include **improved equity** and **livelihoods**. CE practices enable more equitable access to water resources, especially for smallholder farmers, and support community development through local employment opportunities in infrastructure and system management. These findings underscore the potential of CE to strengthen the social fabric of agricultural communities, as noted in stakeholder perspectives.

However, significant challenges hinder the widespread adoption of circular economy principles. **Technological barriers**, such as the **high cost** and **limited availability of testing tools**, especially for heavy metals, limit safe wastewater reuse. **Financial challenges**, including **infrastructure investment** and **ongoing testing costs**, deter many farmers. **Regulatory gaps** and **bureaucratic inefficiencies**, as seen in Colombia and India, hinder implementation, while operational complexities, such as tailoring reuse practices to crop-specific needs, require expertise and resources. **Public resistance** to wastewater reuse, often driven by cultural stigmas and safety concerns, further complicates adoption.

Overall, the findings demonstrate the significant promise of CE for sustainable agricultural water management, tempered by critical barriers that require tailored, context-specific solutions for implementation. Maximizing CE strategies requires a **case-by-case approach** that considers regional regulatory frameworks, resource availability, and cultural factors to address local challenges and leverage opportunities.

5.2 Limitations of the Thesis and Future Research Directions

This thesis provides valuable insights into CE principles in agricultural water management but has several limitations.

First, the small sample size of six participants, while diverse across stakeholder groups and regions, may not fully capture the variability of experiences, particularly among farmers whose

Conclusion

challenges vary by geography and socioeconomic context.

Second, while the thesis includes perspectives from regions such as Portugal, Mozambique, Colombia, Denmark, and India, the findings are not universally applicable due to regional differences in water policies, infrastructure, and cultural attitudes. These contextual variations limit the generalizability of the findings.

Third, the reliance on qualitative interviews provides rich, contextual insights but introduces potential subjective biases. The lack of quantitative data, such as cost-benefit analyses or environmental metrics, limits the validation of findings with measurable evidence.

Fourth, the analysis of regulatory challenges is based on participant insights and secondary literature rather than a detailed review of policy frameworks. This limits a comprehensive understanding of the governance influences on CE adoption.

Finally, the thesis focuses on existing technologies and practices with limited exploration of emerging innovations, potentially underrepresenting future solutions with transformative potential.

These limitations highlight the need for future research to address the following areas: 1) Expanding sample sizes to include a wider range of stakeholders, particularly smallholder farmers in diverse geographic contexts. 2) Conducting comparative studies across regions with varying levels of water scarcity and regulatory maturity. 3) Incorporating quantitative methods, such as life-cycle assessments or economic modeling, to validate qualitative findings and assess trade-offs. 4) Exploring emerging technologies and innovative approaches that have yet to be widely implemented. 5) Analyzing policy frameworks in greater detail to identify actionable strategies for overcoming regulatory barriers.

By bridging these gaps, future research can expand on the findings of this thesis to advance the adoption of CE principles in water management in the agricultural sector.

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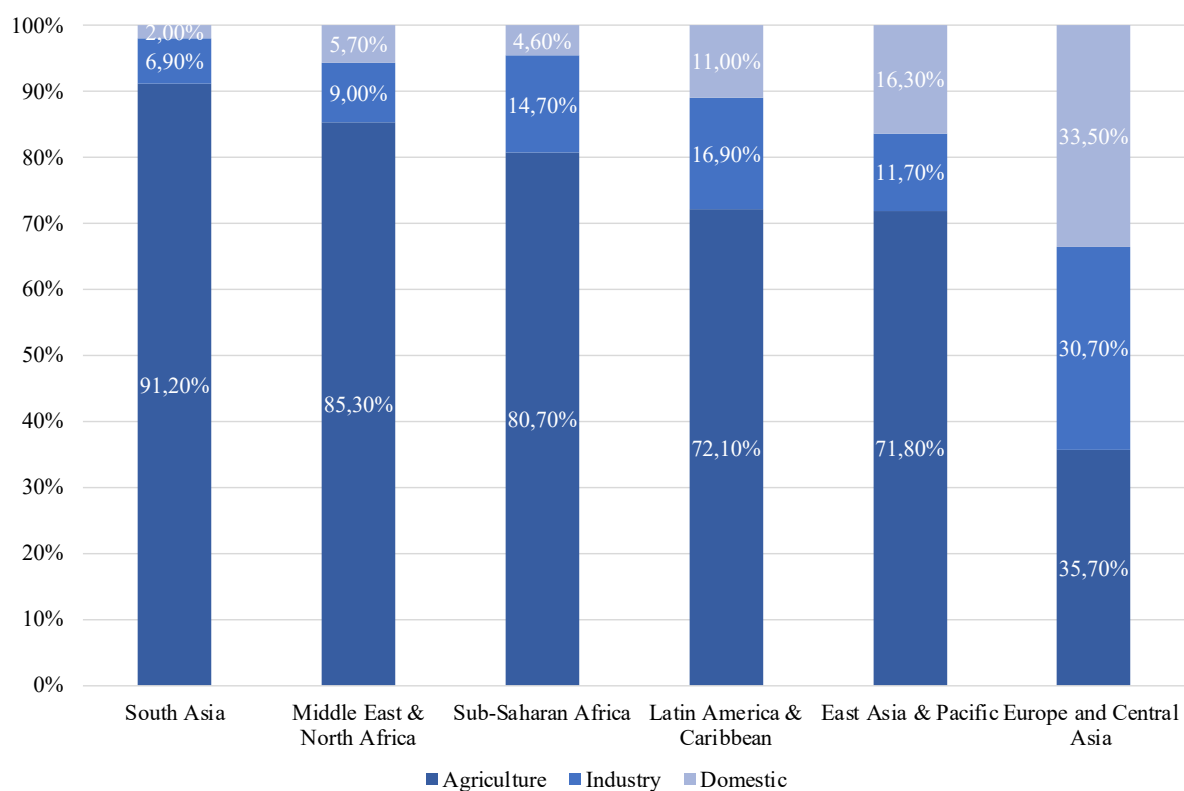
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7. Appendix

Appendix 1: List of Abbreviations

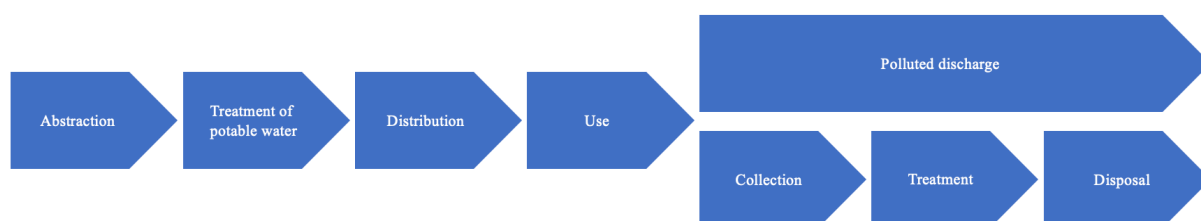
Abbreviation	Explanation
CE	Circular Economy
IoT	Internet of Things
SDG	Sustainable Development Goal
WWTP	Wastewater Treatment Plant

Appendix 2: Share of freshwater withdrawals by sector (%) in 2014



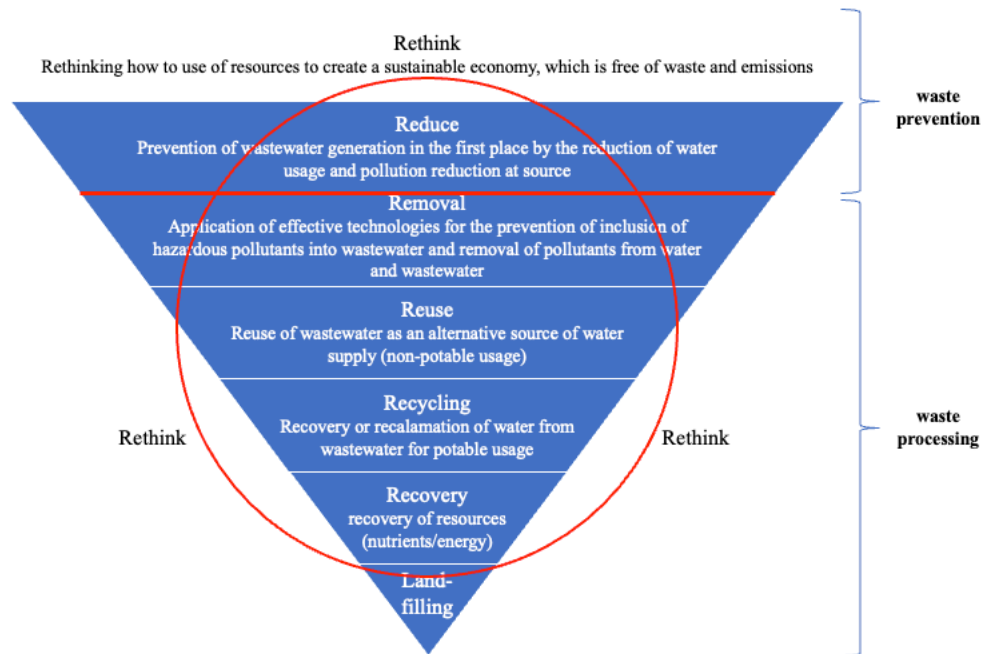
Source: Illustrated according to Khokhar 2024

Appendix 3: The Linear Approach



Source: Illustrated according to World Bank Group 2024

Appendix 4: The CE Model Framework in the Water and Wastewater Sector



Source: Illustrated according to Smol, Adam and Preisner 2020

Appendix 5: Interview Guide

1. Could you please describe your role and your experience in agriculture or water management, specifically regarding any involvement in implementing circular economy practices?

.....

2. What circular economy principles if any, does your organization use in water management?

(Check all that apply, and provide specific examples if applicable)

☐ Water reuse (e.g., using treated wastewater for irrigation)

.....

☐ Water recycling (e.g., nutrient-rich runoff in other parts of the farm)

.....

☐ Water reduction (e.g., precision irrigation, efficient technology)

.....

☐ Other (please specify):

3. What are the main opportunities you have observed from implementing these circular management practices?

(Please discuss any environmental, economic, or operational advantages you've noticed)

Environmental Opportunities

.....

Economic Opportunities

.....

Operational Opportunities

.....

4. Are there any specific challenges you have encountered when implementing circular water management practices?

(Please discuss any technological, financial, or operational challenges you've noticed)

Technological Challenges

.....

Financial Challenges

.....

Practical and Operational Challenges

.....

Other challenges (please specify):

.....

5. How do you measure the economic or environmental impact of these practices in your operations?

(Check all that apply, and feel free to add others)

Economic measures

- ☐ Cost savings on water use
- ☐ Reduction in water-related operational expenses

Environmental measures

- ☐ Volume of water conserved or reused
- ☐ Decrease in water pollution or runoff
- ☐ Improvements in soil or crop health

Other measures (Please specify):

.....

6. What role do government incentives or subsidies play in supporting or hindering these practices?

(Check all that apply, and feel free to add others)

- ☐ Government incentives (e.g., subsidies or grants) have supported adoption
- ☐ Lack of incentives or insufficient funding has been a barrier
- ☐ Policy instability or lack of clarity has hindered progress
- ☐ Incentives exist but are difficult to access or qualify for
- ☐ Other factors (please specify):

7. Are there environmental risks or concerns associated with water reuse in agriculture that you think are important?

- ☐ Risk of soil contamination (e.g., heavy metals, salts)
- ☐ Potential crop contamination from reused water
- ☐ Concerns about pathogen presence in treated wastewater
- ☐ Negative impacts on long-term soil health
- ☐ No significant environmental risks encountered
- ☐ Other concerns (please specify):

8. What practices or lessons learned would you share with others considering circular economy water management strategies in the agricultural sector?

(Provide a short list of key practices, with space to add other insights)

.....

Appendix 6: Interview Partners

Experts from Water Management Organizations

Name	Title/Role	Organization	Location	Contact
Alex Grumbley	Water Sector Leader	SNV Mozambique	Mozambique	agrumbley@snv.org
Antonio Ventura	Vice President	Aguas de Portugal	Portugal	a.ventura@adp.pt

Appendix

Research and Innovation Experts

Name	Title/Role	Organization	Location	Contact
Marisa Rio	Director	Fraunhofer Portugal AWAM	Portugal	marisa.rio@awam.fraunhofer.pt
Veena Srinivasan	Researcher	IFMR, Krea University; International Water Management Institute	India	linkedin.com/in/veenasrinivasan

Farmers

Name	Title/Role	Organization	Location	Contact
Boris Wortmann	Founder	Happy Food Forest	Denmark	linkedin.com/in/boriswortmann
Daniel Gutierrez	Farmer	Production of Roses	Colombia	linkedin.com/in/daniel-gutierrez-1b72721bb