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Rethinking Wastewater: Sustainability Transition Assessment of Nutrient Recycling Systems from Source-Separated Wastewater

Focused on Urine concentration and recycling

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Cover: The artwork represents the transformation toward circular sanitation systems, where source-separated urine is recycled to recover nutrients (N, P, K), reduce pollution, and support sustainable food production. The interconnected visual elements symbolize systemic change linking cities, ecosystems, and agriculture within a circular economy. Created using generative design tools and edited by the author.

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Sustainability Transition Assessment of Nutrient Recycling Systems from Source-Separated Wastewater

Abstract

Conventional sanitation systems contribute to environmental issues, such as greenhouse gas emissions, eutrophication, and resource depletion. Urine recycling, a form of source separation, offers a pathway toward circular sanitation by recovering nutrients and reducing emissions. Despite its clear environmental benefits, large-scale adoption remains limited. This thesis investigates how urine recycling can support sustainable sanitation transitions and identifies the environmental, institutional, and social factors that facilitate its adoption. A transition-focused framework combining life cycle assessment (LCA), technological innovation systems (TIS), and system dynamics modeling (SDM) was developed and utilized to analyze environmental performance, system functions, and adoption dynamics.

Results showed that source-separated sanitation systems, which include urine recycling, can reduce the carbon footprint of conventional wastewater treatment by up to 20% and even achieve carbon-negative results under optimized configurations. However, large-scale adoption remains limited due to regulatory uncertainty, an underdeveloped market for urine-derived fertilizers, and weak institutional support. The TIS analysis revealed that establishing a clear regulatory framework – such as product certification for urine-based fertilizers, financial incentives for early adopters and municipalities implementing collection systems, and well-defined coordination among utilities, regulators, and farmers – greatly improves adoption. Without these measures, the innovation system tends to stall. SDM simulations also indicated that large-scale adoption depends on reinforcing feedback among institutional support, social visibility, and system reliability, with adoption accelerating once public awareness crosses a critical threshold.

By operationalizing the integrated LCA–TIS–SDM framework that links environmental outcomes with socio-technical dynamics, practical recommendations are obtained for decision-makers and water management organizations on how certification, operational reliability, and incentive design can be combined to transform pilot projects into functioning urban systems. In conclusion, urine recycling emerges not only as an environmental innovation but as a strategic path to transform sanitation systems into circular, climate-adapted solutions.

Keywords: Source separation, Urine recycling, Circular sanitation, Nutrient recovery, Life Cycle Assessment, Technological Innovation System, System dynamics modelling.

Bedömning av hållbar omställning för näringsåtervinningssystem från källsorterat avloppsvatten

Sammanfattning

Konventionella avloppssystem bidrar till miljöproblem såsom växthusgasutsläpp, övergödning och utarmning av naturresurser. Urinåtervinning, som är en form av källsorterat avloppssystem, möjliggör krestlopp genom återvinning av näringsämnen som i sin tur minskar utsläppen. Trots tydliga miljöfördelar är storskalig implementering av utinrsortering fortfarande begränsad. Denna avhandling utvärderar urinsorteringen bidrag till hållbar omställning inom sanitetssektorn genom att identifiera miljömässiga, institutionella och sociala faktorer som underlättar införandet. Ett omställningsinriktat ramverk som kombinerar livscykelanalys (LCA), teknologiska innovationssystem (TIS) och systemdynamisk modellering (SDM) utvecklades och användes för att analysera miljöprestanda, systemfunktioner och spridningsdynamik.

Resultaten visade att urinsorterande avloppssystem, kan minska koldioxidavtrycket för den konventionell avloppsrening av resterande avlopp med upp till 20 % och till och med uppnå koldioxidnegativt resultat under optimerade förhållanden. Den begränsade spridningen av systemet beror främst på regulatorisk osäkerhet, en outvecklad marknad för urinbaserade gödselprodukter samt svagt institutionellt stöd. TIS-analysen visade att möjligheten till införande förbättras avsevärt om ett tydligt regelverk etableras. – Dessa regelverk kan till exempel vara produktcertifiering för urinbaserade gödselmedel, ekonomiska incitament för införandet av urinsorterande system till tidiga användare och kommuner., Ytterligare faktorer är väldefinierad samordning mellan kommunala VA-aktörer, tillsynsmyndigheter och lantbrukare. Utan dessa åtgärder tenderar innovationssystemet att stagnera. Den systemdynamiska modelleringen indikerade att storskaligt införande beror på förstärkande återkoppling mellan institutionellt stöd, social synlighet och systemets tillförlitlighet, där spridningen accelererar när den allmänna medvetenheten passerar en kritisk tröskel.

Genom att operationalisera och integrera LCA–TIS–SDM-ramverk som kopplar samman miljömässiga resultat med socio-tekniska dynamiker fås praktiskt tillämpbara rekommendationer till beslutsfattare och VA-organisationer om hur certifiering, driftsäkerhet och incitamentsdesign kan kombineras för att omvandla pilotprojekt till fungerande urbana system. Sammanfattningsvis framträder urinåtervinning inte bara som en miljöinnovation, utan som en strategisk väg för att omforma sanitetssystem till cirkulära, klimat-anpassade lösningar.

Nyckelord: Källsortering, Urinåtervinning, Cirkulär sanitet, Näringsåtervinning, Livscykelanalys, Teknologiskt innovationssystem, Systemdynamisk modellering.

Preface

Sustainability is not achieved solely by technology, but by aligning vision, action, and collective will.

Dedication

Every story has three sides: yours, mine, and the quiet, unyielding truth.

To those who do not flinch in its presence, who seek it in shadows and silence, who honor it not for comfort but for conviction—this work is dedicated to you. May your courage never bend, and may truth, in all its forms, find you.

To Yamma, Yaba, Joseph, and in loving memory of Tariq.

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. **Aliahmad**, A., Lima, P. M., Kjerstadius, H., Simha, P., Vinneras, B., & McConville, J. (2025a). Consequential life cycle assessment of urban source-separating sanitation systems complementing centralized wastewater treatment in Lund, Sweden. Water Research, 268. https://doi.org/10.1016/j.watres.2024.122741

II. **Aliahmad**, A., Harder, R., Simha, P., Vinnerås, B., & McConville, J. (2022). Knowledge evolution within human urine recycling technological innovation system (TIS): Focus on technologies for recovering plant-essential nutrients. Journal of Cleaner Production, 379. https://doi.org/10.1016/j.jclepro.2022.134786

III. **Aliahmad**, A., Kanda, W., & McConville, J. (2023). Urine recycling - Diffusion barriers and upscaling potential; case studies from Sweden and Switzerland. Journal of Cleaner Production, 414. https://doi.org/10.1016/j.jclepro.2023.137583

IV. **Aliahmad**, A., Simha, P., Vinneras, B., & McConville, J. (2025b). Comparative Environmental Assessment of Three Urine Recycling Scenarios: Influence of Treatment Configurations and Life Cycle Modeling Approaches. Environmental Science & Technology, 59(39). https://doi.org/10.1021/acs.est.5c09248

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The contribution of Abdulhamid Aliahmad to the papers included in this thesis was as follows:

I. Aliahmad, Simha, Vinneras, and McConville planned the study. Aliahmad is responsible for the data collection, modeling, and analysis. Lima, Kjerstadius, Simha, McConville, and Vinneras contributed to data collection and validation. Aliahmad wrote the paper, with revisions by the co-authors.

II. Aliahmad, Harder, Simha, Vinneras, and McConville planned the study. Aliahmad is responsible for the data collection, modeling, and analysis. Harder contributed to part of the data coding. Aliahmad wrote the paper, with revisions by the co-authors.

III. Aliahmad, Kanda, and McConville planned the study. Aliahmad is responsible for the data collection, modeling, and analysis. McConville contributed to data collection. Aliahmad wrote the paper, with revisions by the co-authors.

IV. Aliahmad, Simha, Vinneras, and McConville planned the study. Aliahmad is responsible for the data collection, modeling, and analysis. Simha, Vinneras, and McConville contributed to data collection and model validation. Aliahmad wrote the paper, with revisions by the co-authors.

V. Aliahmad, Simha, Vinneras, and McConville planned the SDM study. Mihelcic, Zhang, McAlister, and Vicario provided supervision to part of the modeling and discussion. Aliahmad is responsible for the data collection, modeling, and analysis.

Language editing for grammar and text flow was supported by Grammarly, and AI-assisted translation was used to produce the Swedish version of the abstract and popular science.

Papers produced but not included in the thesis:

I. Dioba, A., Schmid, A., **Aliahmad**, A., Struthers, D., & Fróes, I. (2025). Human excreta recycling in Sweden: a PESTEL-SWOT framework analysis –Review. Journal of Environmental Management, 389. https://doi.org/10.1016/j.jenvman.2025.126242

II. McConville, Kvarnstrom, **Aliahmad**, & Lennartsson. (2023). Legitimacy of source-separating wastewater systems with Swedish water utilities. Journal of Environmental Management, 347. https://doi.org/10.1016/j.jenvman.2023.119108.

III. Harder, R., Metson, G. S., Macura, B., Johannesdottir, S., Wielemaker, R., Seddon, D., Lundin, E., **Aliahmad**, A., Karrman, E., & McConville, J. R. (2024). Egestabase - An online evidence platform to discover and explore options to recover plant nutrients from human excreta and domestic wastewater for reuse in agriculture. MethodsX, 12. https://doi.org/10.1016/j.mex.2024.102774

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Abbreviations

WWTP	Wastewater Treatment Plant
UDT	Urine-Diverting Toilet
BW	Blackwater
BW&GW	Blackwater and Greywater
PE	Population Equivalent
PE·y	Population Equivalent per Year
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
ALCA	Attributional Life Cycle Assessment
CLCA	Consequential Life Cycle Assessment
SLCA	Attributional Life Cycle Assessment with Substitution
ALCA+S	Social Life Cycle Assessment
EIA	Environmental Impact Assessment
GHG	Greenhouse Gas
GWP	Global Warming Potential
MEP	Marine Eutrophication Potential
FEP	Freshwater Eutrophication Potential
TAD	Terrestrial Acidification Potential
TIS	Technological Innovation System
CED	Cumulative Energy Demand
EP	EPPI-Reviewer (systematic review software)
MLP	Multi-Level Perspective
NGO	Non-Governmental Organization
RIS	Research Information System (bibliographic file format)
SDG	Sustainable Development Goal
SDM	System Dynamics Model
SNM	Strategic Niche Management

1. Introduction

Today's sanitation systems face urgent environmental challenges, especially related to nutrient pollution, climate change, and resource depletion (Guest et al., 2009; Larsen et al., 2016). Excess nitrogen and phosphorus from wastewater contribute to eutrophication and biodiversity loss, pushing planetary boundaries beyond safe operating spaces (Steffen et al., 2015). At the same time, global agriculture continues to rely heavily on synthetic fertilizers derived from finite, geopolitically sensitive resources (Cordell et al., 2009). This reliance not only increases greenhouse gas emissions, especially from the Haber-Bosch process, but also creates noticeable disparities in fertilizer access, with many regions facing nutrient shortages while others experience nutrient overload (Harder et al., 2021). Addressing these intertwined challenges demands a transition toward more self-sufficient, circular nutrient management systems that can secure long-term sustainability and food security (Simha, 2021).

In response to these interconnected challenges and the growing interest in circular sanitation solutions, source-separated systems have emerged as a promising solution (McConville et al., 2017a). Source separation enables the separation of domestic wastewater from stormwater and the fractionation of domestic wastewater into separate streams, allowing for more efficient, targeted treatment (Otterpohl et al., 2004). By treating source-separated streams individually, the potential for recovering energy, nutrients, and water from wastewater can be significantly increased. Source control is also advantageous from a hygienic perspective, as lower volumes of concentrated waste are easier to sanitize and manage (Skambraks et al., 2017). Moreover, the use of new toilet systems, such as vacuum and low-flush toilets, reduces water consumption and facilitates the collection of concentrated waste streams, aligning with the principles of ecological sanitation (Ihalawatta et al., 2015; Kjerstadius et al., 2015).

Among these source-separated systems, urine recycling has emerged as particularly promising. Although urine constitutes only a small fraction of total wastewater volume, it contains the majority of nutrients, making it a high-value stream for nutrient recovery (Vinnerås et al., 2006). Urine recycling supports multiple Sustainable Development Goals (SDGs), such as SDG 6 (clean water and sanitation), SDG 2 (zero hunger), SDG 11 (building more resilient cities), and SDG 14 (protecting aquatic ecosystems)(Larsen. et al., 2021a). Multiple studies have demonstrated both the technical feasibility and environmental benefits of urine recycling. Yet, despite its potential to advance circularity and mitigate ecological risks, large-scale adoption remains limited (Larsen. et al., 2021a).

Research on urine recycling has mainly focused on technical aspects, reflecting the early stage of proving feasibility and optimizing system performance. While this focus is common for emerging innovations, such a narrow approach risks overlooking the institutional and societal factors that ultimately determine whether these technologies diffuse and grow. Evidence from sustainability transitions theory shows that technological progress alone cannot drive systemic change or a paradigm shift in the sanitation sector; coordinated transformations across social, environmental, and economic dimensions are equally essential (Andersson. et al., 2016; Hackmann et al., 2014).

Despite this theoretical interest, there is still limited practical knowledge of the systemic conditions, actor networks, and policy mechanisms that either promote or hinder the transition of urine recycling from small pilot projects to mainstream sanitation systems. Current studies seldom combine environmental performance assessments with socio-technical transition analysis, leading to a fragmented understanding of how environmental benefits may align with, or at times conflict with, institutional, economic, and behavioral dynamics. This lack of integration limits both strategic policy planning and practical decision-making for adopting circular sanitation solutions.

This thesis aims to address this gap by developing and applying an integrated sustainability transition assessment framework that combines environmental life cycle assessment with sustainability transition theories, including technological innovation system analysis and system dynamics modeling. Through this combined approach, the thesis evaluates both the sustainability potential of urine recycling and the socio-technical barriers limiting its diffusion. By connecting environmental performance with systemic transition dynamics, this work contributes to a more holistic understanding of how circular sanitation technologies can transition from niche innovations toward mainstream adoption.

2. Aim and Scope

The overarching aim of this thesis is to rethink wastewater management by investigating how urine recycling, as a key form of source-separated sanitation, can contribute to sustainability transitions in the sanitation sector. Building on the global challenges and research gaps outlined in Chapter 1, this thesis examines the disparity between the high environmental potential of urine recycling and its limited large-scale adoption. To address this, it develops and applies a transition-oriented sustainability assessment framework that integrates life cycle assessment (LCA), technological innovation system (TIS) analysis, and system dynamics modeling (SDM).

This integrative approach enables simultaneous evaluation of environmental performance, socio-technical barriers, and dynamic adoption trajectories, with the goal of identifying practical strategies that can accelerate diffusion and support a broader transition toward circular sanitation. The framework is tested through empirical analysis of urine-dehydration technology in Sweden, with a comparative institutional analysis in Switzerland. Urine recycling provides a relevant and timely case of an emerging circular sanitation innovation that combines technological potential with systemic complexity. Through comparisons with conventional and other source-separating systems, the thesis explores the environmental implications of introducing urine recycling and the systemic factors that influence its diffusion. In doing so, it demonstrates how integrating environmental assessment with transition analysis can yield actionable insights for developing circular, sustainable sanitation systems.

2.1 Objectives

The main objective is to develop and apply an integrative framework that combines environmental assessment, innovation system analysis, and dynamic modeling to understand and support the transition of urine recycling from niche innovation to a mainstream component of sustainable sanitation systems.

Specific objectives are to –

1. **To evaluate the environmental performance of urine recycling systems relative to conventional and other source-separating sanitation systems, identifying their potential sustainability benefits, environmental trade-offs, and improvement hotspots.**
   This objective evaluates the environmental implications of introducing urine recycling within a Swedish context. It determines under what conditions urine recycling delivers net environmental benefits.
2. **To identify and analyze the socio-technical barriers and enabling factors that influence the scaling up of urine recycling systems.**
   This objective assesses the performance of the technological innovation system in relevant national contexts to understand why diffusion remained limited and what conditions could support broader adoption.
3. **To explore potential diffusion trajectories and implementation scenarios.**
   This objective integrates environmental and institutional insights from Objectives 1 and 2 within a dynamic model, capturing feedback among environmental performance, institutional support, and social acceptance. It also compares the environmental impacts of three implementation scenarios.

2.2 Thesis Structure

This thesis adopts a systems-based framework that sequentially combines sustainability assessment with sustainability transition theories (Figure 1).

- Step 1 (Paper I): A consequential life cycle assessment (CLCA) quantifies the environmental implications of introducing urine recycling into conventional and other source-separating systems.
- Step 2 (Papers II & III): A TIS analysis identifies systemic barriers, functional weaknesses, and enabling conditions influencing diffusion in Sweden and Switzerland.
- Step 3 (SDM): A system dynamics model integrates environmental and institutional insights to simulate adoption trajectories and feedback mechanisms under different policy and behavioral scenarios.
- Step 4 (Paper IV): A second LCA examines environmental trade-offs among different implementation configurations (toilet-, building-, and centralized-level treatment), translating results into decision-oriented recommendations.

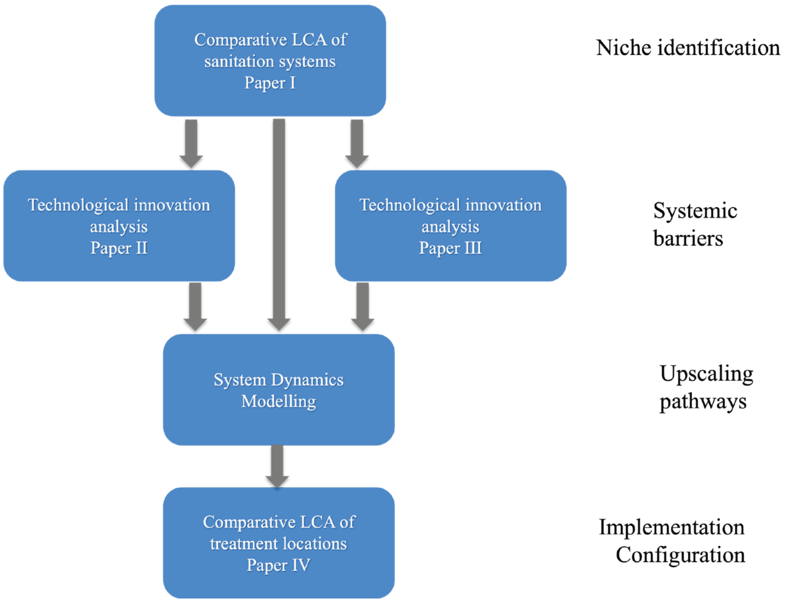

Figure 1: Thesis structure: Each step represents a paper within the thesis. The structure begins with niche identification using LCA, followed by a TIS analysis to identify transition barriers. Finally, it explores implementation trajectories and system configurations.

3. Background

3.1 Need for a Paradigm Shift in Sanitation Systems

Over the past 150 years, centralized sanitation systems have played a crucial role in enhancing public health by removing pathogens and reducing waterborne diseases (Gallardo-Albarrán, 2024). This water-focused approach has shaped infrastructure, regulations, and institutional norms that are now deeply entrenched (Fam & Mitchell, 2013). In high-income countries, prevailing wastewater management models prioritize pollutant removal to protect water bodies, with limited emphasis on recovering valuable resources. As a result, sanitation remains locked in a linear, end-of-pipe model where nutrients are viewed as waste rather than resources (Mutegoa, 2024; World Bank, 2020).

Furthermore, the global replication of this model is constrained in low- and middle-income countries due to its technical complexity and high operational costs, thereby reinforcing inequalities in access to sanitation and environmental health (Sato et al., 2013). This deeply rooted model has resulted in what is often referred to as "lock-in," where technologies, institutions, and actors prioritize compliance with water quality demands over circular goals (Guest et al., 2009).

Conventional methods, such as the widely adopted activated sludge process, prioritize nutrient removal over recovery (Verstraete et al., 2009). However, some modern wastewater treatment plants are shifting toward becoming resource recovery facilities, extracting biogas, phosphorus, biopolymers, and other valuable materials. These developments, although crucial steps toward circularity, still face limitations and often overlook key nutrients like nitrogen and potassium (Rey-Martínez et al., 2024). More importantly, most recovery efforts remain centralized and end-of-pipe, emphasizing the valorization of residuals within existing treatment infrastructures rather than capturing them upstream in source-separating resource systems. Although such measures enhance the efficiency of current models, they do not fundamentally alter the linear approach to wastewater management, which still relies on collecting, treating, and discharging mixed effluents through centralized sewer networks. Additionally, many facilities lack the capacity to remove emerging contaminants, such as pharmaceuticals and hormones (Li et al., 2013), and upgrading these facilities is expensive, resulting in continued pollutant discharge into water bodies (Malnes et al., 2022; Roudbari & Rezakazemi, 2018). This not only undermines environmental protection but also threatens food security and slows progress toward circular water and nutrient management.

Addressing these challenges requires more than technological improvements – it calls for a fundamental redefinition of sanitation's role. To make sanitation a meaningful contributor to planetary health, its role must evolve from a mere water-sector function to an integrated part of a food and resource system (Lehtoranta et al., 2022). Traditionally regarded as a public-health and pollution-control service, sanitation can instead be understood as a critical component of the nutrient and carbon cycles that sustain agriculture and ecosystems (Larsen. et al., 2021a; McConville et al., 2015). In this perspective, human excreta become a renewable source of nitrogen, phosphorus, organic matter, and energy that can substitute for synthetic fertilizers and fossil fuels while enhancing soil fertility (Andersson et al., 2016; SuSanA, 2017). Such a shift could transform wastewater management into a circular bio-resource system linking urban metabolism with food production and climate mitigation (Harder et al., 2019).

This reconceptualization directly addresses one of the key vulnerabilities in today's global food system: its dependence on externally sourced mineral fertilizers. Agriculture remains highly reliant on nitrogen and phosphorus inputs that are resource-intensive, geopolitically sensitive, and increasingly costly (Sniatala et al., 2023). These fertilizers are produced through unsustainable extraction and synthesis methods, such as phosphate mining and the Haber-Bosch process, which together consume 1–2% of global energy (IFIA, 2014; Kok et al., 2018). Their price fluctuations and limited supply threaten food security in regions vulnerable to supply disruptions (Cordell et al., 2009; Menegat et al., 2022). Recent global events have underscored this vulnerability: fertilizer prices surged sharply during the COVID-19 pandemic and again following the 2022 Russia–Ukraine war, as disruptions to natural gas supplies, export bans, and logistical breakdowns restricted the availability of nitrogen- and phosphorus-based fertilizers (FAO, 2023; Heffer, 2022; World Bank, 2023). These shocks highlighted the fragility of global nutrient supply chains and underscored the need to develop locally circular, resource-based alternatives.

Recovering nutrients from wastewater, particularly from source-separated streams such as urine, exemplifies this paradigm shift. It positions wastewater as a strategic resource that can enhance environmental protection, strengthen food system resilience, and reduce dependence on imported fertilizers (Harder et al., 2019; McConville et al., 2017a). By closing nutrient loops locally, such approaches also help maintain planetary boundaries for biogeochemical nitrogen and phosphorus flows (Steffen et al., 2015). Realizing this potential requires overcoming entrenched infrastructural and institutional lock-ins, reconfiguring socio-technical systems, and establishing governance frameworks that enable large-scale nutrient recovery and reuse (Andersson. et al., 2016). These systemic challenges underpin the research in this thesis, which investigates how environmental performance, institutional dynamics, and adoption trajectories interact to determine the viability of scaling circular sanitation systems.

3.1.1 Source-Separated Wastewater Systems

Source separation offers a viable, sustainable alternative to conventional mixed-stream treatment by collecting and processing urine, feces, and greywater separately (Larsen. et al., 2013). This method allows for more targeted, efficient, and context-specific treatment processes that support circular economy principles, resulting in higher nutrient recovery, reduced treatment complexity, lower energy use, and reduced emissions (Jimenez et al., 2015; Kjerstadius et al., 2017).

Urine, which accounts for only about 1% of wastewater volume, contains roughly 80% of the nitrogen, 50% of the phosphorus, and 50% of the potassium. Blackwater, representing about 15% of the volume, contains over 90% of the nitrogen and roughly 80% of the phosphorus (Saliu & Oladoja, 2021). By separating these streams, nutrient recovery rates can be up to ten times higher than those in traditional systems (Lehtoranta et al., 2022), and greenhouse gas emissions are reduced by nearly half (Besson et al., 2021b). Operationally, source separation also decreases chemical inputs, energy consumption, and treatment costs. For example, Xue et al. (2016) comparison of centralized and source-separating sanitation setups in the U.S. found that systems combining blackwater energy recovery and greywater reuse were the least energy-intensive, with blackwater co-digestion offsetting about 40% of the entire lifecycle energy demand. Similar studies in Europe have shown that separating urine or blackwater requires less electricity and chemicals, resulting in lower costs and reduced environmental impacts compared to mixed-stream treatment (Igos et al., 2017).

In the Swedish context, source separation aligns with national environmental objectives, including Zero Eutrophication and A Good Built Environment, as well as the EU Water Framework Directive and Sweden's Circular Economy Strategy. These policies emphasize closing nutrient loops, reducing GHG emissions, and promoting phosphorus reuse in agriculture (Kjerstadius et al., 2016; Skambraks et al., 2017). Life cycle assessment studies specific to Sweden show that source-separating systems, such as blackwater and greywater systems, can reduce carbon footprints by 25–58 kg CO_2-eq per person per year, primarily through enhanced biogas production, fertilizer substitution, and decreased nitrous oxide emissions (Kjerstadius et al., 2017).

Beyond environmental benefits, source-separating systems also enhance food system resilience by reducing dependence on synthetic mineral fertilizers that rely on scarce and geopolitically sensitive resources. Quantitative assessments show that human urine contains sufficient nutrients to replace a significant portion of global agricultural fertilizer needs. According to Simha (2021) the potential of nitrogen substitution through urine recycling can exceed 100% in some low-fertilizer-use countries (e.g., up to 800% in Uganda), while phosphorus recovery from urine and feces could supply about 22% of global agricultural demand (Mihelcic et al., 2011). Although nutrient recovery from mixed wastewater is technically possible, it typically requires more energy and chemicals, resulting in products with higher contamination risks. In contrast, urine-diverting technologies yield nutrient concentrates that are cleaner, more uniform, and better suited for agricultural use (Simha & Ganesapillai, 2017).

Given these benefits, source separation is a practical long-term strategy for enabling decentralized, circular, and low-impact sanitation solutions. In this context, urine recycling has emerged as one of the most promising approaches that directly support nutrient circularity goals (Larsen. et al., 2021a).

3.1.2 Urine Recycling

Urine recycling represents a key innovation within source-separating sanitation systems. It involves diverting, collecting, treating, and recycling human urine, primarily as a nutrient-rich fertilizer, thereby closing the loop on nitrogen, phosphorus, and potassium flows (Larsen et al., 2021b). Besides reducing nutrient discharges and greenhouse gas emissions, it can also replace synthetic mineral fertilizers and support circular economy principles in sanitation (Sohn et al., 2023). Despite these benefits, it remains at the margins of mainstream markets, with most applications still confined to laboratory or pilot scales (McConville et al., 2017b).

One major drawback of urine is that it is about 95% water, which greatly limits its applicability as a fertilizer at scale. On average, it contains 4.5-6 g N L^{-1}, 0.3-0.8 g P L^{-1}, and 1-2 g K L^{-1}, depending on diet and dilution (Larsen et al., 2021b; Simha, 2021). At these concentrations, providing a typical fertilization dose of 90 kg N ha^{-1} for cereal crops would require applying 15,000 –20,000 L ha^{-1} of liquid urine (Simha, 2021). Transporting and storing such large volumes is energy- and cost-intensive, especially in urban areas where collection and application sites are spatially separated (Yan et al., 2021).

To address these challenges, various urine treatment technologies have been developed to stabilize, concentrate, and recover nutrients, transforming urine from a dilute waste stream into a high-value fertilizer. The main goals of these methods are to conserve nutrients, reduce liquid volume, and improve product stability. A shared initial step is stabilization, which prevents urea hydrolysis and ammonia volatilization by inhibiting urease activity. This can be achieved by adjusting pH through acidification (lowering pH < 3) or alkaline treatment (raising pH > 10), both of which keep nitrogen in a stable urea form while reducing microbial activity (Simha, 2021). Another approach is biological nitrification, where nitrifying bacteria convert urea-derived ammonium into nitrate or nitrite, creating a stable, plant-available nitrogen source without extreme pH adjustment (Udert et al., 2003). Phosphorus and potassium are also retained, and in some cases, phosphorus can be recovered as struvite (Randall & Naidoo, 2018; Udert & Wächter, 2012).

Following stabilization, volume reduction and concentration techniques like evaporation, membrane filtration, and distillation are used to remove water content, thereby reducing storage and transportation needs (Larsen et al., 2021b). These methods vary in energy use and complexity, but collectively form the basis for more advanced systems that convert stabilized urine into fertilizers. Among these, urine dehydration has garnered increasing attention due to its balance of simplicity, scalability, and product quality, making it suitable for decentralized applications (Larsen et al., 2021b; Martin et al., 2023).

As shown in Figure 2, urine dehydration combines chemical stabilization with thermal drying to reduce urine volume while preserving nutrients. Stabilization is usually achieved by adding an acid or alkaline agent, such as citric acid, sulfuric acid, or calcium hydroxide, which inhibits urease activity and prevents urea hydrolysis, thereby keeping nitrogen in non-volatile forms (Senecal & Vinnerås, 2017; Simha, 2021). After stabilization, 90% of the water is removed through convective air drying, using warm air (40–50 °C) circulating over the stabilized urine. In larger systems, distillation can improve energy efficiency. The final stage, vacuum evaporation, operates under reduced pressure to lower the boiling point and minimize nitrogen losses. Organic binders can be added during this stage to facilitate pellet formation and improve product handling (Simha, 2021).

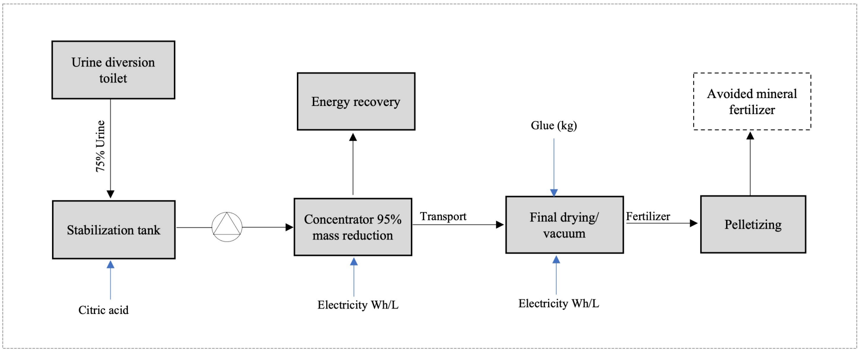

Figure 2: Schematic diagram illustrating urine dehydration system modeled in this thesis

From a process-engineering view, dehydration systems are appealing because they require relatively simple equipment and can achieve high nutrient recovery rates with minimal losses, especially when stabilization and temperature control are optimized (Larsen et al., 2021b). Beyond logistics, the dried products enable accurate nutrient dosing and reduce leaching losses compared to raw or diluted liquid urine (Dash et al., 2025; Ranasinghe et al., 2016). Notably, urine dehydration technologies generate solid, urine-based fertilizers that are well-suited for pelletization, enhancing handling and compatibility with existing agricultural machinery and fertilizer-distribution systems (Simha, 2021). The solid form is stable, compact, and easy to transport, which helps overcome the main logistical challenges of nutrient recycling in urban contexts (Martin et al., 2023).

A remaining challenge for urine-derived fertilizers is the presence of pharmaceutical residues and other organic micropollutants. Source-separated urine accounts for roughly 60–70% of the pharmaceutical load in domestic wastewater, despite its small volume fraction (Özel Duygan et al., 2021). Stabilization and dehydration processes focus primarily on nutrient preservation and don't target organic contaminants, allowing trace compounds to persist in the final fertilizer. Simha et al. (2020) reported that several pharmaceuticals–including ibuprofen, caffeine, bisoprolol, metoprolol, xylometazoline, and naproxen–were detectable in the dehydrated urine fertilizers. Concentrations in the end-product ranged between 0.01 and 19 mg kg^{-1} total solids (TS), corresponding to roughly 10^3–10^4 ng g^{-1} dry matter, with caffeine (≈ 3 mg kg^{-1}) and ibuprofen (≈ 18 mg kg^{-1}) being among the highest. These values are comparable to or lower than concentrations commonly found in sewage sludge used as fertilizer (Verlicchi & Zambello, 2015) and much lower than those measured in untreated wastewater effluent (Diaz-Gamboa et al., 2025; El Hammoudani et al., 2024).

Although the urine dehydration technology doesn't inherently eliminate micropollutants, recent research has demonstrated that advanced oxidation processes (AOPs) and adsorption-based polishing can effectively remove pharmaceuticals from urine matrices. UV/H_2O_2 treatment, for example, degraded more than 90% of 75 micropollutants in urine, while UV/PDS (peroxydisulfate) achieved comparable removal of persistent compounds such as carbamazepine and diclofenac (Demissie et al., 2023; Mehaidli et al., 2024; Zhang et al., 2015). Complementary technologies, such as electrochemical oxidation (Felisardo et al., 2025; Yang et al., 2022) and adsorption using biochar or activated carbon, also show potential to effectively adsorb non-polar pharmaceuticals, such as naproxen and ibuprofen (Solanki & Boyer, 2017). Together, these approaches demonstrate viable pathways to integrate micropollutant control into urine dehydration.

Compared to the current wastewater paradigm, urine recycling shifts the environmental exposure pathway of micropollutants instead of increasing it. In conventional wastewater treatment plants, pharmaceuticals are only partially removed and are continuously released into aquatic environments, where they accumulate and affect aquatic life (Morin-Crini et al., 2022; Shola et al., 2022). In contrast, when urine fertilizers are applied to soil, micropollutants are retained in the topsoil and subject to microbial degradation (Viskari et al., 2018). Therefore, concentrating pharmaceuticals in urine and applying them to soils, where biodegradation is more likely, may be a better environmental trade-off compared to their diffuse release into surface waters.

3.2 Sustainability Science: Concepts and Challenges

In the context of this thesis, sustainability refers to the capacity of socio-technical systems to maintain their essential functions and processes over the long term while supporting human well-being, ecological health, and intergenerational equity. It involves a harmonious integration of environmental health, social equity, and economic viability. In sustainability science, two main research areas aim to understand, analyze, and manage sustainable development: sustainability transitions research and sustainability assessment research (Lindfors et al., 2025).

Sustainability transition research highlights the systemic changes needed in established socio-technical systems, such as energy, water, transportation, and agrifood systems, to develop more sustainable configurations and address critical societal and environmental challenges (Markard et al., 2012). In contrast, sustainability assessments usually focus on measuring impacts across environmental, social, and economic pillars to give decision-makers a snapshot of a system's current or anticipated sustainability performance (Ness et al., 2007).

Every research area has its strengths and limitations, and neither fully addresses all analytical needs (Lindfors et al., 2025). The sustainability transitions research is good at showing the complexity and dynamics of change within a system (Köhler et al., 2019), but it provides limited practical guidance on how to implement such transitions and doesn't sufficiently address the ecological impacts of the systems studied (Andersen & Markard, 2024). Conversely, sustainability assessment research helps compare the sustainability performance of different options, but it often oversimplifies the concept of sustainability and overlooks the systemic dynamics that shape those outcomes (Binder et al., 2020).

Recognizing these complementary strengths and limitations, scholars have called for greater integration between assessment and transition studies (Lindfors et al., 2025). New conceptual directions include transition-focused or future-oriented LCAs that adapt traditional life-cycle thinking to dynamic transition contexts (Arvidsson et al., 2023; Ventura, 2022). These approaches modify functional units, system boundaries, and scenario design to better reflect geographic constraints, evolving technologies, and actor-driven decisions. Similarly, resilience-based and systems-thinking frameworks emphasize the importance of adaptability and learning as key aspects of sustainability (Schilling et al., 2020). These developments collectively promote methods that not only measure sustainability performance but also evaluate the capacity of systems to change, providing both empirical evidence and practical guidance for transition.

3.2.1 Sustainability Transition Research

Several theoretical frameworks have been developed to analyze sustainability transitions, each highlighting different aspects of systemic change (Köhler et al., 2019). Some of the most well-known frameworks include the following: The multi-level perspective (MLP) examines transitions as interactions across three levels — niche innovations, socio-technical regimes, and broader landscape pressures (Geels, 2002). Strategic niche management (SNM) emphasizes how protected spaces enable emerging technologies to mature (Schot & Geels, 2008). Transition management (TM) aims to guide transitions through participatory visioning and adaptive governance (Loorbach, 2009).

In contrast, the technological innovation system (TIS) framework explicitly focuses on the development and diffusion of specific technologies, making it particularly useful for analyzing emerging innovations. Developed by Carlsson and Stankiewicz (1991) and elaborated by Bergek et al. (2008a), TIS analyzes the networks of actors, institutions, and interactions involved in the development and diffusion of emerging technologies. It evaluates key system functions such as entrepreneurial experimentation, knowledge development and diffusion, guidance of the search, market formation, resource mobilization, and legitimacy creation (Hekkert et al., 2007). TIS research has been widely applied to energy and environmental technologies to identify barriers and enabling conditions across the innovation value chain (Hekkert & Negro, 2009; Markard & Truffer, 2008).

In sanitation research, TIS provides a lens for understanding how novel systems, such as source separation, evolve, why they face institutional inertia, and which functions require strengthening to facilitate diffusion. Its compatibility with both qualitative and semi-quantitative data makes it particularly suited for analyzing emerging, pre-commercial systems (Makkonen & Inkinen, 2021).

Complementing these frameworks, system dynamics modeling (SDM) provides a quantitative, simulation-based approach for exploring transition dynamics. Developed initially by Forrester (1961) for industrial systems and later advanced by Sterman (2000), SDM focuses on the feedback loops and non-linearities that characterize socio-technical change. In sustainability transition studies, SDM has been used to simulate technology diffusion processes, policy interactions, and path dependencies (Frantzeskaki & Rok, 2018; Pruyt, 2013; Shiu et al., 2023). It thus provides a dynamic complement to the explanatory depth of TIS and other transition theories by enabling the exploration of "what-if" scenarios and the long-term systemic consequences of interventions (Meadows, 2008)

3.2.2 Sustainability Assessment Research

Sustainability assessment research uses various methods (e.g., life cycle assessment, multi-criteria analysis, material flow analysis, and sustainability impact assessment) to quantify performance across the three pillars of sustainability (Ness et al., 2007). Environmental impact was the first to be systematically evaluated, with life cycle assessment (LCA) and environmental impact assessment (EIA) becoming the most prominent methods, gaining recognition through international standardization (Lindfors et al., 2025). At the product and service level, LCA is the most established and widely used method for evaluating environmental impacts (Singh et al., 2009). Defined by ISO 14040 (2006), LCA quantifies the impacts of products and systems from resource extraction to end-of-life. Two main variants are used: attributional LCA (ALCA), which allocates environmental burdens to products based on average system conditions, and consequential LCA (CLCA), which models system-wide changes in response to decisions, accounting for market substitutions and indirect effects (Ekvall, 2020; Weidema et al., 2018; Wernet et al., 2016). Each method has its strengths: ALCA supports environmental accounting and comparability, while CLCA captures marginal and systemic effects, making it valuable for analyzing emerging technologies.

Other complementary methods–such as social LCA (SLCA) and life cycle costing (LCC) –extend the analysis to social and economic dimensions but remain less mature due to data and methodological limitations (Fan et al., 2015; Gluch & Baumann, 2004; Kambanou, 2020). Collectively, these tools provide evidence-based insights into sustainability performance, guiding design optimization, technology selection, and policy evaluation.

4. Sustainability Transition Assessment Framework

4.1 Sequential Integration of Methods

This chapter presents the integrated methodological framework that forms the core contribution of this thesis. The framework shown in Figure 3, referred to here as the sustainability transition assessment framework, combines life cycle assessment (Section 4.2.1), technological innovation systems analysis (Section 4.2.2), and system dynamics modeling (Section 4.2.3) within a sequential and iterative structure. Its primary goal is to link environmental performance with the socio-technical and dynamic factors that influence how emerging sanitation innovations, such as urine recycling, can transition to mainstream markets.

The framework applies the three methods in a logical sequence that reflects the analytical aim and scope of the thesis. It begins with an environmental assessment using LCA to quantify the potential impacts of introducing urine recycling into conventional and source-separating sanitation systems. This step identifies whether, and under what conditions, urine recycling offers net environmental benefits and serves as an initial sustainability screening. The findings from the LCA then inform the TIS analysis, which investigates the institutional and functional conditions that enable or constrain diffusion. The TIS component focuses on how actor networks, policy frameworks, and market structures influence the development of urine recycling and how legitimacy, knowledge, and resource flows shape its potential transition pathway. Then, SDM builds on results from both LCA and TIS to simulate adoption trajectories, capturing feedback mechanisms and time-dependent interactions among environmental, institutional, and behavioral variables. Finally, we reach the stage where we communicate with decision-makers on how to implement urine recycling. This is achieved through a second LCA that compares three urine recycling configurations in three different treatment locations. Through this sequential integration, the framework provides complementary perspectives that link environmental outcomes with the systemic dynamics of socio-technical change.

This framework responds to recent methodological discussions that call for closer integration between sustainability assessment and transition research (Lindfors et al., 2025). It also draws conceptually on advances in both life-cycle and innovation-system research. In particular, it adopts the spirit of transition-focused and future-oriented approaches to LCA (Arvidsson et al., 2023; Ventura, 2022), aligning with their motivation to move environmental assessment toward a system-transition perspective rather than remaining at the product level. While this thesis does not formally apply these new LCA types, it contributes to the broader discussion on how established LCA methods –here, a comparative consequential LCA– can serve as an informative step for transition theories to identify which niche to empower for transition. Similarly, the framework builds on the structured system-innovation perspective in TIS research (Andersson et al., 2023), recognizing that technological innovation systems include interconnected social and technical structures. Therefore, the thesis contributes to recent cross-disciplinary efforts to develop integrated methodologies that can both measure sustainability and explain the processes through which it develops.

By linking environmental assessment, innovation-system analysis, and dynamic modeling, the sustainability transition assessment framework developed in this thesis provides an integrated approach for understanding both the potential and the constraints of circular sanitation systems. It captures not only the environmental outcomes of technological change but also the institutional conditions and feedback mechanisms that govern how such change unfolds over time. This sequential integration establishes a coherent methodological foundation for analyzing the transition of urine recycling from a niche innovation toward a mainstream component of sustainable sanitation.

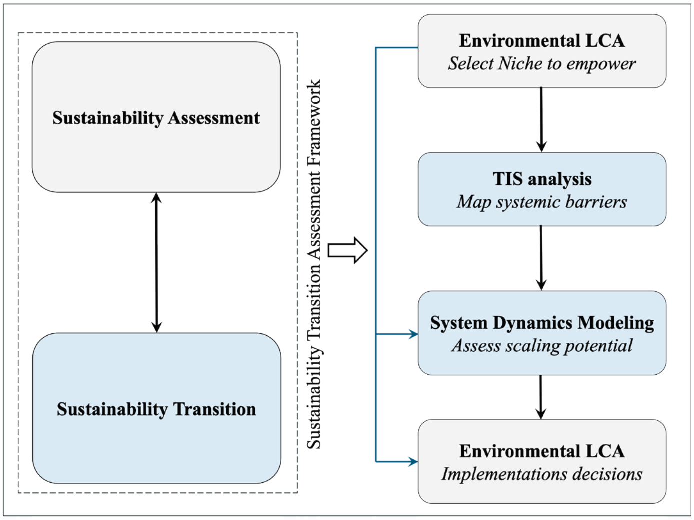

Figure 3: Sustainability Transition Assessment Framework integrating Sustainability Assessment (LCA) and Sustainability Transitions (TIS + System Dynamics) through a sequential and iterative process.

4.2 Conceptual Foundations

4.2.1 Environmental Assessment LCA

The environmental component of the framework begins with consequential life cycle assessment (CLCA) to explore the potential environmental benefits of introducing urine recycling to conventional and source-separation sanitation systems. The selection of LCA as the environmental component of the framework is deliberate. Unlike environmental impact assessment (EIA), which is designed for project-specific regulatory evaluation, LCA provides a standardized, system-based method that enables comparative assessment of technologies. This makes it particularly suitable for early-stage innovations such as urine recycling, where design options, system configurations, and operational scales are still evolving. Moreover, the use of consequential LCA (CLCA) rather than attributional LCA (ALCA) aligns the environmental assessment with the transition-oriented nature of the research. CLCA models the consequences of introducing new systems by accounting for market substitution and indirect effects, which are crucial for innovations that replace mineral fertilizers or alter wastewater treatment loads (Heimersson et al., 2019).

In the context of sanitation planning, LCA enables urban planners, engineers, and decision-makers to understand the environmental impacts and trade-offs associated with different sanitation systems. This, in turn, supports more informed and sustainable choices in both system design and policymaking (Corominas et al., 2020). Therefore, a comparison between the two LCA methods has been conducted to highlight the importance of transparency in LCA modeling and the effect of methodological choices on decision-makers' interpretation of the results.

4.2.2 Technological Innovation Systems (TIS) Analysis

Following environmental evaluation, the framework employs TIS analysis to examine how socio-technical structures and functions influence the development and diffusion of the innovation. TIS is chosen over other transition theories because it is a technology-specific method that provides practical diagnostic power for early-stage innovations (Bergek et al., 2008a). This makes it particularly suitable for studying early-stage sanitation innovations, such as urine recycling, which are still evolving and face systemic barriers to scaling.

Within this framework, the TIS analysis examines how institutional, organizational, and market conditions influence the potential for urine recycling to transition from experimental settings to mainstream implementation. It combines structural and functional perspectives: structural analysis maps actors, networks, and institutions across the value chain, while functional analysis evaluates key system processes, including entrepreneurial experimentation, knowledge development and diffusion, guidance of the search, market formation, resource mobilization, and legitimacy creation (Hekkert et al., 2007). Assessing the strength and interlinkages of these functions clarifies which mechanisms enable or block system growth and highlights leverage points for policy and stakeholder action.

Overall, applying TIS in this thesis provides a systematic way to diagnose why promising environmental technologies, such as urine recycling, often remain confined to niche experiments. It complements the LCA by explaining how institutional structures and actor networks mediate the translation of technical potential into real-world adoption. By identifying structural gaps and functional weaknesses, the TIS analysis offers evidence-based recommendations for supporting a sustainable transition in the sanitation sector.

4.2.3 System-Dynamics Modeling (SDM)

The third component, system-dynamics modeling, integrates insights from LCA and TIS into a dynamic, feedback-based representation of transition processes. The choice of SDM over other integrative tools –such as multi-criteria assessment (MCA), agent-based modeling, or static scenario analysis– is because of SDM's capacity to capture feedback loops, time delays, and nonlinear interactions among environmental, institutional, and behavioral variables (Forrester, 1961; J. Sterman, 2000). While MCA evaluates predefined alternatives based on weighted criteria, SDM models how systems change over time, revealing the feedback structures that either promote or hinder transitions. This makes SDM especially useful for investigating long-term diffusion and policy dynamics in emerging socio-technical systems.

Although SDM originated in systems analysis and integrated sustainability assessment, it has become increasingly used in sustainability transition research to study dynamic changes in complex socio-technical systems (Shiu et al., 2023; Sušnik & Mellios, 2025). In this thesis, SDM bridges the gap between previous LCA and TIS studies by transforming causal relationships identified in those analyses into formal feedback loops and stock–flow structures. This allows for examining how technological performance, institutional support, and user behavior interact over time to impact diffusion outcomes (Nabavi et al., 2017).

Here, SDM is employed not as a predictive forecast tool but as an exploratory framework for testing hypotheses and analyzing scenarios. The model simulates potential adoption trajectories of urine recycling in Sweden, including feedback mechanisms like user satisfaction, environmental benefits, institutional support, and abandonment rates. These simulations help SDM identify reinforcing and balancing feedback loops that influence how quickly and stably transitions occur, while also highlighting cross-sectoral leverage points to accelerate diffusion.

By integrating insights from LCA and TIS within a dynamic, feedback-driven model, SDM extends the analysis from static assessment to system evolution. It functions as both an integrative sustainability assessment tool and a transition-focused modeling method, offering a full view of how circular sanitations can expand under different policy and market scenarios (Yi et al., 2023).

4.3 Methodological Reflections

The design of the Sustainability Transition Assessment Framework reflects a deliberate attempt to bridge analytical depth with practical feasibility. Its sequential structure – linking LCA, TIS, and SDM– creates a logical progression from assessing environmental performance to analyzing socio-technical conditions and simulating transition dynamics. Each method addresses a distinct aspect of system transformation, and their interconnection ensures that environmental insights are interpreted within institutional and behavioral contexts. In this way, the framework connects static performance evaluation with dynamic transition processes, allowing for a more comprehensive understanding of how circular sanitation innovations may evolve over time.

Despite this complementarity, each method has inherent limitations that must be acknowledged. Beginning with the environmental component, LCA offers quantitative rigor and comparability but can overemphasize measurable impacts while overlooking institutional and social complexities. This risk is mitigated in the framework by embedding LCA within a broader transition-oriented analysis rather than treating it as an endpoint. Moreover, the applicability of LCA depends strongly on system maturity. Source-separating sanitation systems, such as urine recycling, are still emerging niches, where data scarcity, technological immaturity, and uncertain market conditions introduce considerable uncertainty. Related tools such as social life cycle assessment (SLCA), life cycle costing (LCC), or cost–benefit analysis often require mature systems with stable market data, established user behavior, and consistent product pricing–conditions rarely met by early-stage innovations (Fan et al., 2015; Gluch & Baumann, 2004).

The TIS component is specifically designed to analyze early-stage, disruptive innovations, addressing socio-political barriers and stakeholder dynamics that SLCA or LCC often overlook (Peña & Rovira-Val, 2020; Pollok et al., 2021). It examines market formation, legitimacy building, and institutional change – factors that are essential to understanding how innovations move from niche to regime level. However, TIS also has limitations. Its focus on actors, networks, and institutions can underrepresent material and environmental feedback, and its functional mapping may be influenced by subjective interpretation of qualitative data (Ulmanen & Bergek, 2021). Moreover, TIS is primarily diagnostic rather than predictive; it identifies barriers and enablers but does not quantify their relative influence over time. These weaknesses are partly compensated for in this framework by linking TIS with LCA, which grounds the analysis in measurable environmental outcomes, and SDM, which explores the dynamic implications of system interactions.

Similarly, SDM introduces its own methodological challenges. While it provides a valuable dynamic representation of feedback and time delays, model construction relies heavily on assumptions and simplified causal relationships derived from empirical studies. As such, results are exploratory rather than predictive, serving to test hypotheses and reveal system sensitivities rather than to forecast exact outcomes. The accuracy of SDM outputs, therefore, depends on the quality of underlying data and the transparency of assumptions.

Taken together, these reflections illustrate that no single method can fully capture the complexity of sustainability transitions. However, combining them in an integrated, sequential manner allows their strengths to compensate for individual weaknesses. LCA provides a quantitative evidence base, TIS situates technological performance within socio-institutional contexts, and SDM reveals how feedback among these elements unfolds over time (Binder et al., 2020). This triangulation enhances explanatory power and practical relevance while maintaining methodological transparency. By aligning methodological choice with system maturity and research objectives, the framework provides a flexible structure that can evolve as urine-recycling technologies mature. At later stages, complementing this framework with social life cycle, life cycle costing, or other quantitative assessments could enrich the analysis of social and economic dimensions. For now, the combined application of LCA, TIS, and SDM provides a coherent and empirically grounded foundation for investigating how circular sanitation systems can transition from pilot scale to mainstream markets.

5. Research Material and Methods

This thesis applied a sustainability transition assessment framework (Chapter 4) that combined environmental life cycle assessment with technological innovation systems analysis and system dynamics modeling. The framework is sequential, designed to first establish the environmental rationale for urine recycling, then explore socio-technical barriers, subsequently simulate adoption paths, and finally offer decision-relevant implementation guidance. Each step was linked to one or more of the appended papers (Papers I–IV), ensuring methodological rigor and coherence throughout the thesis.

5.1 Step 1: Environmental Assessment (Paper I)

The first step assessed the potential environmental impacts of introducing urine recycling into various sanitation systems, thereby addressing Objective 1. This was accomplished through a CLCA of sanitation scenarios for the new district of Brunnshög in Lund, Sweden (Paper I). The site was chosen because it represents a new, large-scale urban development (approximately 40,000 inhabitants) where sanitation options were still being considered, and where regional wastewater treatment capacity is limited.

The included scenarios were: (1) local wastewater treatment plant (WWTP) (as a reference scenario), (2) urine recycling alongside the reference WWTP, (3) a decentralized black- and greywater system, and (4) a hybrid system combining urine recycling with decentralized black- and greywater separation. The functional unit used was the treatment of wastewater generated per person annually. System boundaries extended beyond treatment plants to cover collection infrastructure, fertilizer, and biogas substitution. The life cycle inventory (LCI) included components such as piping and porcelain for collection, sewer infrastructure (piping, excavation, and backfilling), treatment plant operation details (chemical and energy use), and construction. Data sources comprised utility reports, pilot studies, and literature. Modeling was performed in SimaPro® using the ReCiPe® 2016 Midpoint (World, Hierarchist) method. Impact categories were customized, focusing on five key indicators: global warming potential (GWP, kg CO_2-eq), stratospheric ozone depletion (SOD, kg CFC-11 eq), terrestrial acidification (TAD, kg SO_2-eq), freshwater eutrophication (FEP, kg P-eq), and marine eutrophication (MEP, kg N-eq). The urine recycling system captured 75% of the urine; thus, it was assumed that the remaining 25% together with the remaining wastewater, were transported to the WWTP, which was modeled accordingly to account for changes in nitrogen and phosphorus removal (scenario 2). The consequential approach was used to account for system-wide effects, such as fertilizer substitution and reduced WWTP loads.

By quantifying the environmental benefits urine recycling can provide to conventional and source separation systems, this step defined the environmental 'why' for subsequent transition analysis.

5.2 Step 2: Technological Innovation System (Papers II - III)

While Paper I demonstrated that urine recycling is environmentally promising, its limited adoption raised the core transition question: why has this system not diffused despite proven environmental benefits? This was addressed in Objective 2 using the Technological Innovation System, in two complementary studies.

5.2.1 Knowledge Evolution within Urine Recycling TIS (Paper II)

Paper II focused on the primary function of the technological innovation system (TIS): knowledge development and diffusion. This function is widely regarded as the most crucial in early-stage TIS analyses, as it signals the breadth and depth of the knowledge base, the pace of technological progress, and the mechanisms by which knowledge circulates among actors (Bergek et al., 2008a). For emerging technologies such as urine recycling, a systematic assessment of knowledge development and diffusion provides insights into whether a sufficiently robust TIS is taking shape and where gaps remain.

To investigate this, Paper II conducted a bibliometric analysis to map and code existing knowledge about urine recycling from 1990 to 2022. After mapping, the thesis developed a multi-criteria evaluation framework (Table 1) to assess the performance of the knowledge function. Criteria included: (i) the growth in the number of publications over time, (ii) evidence of technological innovation in scientific research, (iii) knowledge diversity across disciplines, (iv) geographic spread of knowledge across countries, (v) the volume of knowledge compared to conventional sanitation, and (vi) the level of actor engagement.

Each criterion was rated on a 1–5 scale. These criteria were formulated through a review of relevant TIS literature and prior studies applying TIS frameworks to emerging technologies. Their rationale stems from established characteristics used to detect and evaluate emerging technological fields (see Paper II).

By combining bibliometric mapping with a multi-criteria assessment, Paper II provided a comprehensive picture of the knowledge base underpinning urine recycling. This allowed both quantitative tracking of knowledge growth and a qualitative evaluation of how well the TIS's knowledge function is performing relative to the requirements of system emergence and diffusion.

Table 1: Multi-criteria framework for assessing the knowledge development and diffusion function of the urine recycling technological innovation system (adapted from Paper II, read Paper II for a more elaborate explanation).

Criterion	Description	Assessment scale examples (1–5)
Growth in publications	Increase in the number of peer-reviewed publications on urine recycling over time.	1 = Publications increased zero-fold* per decade.; 5 = increased ≥ 8-fold
Disciplinary innovation	Number of pilot-scale trials, and follow-up publications per technology	1 = Zero pilot-scale trials, and follow-up publications per technology.; 5 = >30 pilot-scale trials, and follow-up publications per technology.
Technological diversity	Number of new technologies entering the TIS per decade.	1 = Zero new technologies; 5 = >30 new technologies
Geographical diffusion	Number of countries actively contributing to urine recycling research.	1 = Zero new countries per decade; 5 = >30 new countries per decade
Relative knowledge volume	Proportion of urine recycling publications compared to the wider sanitation field.	1 = TIS publications < 1% of sanitation & conferences < 5% per year.; 5 = 12% ≤ TIS publications ≤ 15% sanitation & 12% ≤ conferences ≤ 15% per year.
Temporal trend	Consistency and continuity of research activity over the study period.	1 = Negative trend.; 5 = Positive trend

5.2.2 Urine Recycling TIS Evaluation (Paper III)

Paper III expanded the analysis to include a comparative evaluation of urine recycling TISs in Sweden and Switzerland, two countries at the forefront of technological experimentation in urine recycling. While both have pioneered developments in urine recycling, their institutional contexts and trajectories of adoption differ, offering a valuable opportunity to examine the role of system functions in shaping transition potential.

The analysis involved two steps: Step 1: Structural analysis of the focal urine recycling TIS, which included mapping structural elements and identifying the types of actors involved in the supply chain. Actors were categorized into four groups: (i) industry and infrastructure (e.g., private companies, wastewater treatment plants), (ii) knowledge institutions (e.g., universities, research institutes), (iii) government and supporting organizations (e.g., municipalities, NGOs), and (iv) financiers (e.g., banks, funding agencies). This mapping provided an overview of actor diversity and system-level organization in both countries. Step 2: Functional pattern analysis of the focal urine recycling TIS, which examined functional performance in Sweden and Switzerland. A set of diagnostic questions, in the form of indicators, was developed for each TIS function. These indicators were created through desk research, literature reviews, and expert input, and were refined based on feedback from co-author roundtable discussions (see Table 2).

For the evaluation phase, a combination of survey analysis and a modified Delphi method was employed. The Delphi method is a well-known expert-based approach that gathers informed judgments through an iterative, anonymous process to reduce bias and reach consensus (Gallego & Bueno, 2014). In this study, the standard two-round Delphi was adapted: the first round involved expert surveys, and the second round was replaced with two focused workshops. In these workshops, a diverse group of experts from Sweden and Switzerland convened to directly assess the functional performance of their respective TISs. Experts engaged in structured discussions without interference from analysts, preserving the advantages of their deliberation while providing more qualitative insights into system dynamics.

Table 2: Indicators used to evaluate the functional performance of the urine recycling technological innovation system (adapted from Paper III, inspired by Bergek et al. (2008a).

Function	Definition	Key indicators
Entrepreneurial experimentation	Extent and diversity of practical trials and demonstrations of urine recycling technologies.	Number and scale of pilots; diversity of actors involved; transition from lab to field
Knowledge development	Creation of new technical, market, and policy knowledge relevant to urine recycling.	Quantity and quality of research; range of knowledge domains covered
Knowledge diffusion	Exchange of knowledge among actors and across contexts.	Frequency of cross-sectoral collaboration; participation in conferences/networks
Guidance of the search	Existence of shared visions, goals, and roadmaps guiding technology development.	Presence of national strategies; alignment of actor expectations
Market formation	Development of stable demand and supply for urine-derived products and services.	Existence of pilot scales, customers; price competitiveness; market size
Resource mobilization	Availability of human, financial, and infrastructural resources to support scaling.	Number of human and infrastructure resources
Creation of legitimacy	Social acceptance and institutional support for urine recycling.	public perception; lobbying activity; regulatory recognition.

Beyond the standard functional set, participants also discussed shared visions for the future of urine recycling, offering insight into expectations, alignment, and perceived transition pathways. Although not a formal TIS function, the inclusion of visions follows the reasoning in transition studies that emphasize their role in guiding and coordinating innovation (Weckowska et al., 2025).

By combining structural, functional, and visionary perspectives, Paper III provided a comparative and future-oriented assessment of the urine recycling innovation system. The analysis revealed where the TIS functions effectively, where bottlenecks persist, and how actor expectations shape the potential for upscaling in each national context.

5.3 Step 3: System Dynamics Modeling

System dynamics modeling (SDM) was used as the third analytical step to synthesize and operationalize findings from Papers I–III within a dynamic framework that captures feedback loops and nonlinear interactions among environmental and socio-technical factors. While the LCA in Paper I provided a static assessment of environmental performance, and the TIS analysis in Papers II and III identified structural and functional conditions affecting diffusion, SDM extended the analysis by showing how these factors evolve and interact over time. The model was primarily intended for exploration and heuristic learning, rather than as a predictive instrument, aiming to examine how varying policies, knowledge flows, and user behaviors might influence the long-term adoption of urine recycling.

The model-building process followed the standard stages outlined by Sterman (2000): problem articulation, conceptualization, formulation, testing, and scenario design. The problem definition was based on previous studies indicating that, despite environmental benefits, urine-diverting sanitation technologies in Sweden remain limited and often fragmented (Dioba et al., 2025; Kvarnström et al., 2006; McConville et al., 2017b). The model, therefore, aimed to identify the feedback mechanisms underlying this stagnation and to examine the conditions under which adoption might shift from low to high levels. Conceptualization drew on empirical insights from Papers I–III. Paper I provided quantitative data on nutrient recovery and environmental benefits; Paper II informed knowledge and diffusion dynamics, operationalized as learning, maintenance quality, and institutional support; and Paper III contributed insights on institutional barriers, policy conditions, and behavioral factors. These elements were integrated through causal-loop diagrams that mapped the hypothesized feedback guiding UDT diffusion.

The resulting conceptual structure included four main reinforcing loops– Policy/Legitimacy (R1), Market Demand (R2), Visibility/Acceptance (R3), and Service Quality (R4) – and one balancing loop, System Abandonment (B1). The policy–legitimacy mechanism (R1) describes how increased policy support enhances legitimacy, encouraging further adoption and justifying ongoing political attention. The second reinforcing loop (R2) captured the interaction between nutrient recovery and market demand: as installations grow, more nutrients are recovered, increasing the supply of urine-derived fertilizer, lowering its price, and encouraging market uptake. The third reinforcing loop (R3) illustrated the process of visibility and social acceptance, where greater exposure to operational systems builds familiarity and confidence, leading to a higher willingness to adopt. The fourth reinforcing loop (R4) focused on service quality, demonstrating how improved maintenance and user satisfaction sustain performance and promote new adoptions. Conversely, the balancing loop (B1) represented system abandonment, in which technical failures, poor maintenance, or unsatisfactory experiences reduce installed stock and undermine legitimacy. Collectively, these feedback loops define the dynamic structure of the sanitation transition process.

This conceptual structure was then translated into a quantitative stock-and-flow model implemented in Vensim DSS (version 9.3), shown in Figure 4. The core stock variable represents the cumulative number of operational UDTs in Sweden. The inflow to this stock (adoption rate) reflects the annual number of new UDT installations, while the outflow (abandonment rate) represents the number of UDT discontinued due to technical or social factors. The adoption rate depends on willingness to adopt, policy incentives, and alignment with national sustainability goals, whereas abandonment is primarily driven by system performance and user satisfaction. These flows connect policy, behavioral, and environmental factors into an integrated dynamic structure. Simulations run from 2025 to 2050, with an initial installed base of 100 UDTs, chosen to reflect a small, existing niche consistent with Swedish pilot activity.

To represent the behavioral and institutional dynamics realistically, several mathematical functions grounded in empirical data and theoretical reasoning were employed to capture typical patterns of change and interaction observed in socio-technical systems (Table 3). The nutrient recovery subsystem quantified nitrogen (N), phosphorus (P), and potassium (K) flows based on Paper I, assuming four users per UDT and average annual excretion rates of 3.97 kg N, 0.33 kg P, and 0.9 kg K per person. These flows were aggregated to calculate total fertilizer output in nutrient equivalents ($N + P_2O_5 + K_2O$). The fertilizer quantity then influenced the base market price through a non-linear inverse relationship reflecting economies of scale: as production increased, price decreased, capturing realistic market learning effects and reinforcing feedback between supply and demand.

Institutional and policy processes were modeled using logistic functions, which describe growth that accelerates rapidly at first and then slows as it approaches a limit – a common pattern in social or institutional adoption processes (Sterman, 2000). For example, lobbying activity was modeled as a function of knowledge development and perceived environmental benefits, illustrating the feedback loop between scientific evidence, stakeholder advocacy, and institutional response –an interaction observed in the Swedish context described in Paper III. The parameter values in the lobbying pressure equation are based on the assumption that lobbying activity gradually responds to growing evidence and awareness but accelerates once institutional actors recognize clear environmental and political benefits. The growth rate ($k = 0.001$) determines the steepness of the logistic curve, indicating how quickly change happens around the tipping point and reflecting the inertia typical of policy development. The tipping point ($TP = 25$) signifies the approximate level of combined knowledge and perceived environmental benefit (in normalized units) needed for lobbying to gain significant momentum. The maximum lobbying capacity (max lobbying = 50) sets the upper limit of institutional mobilization, ensuring the model remains stable and comparable with other variables on a similar 0–50 scale. This cap represents the idea that lobbying intensity cannot surpass certain political or organizational limits.

Subsidy levels were modeled similarly, increasing with lobbying pressure in a saturating curve that reflects diminishing returns – initial efforts yield substantial impacts, but influence decreases once political or financial limits are reached. Using the same growth rate ($k = 0.001$) and a higher tipping point ($TP = 40$), it suggests that strong lobbying and legitimacy are necessary before significant subsidies appear. The maximum subsidy (max subsidy = 15) represents the upper limit of financial support, scaled relative to fertilizer price (≈15 SEK/kg as a reference ceiling, assuming government subsidies are unlikely to exceed this).

Behavioral processes, such as social exposure and willingness to use urine-derived fertilizer, were represented using smoothed functions, which introduce delays that mimic the gradual nature of social learning and behavioral adaptation – people and institutions rarely change instantaneously in response to new information. Willingness to adopt UDTs was formulated as a combined function of perceived benefits, system performance, and social visibility, thereby connecting social perception with technical reliability and institutional framing.

The technical variables, such as maintenance quality, improved through knowledge provision and accumulated experience (learning-by-doing), while system performance was defined as a weighted function of maintenance quality and user satisfaction, with different importance (weights) assigned to each contributing variable. Satisfaction increased with reliability and perceived environmental benefits but decreased when performance was poor. Abandonment was modeled as an inverse function of performance, scaled by the abandonment rate, capturing diminishing returns as performance and satisfaction improve – meaning the abandonment rate declines. This setup allowed the model to replicate the observed tendency for negative user experiences to reduce broader system legitimacy (Paper III).

Environmental benefits were modeled as a dynamic variable linking the technical and social subsystems. Building on Paper I, a scale-dependent power-law relationship was used to describe how total reductions in global warming potential (GWP) increase with the number of installations, while marginal benefits decrease slightly with scale. These environmental improvements fed back into lobbying and perceived benefits, creating a reinforcing feedback loop between environmental evidence and social legitimacy.

Model validation included structural, dimensional, and behavioral checks in Vensim, along with expert validation involving researchers and practitioners familiar with urine-recycling systems in Sweden. Sensitivity analysis further examined the influence of key parameters, including policy support, lobbying pressure, and the baseline abandonment rate. The purpose was not to quantify statistical uncertainty but to identify leverage points where targeted interventions could most effectively alter diffusion outcomes.

These logistic relationships regulate the intensity and timing of key reinforcing and balancing loops. In the Policy/Legitimacy loop (R1), the logistic function for lobbying pressure ensures that institutional influence remains limited until knowledge development and environmental benefits surpass the tipping point (≈ 25), after which lobbying grows rapidly, triggering the expansion of financial subsidies up to their maximum potential (≈ 15 SEK). This feedback reinforces legitimacy and accelerates adoption. In the Market Demand loop (R2), the logistic formulation of perceived benefits – with a tipping point of 50 and growth rate of 0.05 – captures how user awareness and social acceptance increase slowly at first but rise sharply once exposure to operational UDT systems and visible environmental outcomes becomes widespread. These behavioral and institutional thresholds collectively determine when the system transitions from a niche phase of experimentation to broader diffusion.

The same functional form indirectly contributes to the Visibility/Acceptance (R3) and Service Quality (R4) loops, ensuring that social willingness and satisfaction follow realistic, saturating dynamics rather than instantaneous shifts. By incorporating these parameterized logistic relationships, the model reproduces the gradual yet accelerating nature of socio-technical transitions, in which institutional support, market response, and social perception co-evolve through cumulative, feedback-driven processes rather than linear cause-and-effect progressions.

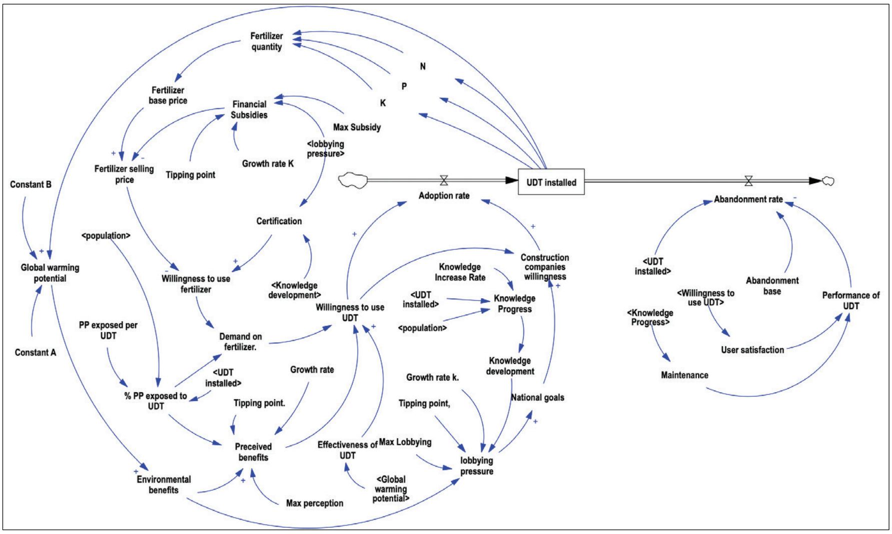

Figure 4: Stock-and-flow diagram of the urine recycling system showing the feedback structure linking policy support, market demand, visibility, and service quality.

Scenario design tested how institutional support and behavioral reinforcement shaped long-term diffusion. Three contrasting scenarios were simulated to reflect different systemic conditions. The first was a policy-push scenario, characterized by strong institutional engagement, certification schemes, financial incentives, high service quality, and market demand. The second represented low-legitimacy pressure, reflecting weak institutional backing and limited coordination; in this scenario, the maximum lobbying pressure and tipping-point values were lowered to 10, while the maximum subsidy was set to 5. The third, a no-policy scenario, excluded incentives, certification, and lobbying altogether and was assigned a value of zero. The resulting simulations and diffusion trajectories are presented in Chapter 6.

Table 3: Parameters and data sources examples used in the system dynamics model of urine-diverting toilet adoption in Sweden (2025–2050)

Parameter	Unit	Value / Range	Source
Installed UDTs	Units	Dynamic (initial = 100)	Model
Adoption rate	Units yr^{-1}	Influenced by policy, market, and awareness loops	Calculations
Abandonment rate	Units yr^{-1}	Decreases with improved maintenance and satisfaction	Calculations
GWP per UDT	kg CO_2-eq/UDT/year	GWP * (UDT installed) ^ (Constant B)	Paper I
Nutrient recovery	kg/year	N: 3.5, P: 0.4, K: 1.0: N + (P * (100/43.6)) + (K * (100 / 83)	Paper I
Fertilizer base price	Swedish kroner per kg	MAX(10, IF THEN ELSE(Fertilizer quantity < 39400, 50, 50 * (0.98 ^ (MIN(50, MAX(-50, (Fertilizer quantity - 39400) / 40000))))))	Calculations
Fertilizer selling price	Swedish kroner per kg	Fertilizer base price - Financial Subsidies (Max Subsidy / 1 + EXP(- Growth rate K * (lobbying pressure - Tipping point)). Max Subsidy=15, TP=40	Calculations
Fertilizer demand	—	SMOOTH(Willingness to use fertilizer * "% PP exposed to UDT" * 100 , 10)	Calculations
Policy support	0–1	Scenario-specific	Paper III
Lobbying pressure	—	Scenario-specific: Max Lobbying/(1+EXP(MIN(50, MAX(-50, -"Growth rate k." * ((Knowledge development * environmental benefits) - "Tipping point,"))))) k = 0.01, TP = 20	Paper III
Perceived benefits	%	Max perception / (1 + EXP(- Growth rate * (Environmental benefits * "% PP exposed to UDT" - "Tipping point."))) where exposer = UDT installed*PP exposed per UDT)/population)*100)	Calculations
Maintenance	%	Improves with knowledge provision	Paper II-III,
UDT Performance	0–1	Influenced by the willingness and satisfaction = (0.6 * Maintenance + 0.4 * User satisfaction)	Paper III,

5.4 Step 4: Environmental Assessment of Implementation (Paper IV)

The final step revisits LCA to provide decision-making guidance relevant to implementation. In this step, the same urine-dehydration technology as in Paper I was analyzed at three potential treatment locations: toilet, building basement, and centralized levels (Paper IV). By keeping the technology constant, the analysis focused on the effects of treatment location, thereby clarifying where and how urine recycling offers the best environmental benefits.

Both consequential and attributional LCAs were used to examine how methodological framing influences results. The functional unit was one person-year of urine treatment, and the system boundaries covered collection logistics, stabilization, concentration, drying, transport, fertilizer substitution, and energy recovery. The ReCiPe® 2016 Midpoint (World – Hierarchist version) method was applied for both LCAs (Paper I & Paper IV), using Simapro® and Ecoinvent 3.8 to model environmental impacts. Five impact categories were evaluated: Global warming potential (GWP) in kg CO_2-eq, Terrestrial acidification potential (TAD) in kg SO_2-eq, Freshwater eutrophication (FEP) in kg P-eq, Marine eutrophication (MEP) in kg N-eq, and Cumulative energy demand (CED) in MJ. Sensitivity analyses tested variations in electricity mixes, acid types, transport distances, and recovery efficiencies.

This final step directly informs decision-makers on implementation decisions: whereas earlier steps justified the urine recycling conceptually and analyzed adoption dynamics, Paper IV identified which configurations are preferable in practice under different conditions.

6. Results

6.1 Environmental Sustainability Assessment (Paper I)

Paper I, addressing Objective 1, explored the potential environmental implications of introducing urine recycling into both conventional and alternative source-separating sanitation systems. Using CLCA, four sanitation configurations were evaluated for the Brunnshög district in Lund, Sweden: a reference wastewater treatment plant (WWTP), urine recycling integrated with the WWTP, a decentralized black- and greywater (BW & GW) system, and a hybrid system combining urine recycling with BW & GW separation (Table 4).

Table 4: Summary of sanitation scenarios including advantages, key burdens, and assumptions (Paper I- results)

Scenario	Key processes included	Environmental advantages	Key burdens / trade-offs
S1: Reference WWTP	Sewer & building collection, plant operation & construction, resource recovery.	Established technology, heat, biogas and sludge recovery potential	High energy and chemical demands, GHG emissions (N_2O & CH_4)
S2: Urine recycling + WWTP	Urine collection, system operation & construction, nutrient recovery + WWTP	Reduces GHG emissions via avoided N_2O and CH_4, nutrient recovery potential	Energy demand for concentration, chemical use for stabilization
S3: BW&GW system	Black and greywater collection, system operation & construction, resource recovery.	Large GHG reduction, heat, biogas and nutrient recovery potential	High chemical use, process complexity
S4: Hybrid (urine + S3)	Combines unit processes from urine and S3	Large GHG reduction and resource recovery potential	More complex logistics, requires high separation efficiency.

The estimated global-warming potentials (GWP) for scenarios 1–4 were 78, 62, 32, and 24 kg CO_2-eq per person per year, respectively (Table 5). Reductions in GWP across scenarios 2, 3, and 4 demonstrated that integrating source separation significantly improved environmental outcomes, particularly in decentralized configurations.

Process-level analysis (Figure 5) showed that, in the reference WWTP scenario, most emissions originated from electricity use, nitrous oxide from biological treatment, and methane from digestion, with heat recovery partly offsetting these emissions (−17.7 kg CO_2-eq/PE·y). Introducing urine recycling (S2) reduced the WWTP's GWP by about 20 % through avoided N_2O and CH_4 emissions and fertilizer substitution, though this was partially burdened by higher energy use for concentration and chemical stabilization. BW&GW (S3) achieved a ~ 60% GWP reduction through biogas recovery, irrigation reuse, and fertilizer substitution, but was burdened by chemical use in ammonia stripping and struvite precipitation. The hybrid system (S4) performed best overall, maximizing nutrient recovery and offsetting the chemical-intensive processes in S3, achieving nearly 70% in GWP reduction and improvements across all other impact categories.

Table 5: Net life cycle environmental impacts of the four sanitation scenarios, ReCiPe® 2016 Midpoint (World–H) method (adapted from Paper I). Values are per person equivalent per year; negative values indicate environmental savings.

Scenario	**GWP (kg CO_2-eq)**	**SOD (kg CFC11-eq)**	**TAD (kg SO_2-eq)**	**FEP (kg P-eq)**	**MEP (kg N-eq)**
S1. WWTP (reference)	78	8.2E-04	3.3E-01	8.8E-03	5.0E-01
S2. Urine + WWTP	62	2.9E-04	1.8E-01	7.0E-03	2.2E-01
S3. BW&GW	32	6.0E-05	7.2E-02	2.0E-03	2.7E-02
S4. Hybrid	24	4.7E-05	-1.2E-01	1.2E-02	2.9E-02

Although the hybrid configuration delivered the lowest impacts, two factors justify the continued focus on urine recycling in this thesis. First, the results show that urine recycling is a key enabling component across all improved configurations: its integration enhances the environmental performance of both the conventional WWTP and other source-separating systems. Second, while BW & GW systems are already being scaled up in Sweden – for instance, in the Helsingborg Oceanhamnen project (Kjerstadius et al., 2017; Sarkheyli et al., 2025) – urine-recycling systems remain at a pre-commercial stage despite their strong environmental potential. This difference makes urine recycling a particularly relevant subject for transition analysis: the environmental benefits look promising, but the social-technical and institutional conditions needed for scaling are not yet in place.

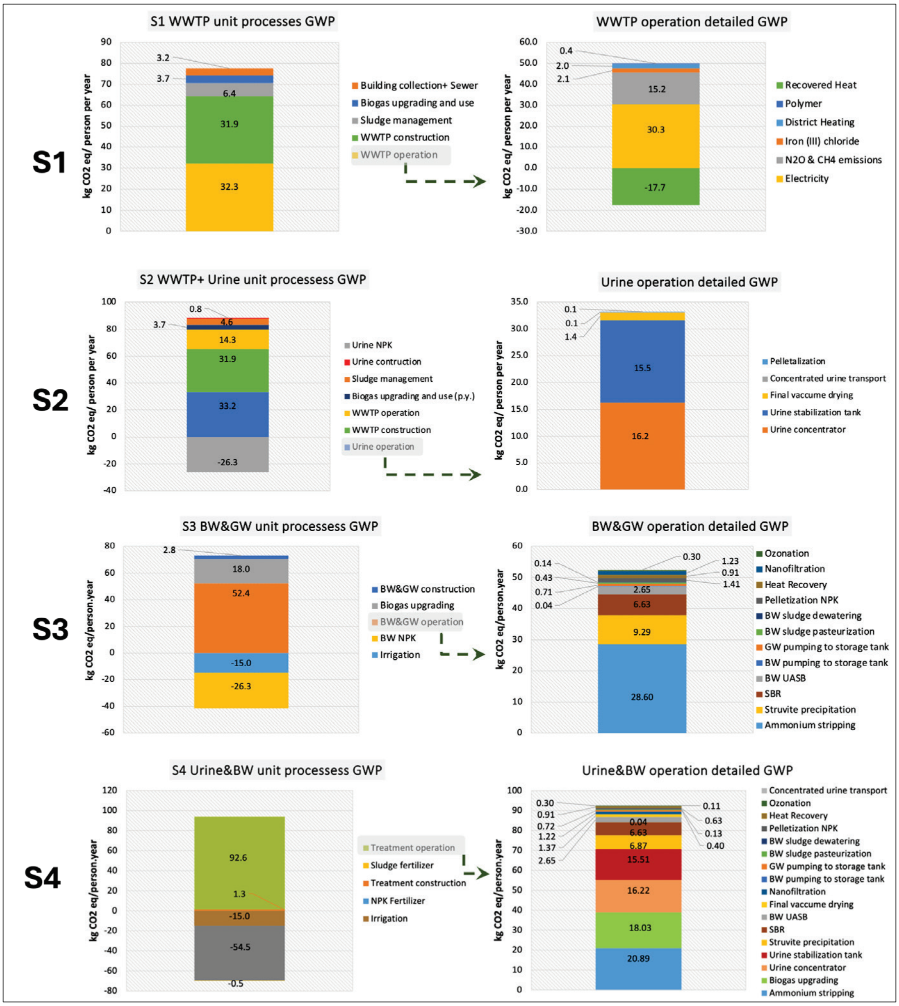

Figure 5: Unit process-level global warming potential (GWP) results for four scenarios: (S1)– GWP contributions from WWTP unit processes and its operations; (S2) – GWP contributions from urine and WWTP unit processes and its operations; (S3) – GWP contributions from blackwater (BW) and greywater (GW) unit processes and its operations; (S4) – GWP contributions from urine and BW unit processes and its operations. Adapted from Paper 1.

6.2 Sustainability Transition Assessment (Papers II & III)

Addressing Objective 2, Papers II and III examined the socio-technical conditions shaping the development and diffusion of urine recycling through a Technological Innovation Systems (TIS) lens. Paper II focused on the evolution of the knowledge base underpinning urine recycling, while Paper III assessed the broader functional performance of the urine recycling TIS in Sweden and Switzerland, identifying barriers, strengths, and opportunities for upscaling. Together, these studies revealed both the "potential and preparedness" of the urine innovation system and the "practical barriers to diffusion".

6.2.1 Knowledge Development and Diffusion (Paper II)

Paper II showed that knowledge production in urine recycling has grown substantially, with a sharp increase in scientific publications between 2011 and 2021 compared to 1990 –2010 (Table 6). This reflected a growing global interest in nutrient recovery from urine. However, the analysis also revealed critical limitations that constrain the system's readiness to transition:

- Limited innovation diversity: Despite the rise in the number of studies, innovation remained concentrated among a few dominant technologies, with a limited emergence of new approaches each decade.
- Scarcity of pilot-scale demonstrations: There were few pilot- or field-scale implementations globally, limiting real-world validation and broader acceptance of these technologies.
- Marginal role in the conventional sanitation discourse: Research on urine recycling accounted for a marginal fraction (less than 1%) of academic output and conference activity compared to conventional wastewater treatment technologies.
- Geographical concentration: Although more countries entered the TIS. Most innovations were concentrated in a limited number of countries, suggesting a restricted global diffusion of practices despite moderate knowledge dissemination.

Table 6: Multi-criteria evaluation of knowledge development and diffusion in the urine recycling TIS (Paper II).

Criterion	Key findings	Score (1–5)
Growth in publications	Sharp increase between 2011–2021 compared to 1990–2010. between 5 and 10 folds over the decades.	4
Disciplinary innovation	Low number of pilot-scale trials, and follow-up publications per technology	2
Technological diversity	Moderate number of new technologies entering the TIS per decade.	3
Geographical diffusion	10 to 30 countries entered the urine recycling TIS in the past two decades	4
Share in sanitation discourse	Less than 1% of academic and conference output compared to conventional wastewater treatment	1
Temporal trend	Consistency and continuity of research activity over the study period	4

The findings of Paper II indicate that although urine recycling is emerging as a promising research area, its knowledge system remains underdeveloped and disconnected from mainstream sanitation research. While such isolation is typical in early innovation niches, its persistence after several decades suggests a slow progression from isolated experimentation toward a coordinated and mature innovation system. The knowledge function is therefore expanding in volume but remains limited in diversity, application orientation, and institutional anchoring, constraining the system's capacity to support large-scale transition.

6.2.2 Functional Performance of Urine Recycling TIS (Paper III)

Paper III extended this analysis by evaluating the functional performance of urine recycling in Sweden and Switzerland across key innovation functions. The results showed that structural weaknesses in knowledge (identified in Paper II) translate directly into functional shortcomings that limit scaling (Table 7). Several barriers were identified, as shown below:

- Entrepreneurial experimentation: Both countries were actively involved in lab-scale testing, but real-world testing was limited to a few utilities. Switzerland showed greater actor diversity and engagement, suggesting more advanced entrepreneurial dynamics. In Sweden, experimentation mostly remained an academic activity.
- Knowledge development and diffusion: Findings from Paper II were corroborated, indicating that knowledge generation was stronger in Switzerland than in Sweden, while diffusion across actor groups and borders remained weak in both countries. The functional analysis also revealed that much of the available knowledge is not sufficiently targeted toward scaling or commercialization.
- Search guidance and institutional support: Both countries faced a significant bottleneck due to a lack of a clear national strategy and policy incentives. Regulatory uncertainty undermined stakeholder confidence and limited long-term investment. This absence of vision hindered the establishment of strong guiding signals within the system.
- Market formation: Market development remained limited. Although there were pilot projects, their quantity and scale were inadequate to stimulate demand. Costs associated with urine-diverting toilets and recycling services remained prohibitively high, and engagement from the agricultural sector was low.
- Resource mobilization: Switzerland had a better availability of human and financial resources for urine recycling; however, both countries lacked the necessary infrastructure and long-term funding mechanisms for upscaling.
- Legitimacy creation: The legitimacy of urine recycling remained fragile. Social acceptance was moderate; however, advocacy and lobbying efforts were limited. Furthermore, resistance in both countries came from established wastewater treatment sectors, which viewed urine recycling as a disruptive alternative.

Table 7: Comparative functional performance of the urine recycling technological innovation system in Sweden and Switzerland (adapted from Paper III). Ratings are on a low-medium-high scale.

Function	Sweden rating	Switzerland rating	Notes on differences
Entrepreneurial experimentation	low	medium	Sweden's activity remained mainly academic at lab scale with emerging pilot projects; Switzerland had more diverse actors and broader field trials.
Knowledge development	low	medium	Both countries had strong research capacity, but Switzerland's efforts were more application oriented.
Knowledge diffusion	high	high	Results from Paper II.
Guidance of the search	low	low	No national supportive regulations in either country. Lack of national strategy and incentives.
Market formation	low	low	Limited in both countries; Switzerland showed slightly more demand through targeted agricultural engagement.
Resource mobilization	low	low	More financial and human resources available in Switzerland, though infrastructure gaps persisted in both contexts.
Creation of legitimacy	low	low	Lack of strong lobbying and high sectoral resistance; Swedish utilities remained cautious.

The functional performance assessment showed that the Swedish and Swiss urine recycling TISs differed not only in performance but also in how actors defined "success." In contrast to our earlier summary, Paper III showed that although both countries shared the overarching aim of embedding urine recycling into sustainable sanitation infrastructure and circular economy strategies, they articulated different visions and defined near-term success differently, which partly explained the more positive Swiss assessments.

Swiss experts described near-term success as achieving a large adoption of UDTs in summer houses, with carefully planned, well-scoped implementations. By this standard, the Swiss saw a clear path forward and evaluated several indicators more positively. In contrast, Swedish experts did not see summer houses or ecovillages as meaningful next steps, as Sweden had already experienced a wave of such installations in the 1990s through grassroots efforts. For Sweden, “success” meant integrating urine recycling into urban areas and developing more mature, service-oriented systems – a more challenging goal that raised the standards for current performance. These different ideas of success stemmed from distinct historical paths: Sweden’s early bottom-up diffusion and subsequent backlash made stakeholders cautious about small-scale niche deployments, whereas Switzerland’s more organized, interdisciplinary efforts (such as NoMix/Novaquatis research programs) fostered a careful, step-by-step approach focused on clear goals and staged learning. As Paper III further suggested, both contexts agreed on the importance of combining top-down and bottom-up efforts –policy support, advocacy, knowledge sharing, municipal facilitation, high-quality pilots, and credible product certification – but they differed in their near-term goals: urban integration in Sweden versus smaller projects in Switzerland.

Together, Papers II and III offered a dual perspective on Objective 2. Paper II described the "potential and preparedness" of the system, characterized by a growing yet fragmented knowledge base, a small but active research community, and several promising technologies. Paper III highlighted the "practical barriers to diffusion": weak coordination, regulatory inertia, low legitimacy, and limited market traction. These findings indicated that although urine recycling is intellectually active and environmentally promising, it remained stalled in the development stage of the TIS life cycle. Bridging the gap between laboratory success and large-scale societal adoption will require integrating knowledge creation with institutional frameworks, establishing clear market pathways, and actively building legitimacy. These insights directly inform the scaling strategies evaluated in Objective 3 (Papers IV and the SDM analysis) by clarifying the systemic conditions that need to be addressed for urine recycling to shift from niche innovation to mainstream adoption.

6.3 System Dynamics Modeling

The SDM results provided a dynamic illustration of how urine-diverting toilets might diffuse in Sweden under different institutional and behavioral scenarios. The simulations revealed how reinforcing and balancing feedback loops jointly determine whether the system transitions into self-sustaining growth or remains locked in a state of stagnation. By integrating environmental, institutional, and behavioral insights from Papers I–III, the model offers a temporal perspective on how systemic change can unfold.

The simulations explored three contrasting scenarios representing different levels of institutional engagement and social legitimacy (Figure 6). The best-case (policy-push) scenario assumed strong lobbying pressure, certification schemes, and financial incentives – conditions reflecting proactive national support. The low lobbying pressure scenario represented weak but existing financial incentives, with some lobbying pressure. The no-policy scenario depicted the absence of lobbying pressure, incentives, or certification, reflecting minimal legitimacy and weak system coordination.

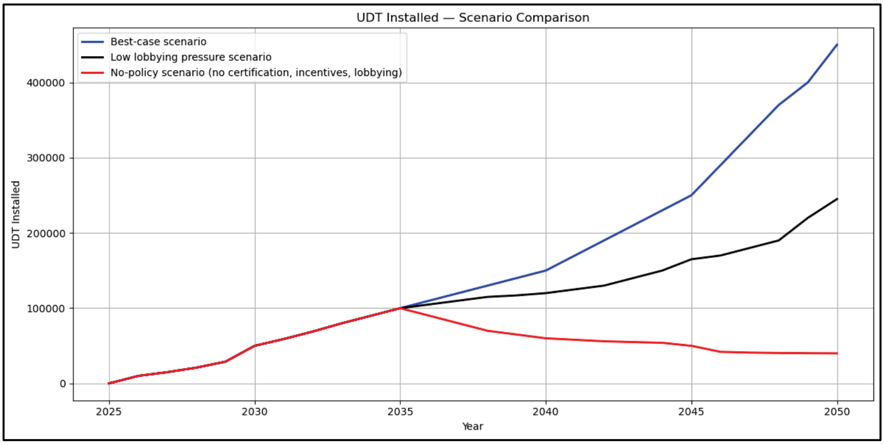

Figure 6: Compared the diffusion trajectories across the three scenarios. The blue curve depicted the policy-push scenario, the black curve the low-legitimacy pressure scenario, and the red curve the no-policy baseline.

All three scenarios experienced modest adoption in the first decade. This pattern indicates initial inertia within both market and institutional systems: knowledge diffusion, lobbying efforts, and user familiarity grow slowly, while the total fertilizer recovered hasn't yet reached a level to significantly lower prices. During this time, environmental benefits begin to build, although their visibility and impact on legitimacy are still limited. As fertilizer quantities increase and prices decline gradually, user willingness and perceived benefits begin to grow, setting the stage for faster adoption after 2035. Therefore, the early adoption phase reflects the period needed for social learning, trust development, and scale effects in fertilizer production to be established across all scenarios.

In the policy-push scenario, adoption begins slowly but gains momentum once targeted lobbying, certification, and subsidy mechanisms are introduced around 2035. Legitimacy then grows, creating positive feedback between institutional confidence and user willingness. Improved system performance and visibility reinforce satisfaction and trust, while large-scale nutrient recovery lowers the cost of urine-derived fertilizers, encouraging market adoption. These combined effects activate reinforcing loops R1–R3 (Policy/Legitimacy, Market Demand, and Visibility/Acceptance). After 2040, growth accelerates sharply, reaching a system-level tipping point around 2045. This is not one of the fixed tipping-point parameters in the logistic equations (e.g., TP = 25 for lobbying) but an emergent tipping point – the moment when multiple reinforcing loops dominate the balancing ones and self-sustaining diffusion begins. From 2045 onward, adoption outpaces abandonment, leading to exponential growth in installed units that surpass 400,000 by 2050. This turning point coincides with widespread social visibility (≈ 50% of the population exposed) and strong institutional legitimacy, confirming that feedback alignment drives transition.

In the low-legitimacy scenario, the maximum lobbying capacity and subsidies were set to lower values than those of the policy-push case (max lobbying = 10, max subsidy = 5). The resulting trajectory showed slower progress and diffusion. Adoption increased modestly, similar to the first scenario, until around 2035, when the curve's steepness and pace began to slow. Limited lobbying and partial subsidies provided only short-term boosts, which were significantly weaker than those in the policy-push case. Without clear institutional support, user confidence grew only slightly, and social exposure remained too limited to normalize UDTs in mainstream contexts. This outcome represents a soft lock-in effect: moderate activity continues without major expansion, reflecting the fragmented pilot culture described in Paper III. Empirically, this setup may closely resemble the current

Swiss situation, where some local policy support and financial initiatives exist; however, diffusion remains limited due to weak national coordination.

In the no-policy scenario, all variables –including lobbying, certification, and subsidies– were set to zero. Adoption increased modestly during the first decade, similar to the other two scenarios, but soon stabilized as abandonment began to offset new installations. Without institutional coordination, reinforcing feedback among awareness, acceptance, and adoption remained too weak to overcome early inertia. Visibility of UDTs stayed limited, restricting knowledge sharing and social normalization. Since the installed base was small, the effects of learning-by-doing on maintenance and reliability were limited, leading to stagnant performance. These technical reliability issues caused dissatisfaction and higher abandonment rates, reinforcing the balancing feedback loop B1. This mirrors patterns seen historically in Sweden during the early 2000s, when inadequate maintenance and coordination triggered public backlash against urine-diverting systems (Kvarnström et al., 2006; McConville et al., 2017b). In this projected future, similar dynamics might reappear: initially, environmental benefits and fertilizer production grow but stay politically unnoticed, preventing them from reinforcing legitimacy. As a result, the system tends to reach a near-equilibrium state where installation and abandonment rates either balance out or abandonment exceeds adoption, leading to a diffusion plateau or decline aligned with current trends.

The simulation demonstrated how environmental performance and social perception interact with each other. The environmental benefits from Paper I were only recognized when lobbying pressure exceeded its tipping point (TP = 25), leading to the initiation of subsidies and certification. This shows that environmental data alone doesn't cause change unless institutions validate and communicate it (Reichardt et al., 2016). Likewise, in the behavioral subsystem, willingness to adopt grew only when benefits were socially endorsed through visibility and positive feedback. This supports arguments from Paper III that system change relies on both technical proof and institutional framing.

SDM results indicate that interconnected feedback among environmental, institutional, and behavioral processes drives urine recycling diffusion in Sweden. Without policy support, the system remains stable due to weak reinforcing mechanisms. Clear policies and maintenance networks shift the balance toward reinforcement, breaking system lock-in and enabling rapid growth. This transition occurs once feedback aligns, showing the threshold-dependent nature of diffusion. SDM helps policymakers identify system thresholds, leverage points, and effective interventions for sustainable sanitation.

6.4 Environmental Assessment of Implementation (Paper IV)

Also contributing to Objective 3, Paper IV examined how different urine recycling configurations performed environmentally when implemented. Building on the scaling trajectories developed through the SDM, this study shifted the focus from potential adoption dynamics to the stage of practical implementation. While the SDM showed how adoption might evolve under various socio-institutional conditions, Paper IV addressed the later question of "where" and "how" urine recycling should be implemented once diffusion started.

To guide such decisions, the study compared three configurations (treatment at the toilet, at the building-basement, and at the centralized facility) under both ALCA and CLCA approaches. This dual modeling strategy reflected the decision-making focus of this stage: attributional modeling gave a static accounting perspective suitable for system benchmarking, while consequential modeling captured system-wide effects and market substitutions, helping to explain the broader implications of large-scale adoption. Comparing both allowed transparent interpretation of environmental results– an essential step when LCA outcomes were used to inform real-world planning and policy.

The results, shown in Table 8, indicated that the basement-level configuration achieved the most balanced environmental performance. With efficient heat recovery during urine dehydration (up to 70%) and moderate infrastructure requirements, it reached a GWP of 8 kg CO_2-eq/PE·y, nearly 50% lower than both the toilet-level and centralized configurations. Even when heat recovery efficiency dropped to 52%, the system remained carbon-negative, highlighting its robustness. It also exhibited the lowest cumulative energy demand, making it particularly suitable for integration into new urban developments.

The toilet-level system, while providing logistical advantages for retrofitting existing buildings, exhibited the highest energy use and a GWP of 17 kg CO_2-eq/PE·y, mainly due to high electricity use for concentration and stabilization. This shows a trade-off between retrofit practicality and environmental impact. Technical optimization is needed for household systems to achieve similar benefits. The centralized system, with up to 85% energy recovery, had a GWP of 16 kg CO_2-eq/PE·y. This indicates that even technically efficient systems can be disadvantaged by large-scale demands, and sewer networks can diminish their environmental performance.

Table 8: Comparative environmental performance of three urine recycling implementation configurations under consequential LCA (CLCA). Units of impact categories: GWP (kg CO_2-eq/PE·y), CED (MJ/PE·y), TAD (kg SO_2-eq/PE·y), FEP (kg P-eq/PE·y), MEP (kg N-eq/PE·y).

Scenario	GWP	CED	TAD	FEP	MEP	Key characteristics
Toilet-level	17	847	6.7E-02	1.9E-03	3.0E-03	Suitable for retrofitting existing buildings; highest electricity demand for concentration/stabilization; easier logistics at small scale.
Basement-level	8	516	5.0E-02	1.0E-03	3.0E-03	Most balanced performer; efficient heat recovery (up to 70%); lowest CED; remains carbon-negative even at 52% heat recovery; best suited for new developments.
Centralized	16	637	8.0E-02	5.1E-03	3.0E-03	Highest technical heat recovery (up to 85%) but penalized by infrastructure emissions; viable mainly where sewer expansion is planned.

Sensitivity analyses underscored the importance of context-specific factors. Transport distances, acid for stabilization, and recovery efficiency all impacted results. For example, replacing citric acid with sulfuric acid lowered GWP but introduced safety concerns that could limit real-world use.

Attributional and consequential modeling produced noticeably different outcomes and rankings among the configurations. Under ALCA, all three systems showed significantly lower global-warming potentials (GWPs) than under CLCA. In particular, the toilet-level scenario achieved a net negative GWP of approximately −8 kg CO_2-eq per capita per year, closely comparable to the basement scenario and better than the centralized scenario (Figure 4 in Paper IV). These differences mainly arise from methodological distinctions between the two approaches – specifically, the use of average versus marginal data and the treatment of substitution effects. In the attributional model, average emission factors were applied, and substitution was included. This resulted in lower reported emissions, especially in contexts like Sweden, where low-carbon renewable sources already dominated the electricity supply. In contrast, the consequential model assumed that incremental electricity demand was met by marginal suppliers, which were generally more carbon-intensive. As a result, CLCA produced higher climate impacts for the same processes, providing a more conservative and system-responsive view of environmental change. This comparison highlighted the importance of transparency in LCA assumptions when results are used to guide investment or regulatory decisions. Policymakers and planners need to understand not only what the impacts are but also why different modeling approaches produce divergent outcomes.

The SDM and LCA in Paper IV together provided a dual perspective on scaling strategies. While the SDM highlighted socio-technical dynamics, feedback loops, and tipping points that affected adoption trajectories, the LCA evaluated the environmental trade-offs of different technical options after adoption. By combining these approaches, this thesis demonstrated that the basement-level system offers the best balance of environmental performance, operational resilience, and scalability for new developments. Toilet-level systems can play a transitional role in retrofitting cases, while centralized options may be less beneficial except in specific infrastructural contexts.

This final step completed the thesis's integrated assessment sequence. It connected the environmental rationale established in Paper I, the socio-technical analysis in Papers II and III, and the dynamic adoption modeling in the SDM to provide concrete implementation guidance. The findings highlighted that effective upscaling depended not only on choosing the most sustainable technical configuration but also on aligning institutional, market, and user conditions to support it. Combining LCA, TIS, and SDM thus enabled a transition-oriented sustainability assessment that was both diagnostic (i.e., identifying environmental and systemic barriers) and prescriptive (i.e., guiding how to overcome them).

7. Discussion

7.1 Rethinking Wastewater: Integrative Insights

This thesis applied a sequential analytical framework combining life cycle assessment (LCA), technological innovation system (TIS) analysis, and system dynamics modelling (SDM) to examine how urine recycling can contribute to sustainable sanitation transitions. Each component addressed a distinct question: the LCA quantified environmental performance and trade-offs, the TIS revealed institutional and social constraints that limit diffusion, and the SDM linked these dimensions dynamically to explore future adoption trajectories. Together, these methods addressed the "what," "why," and "how" of change in ways no single approach could achieve on its own, thereby fulfilling the overall aim of rethinking wastewater management through an integrated sustainability transition approach.

In relation to Objective 1, the consequential LCA (Paper I) demonstrated that conventional WWTPs have the highest environmental impacts, mainly due to energy-intensive nitrogen removal and chemical usage for phosphorus precipitation. Urine recycling lowered these impacts by replacing mineral fertilizers and reducing nitrous oxide and methane emissions. It resulted in a 20% decrease in the WWTP's global warming potential (GWP) and a 55% decrease in eutrophication. These findings align with those of Hilton et al. (2021), who reported that urine diversion and concentration could reduce GWP by 29–47% and eutrophication by 25–64% compared to conventional WWTPs. The black- and greywater system achieved a 60% GWP reduction, corroborating other comparative LCAs; for instance, Besson et al. (2021b) found that source-separating systems can cut greenhouse gas emissions by at least 46%. The hybrid scenario, which combines urine recycling with black- and greywater treatment, achieved the largest reductions – approximately 70% and 22% reductions in GWP – relative to the WWTP reference and the BW scenario, respectively. These results reinforce the notion that nutrient recovery systems can substantially enhance sanitation sustainability (Lima et al., 2023; Remy, 2010), and that nutrient recovery in decentralized networks provides significant circular-economy benefits (Sohn et al., 2023). At a global scale, human excreta could replace 15% –30% of the nitrogen demand for cropland in most countries (Starck & Esculier, 2025), underscoring the global need for nutrient recycling.

A central insight from these results is that urine recycling adds value not only as a stand-alone approach but also as a complementary component within broader sanitation configurations. When integrated with either the conventional WWTP (scenario 2) or the decentralized black- and greywater system (scenario 4), urine recycling enhanced the environmental performance of these systems by increasing nutrient recovery, thereby generating environmental credits. Dynamic modelling of urine recycling in other contexts has shown similar benefits, such as reductions in nitrogen loads, energy demand for nitrification, and GHG emissions, even under partial implementation (Matar et al., 2022). These results collectively echo the conclusions of Fratini et al. (2019) and Monstadt et al. (2022), who emphasized that environmental performance depends less on technology in isolation than on system configuration and governance context.

Paper IV refined this analysis by showing that treatment location is essential. Building-basement systems with effective heat recovery had the lowest GWP and cumulative energy demand, while centralized options were burdened by infrastructure-related emissions, and toilet-level systems required the highest energy input. This supports evidence that configuration and scale impact environmental performance in source-separating systems (Besson et al., 2024). Overall, the LCA results reposition urine recycling as a key driver of circularity, supporting centralized systems or closing nutrient loops in decentralized ones.

While the environmental analyses (Paper I) established a strong rationale for circular sanitation, Papers II and III, in relation to Objective 2, revealed why these benefits have not yet translated into large-scale adoption. Diffusion remains constrained by weak legitimacy, limited market formation, and unclear institutional mandates, findings consistent with transition research emphasizing the importance of guidance of the search, legitimacy, and market formation (Markard et al., 2015). Similar barriers have been documented across Europe and beyond. Kurniawati et al. (2023) showed that the implementation of bio-based fertilizers within the EU was hampered by the complex policy frameworks under the Fertilizing Products Regulation, which created uncertainty for farmers and small producers regarding compliance and market access. Hoey et al. (2025) also demonstrated that in the United States, urine recycling efforts are constrained by fragmented authority and regulatory ambiguity –no single agency "owns" the decision to permit urine collection and reuse– forcing practitioners to navigate inconsistent rules across sectors and scales of government. Together, these studies confirm that institutional weakness and unclear mandates between stakeholders and authorities systematically hinder circular innovation. In Sweden, this dynamic is particularly evident: the absence of a clear regulatory category for urine fertilizers undermines legitimacy, reduces farmer confidence, and private-sector investment (Paper III).

These institutional dynamics are closely intertwined with user experience and system reliability. Studies of user behavior confirm that reliability, hygiene, and maintenance quality are decisive for acceptance (Lamichhane & Babcock, 2013; Simha et al., 2018). Our results (Paper III) align closely with these findings: poor separation reduces nutrient recovery efficiency and undermines credibility, which can be mitigated through dependable service provision and transparent maintenance arrangements. Moreover, as McConville et al. (2017a) observed, successful scaling requires governance models that coordinate municipalities, utilities, and private actors in managing decentralized treatment, logistics, and fertilizer reuse– a principle central to the institutional gaps identified in this thesis. The experts' workshop (Paper III) illustrated how these dynamics differed across contexts. Swiss experts described collaborations between service providers and municipalities, including visible public-space applications of certified urine-derived fertilizer (e.g., football fields), which reinforced legitimacy and demand. In Sweden, experts emphasized that urban integration would require national product recognition first; until then, municipal pilots should be designed to generate the evidence necessary for that regulatory step (Paper III).

The SDM in relation to Objective 3 unified these insights, showing that adoption accelerated only when credibility, reliability, and visibility reinforced one another– indicating threshold-dependent change rather than linear diffusion, a finding consistent with empirical patterns observed in environmental technology diffusion (Noppers et al., 2016).

In summary, these integrated insights illustrate that sustainability transitions depend less on choosing a single "best" technology and more on fostering mutually reinforcing combinations of environmental performance, institutional legitimacy, and social engagement. By integrating LCA, TIS, and SDM, this thesis shows how technical potential becomes reality only when supported by effective governance and public trust, positioning urine recycling as a strategically important part of a circular sanitation portfolio – one that can link local circularity with broader sustainability transitions.

7.2 Major Barriers to Systematic Fundamental Changes

The TIS and SDM analyses (Papers II–III) showed that despite the strong environmental potential demonstrated under Objective 1, adoption remains constrained by institutional lock-in, regulatory ambiguity, and weak legitimacy – core issues underlying Objective 2. Both countries examined, Sweden and Switzerland, exhibited limited market formation and fragmented actor networks, although Switzerland displayed slightly stronger coordination and policy engagement. These findings highlight that transition barriers are systemic rather than technological, stemming from governance structures, incentive design, and social norms.

A central obstacle is the structural lock-in of conventional centralized wastewater systems (Papers II and III). Over the past century, large-scale treatment infrastructure has become deeply embedded in planning practices, investment cycles, and professional norms. High sunk costs, long asset lifespans, and regulatory frameworks built around linear waste removal reinforce the dominance of centralized sanitation and hinder experimentation with radical alternatives. Similar path dependencies are seen in other infrastructure sectors, such as urban energy (Sovacool, 2021) and waste management (Gregson et al., 2015), where existing networks often resist decentralization. In sanitation, this appears as rigid operational mandates and planning approaches that prioritize linear waste removal over resource recovery (Papers III). As other scholars have noted, path dependence tends to promote incremental improvements within the current system rather than fundamental reform (Kiparsky et al., 2013; Söderholm et al., 2022).

Institutional and regulatory ambiguity further constrains diffusion. Human-derived fertilizers such as processed urine often fall into legal grey zones – neither fully recognized as agricultural products nor consistently regulated as waste (Hoey et al., 2025; McConville et al., 2023b; Schönning, 2004). Experts in both Sweden and Switzerland emphasized that unclear hygiene standards, contaminant limits, and liability rules discourage investment and undermine farmer confidence (Paper III). In Sweden, alignment with EU frameworks adds complexity: under EU Regulation (EEG) 2092/91 governing organic agriculture, human urine was not an approved input, restricting its use in organic farming, even though national certifiers such as KRAV did not necessarily oppose it (Kvarnström et al., 2006). In contrast, Switzerland's more flexible federal system – operating outside EU fertilizer directives – enabled faster certification of Aurin, the first urine-based fertilizer approved for market sale in Europe (Dash et al., 2025; vunanexus, 2018). This regulatory clarity created a legitimacy signal that stimulated investment and farmer engagement, validating our TIS findings that guidance of the search and legitimacy are critical functions for innovation diffusion (Paper III). Similar patterns occur in circular economy transitions, where unclear product classification often prevents recovered materials from entering mainstream markets (Corvellec et al., 2021).

Economic structures for urban sanitation also constrain decentralized innovation. Most municipal utilities operate under centralized cost-recovery models that depend on large, capital-intensive infrastructure with long depreciation periods. Such arrangements offer minimal financial incentive for experimenting with smaller, distributed setups, which introduce operational risks and shared responsibilities (Arshad et al., 2025). As shown in Paper III, source-separating systems challenged existing business logic by redistributing costs and benefits across new actors – households investing in toilets, municipalities managing logistics, and private firms handling processing and fertilizer production. The absence of clear value-sharing mechanisms and pricing strategies for recovered nutrients limited market formation and private-sector engagement. Similar structural rigidities have been identified in other infrastructure transitions, such as decentralized energy and waste valorization, where tariff design and ownership models lag behind technical innovation (Loorbach, 2009). At the same time, these constraints point to opportunities: involving private-sector actors such as sanitation companies, agricultural cooperatives, and fertilizer producers could create diverse revenue streams from nutrient recovery, maintenance, and product sales (Otoo et al., 2018). Paper III suggested that municipalities and utilities must establish contractual frameworks that enable decentralized operators to participate in regulated performance and safety standards. Well-defined pricing strategies for recovered nutrients and services could turn source separation from a public expense into a shared economic opportunity, aligning household behavior, municipal planning, and private entrepreneurship within a circular economy.

At the socio-technical level, weak performance in key system functions, especially legitimacy, market formation, and resource mobilization, explains much of the stagnation (Papers II–III). Although knowledge production has increased, actor networks remain fragmented, and learning is not systematically translated into implementation strategies. This pattern aligns with TIS studies, which emphasize that the diffusion of innovations relies on coordinated network building and the development of shared visions (McConville et al., 2017a).

Social acceptance remains a particularly persistent challenge. At the user level, urine-diverting toilets require behavioral adaptation and are sometimes perceived as inconvenient or unhygienic (Lienert & Larsen, 2010). Yet social acceptance extends beyond households: it also involves farmers, regulators, municipal engineers, and policymakers. Farmers need to trust that urine-derived fertilizers are safe, effective, and legally recognized (Cohen et al., 2020); utilities and municipal planners must see decentralized sanitation as a legitimate part of urban infrastructure rather than a niche experiment (McConville et al., 2023a); and policymakers must see it as aligned with public health and environmental goals (Lienert & Larsen, 2009). Concerns about odor, hygiene, and maintenance, if not properly managed, can reinforce social taboos and slow the normalization process (Simha et al., 2018). Additionally, the absence of visible, high-quality demonstrations reduces public familiarity and undermines confidence among decision-makers. Papers II and III showed that legitimacy improved when demonstrations were visible and certified fertilizers were publicly applied, as in Swiss municipalities that used urine-based products on sports fields. These findings suggest that social acceptance is influenced not only by technical reliability but also by transparent governance, credible certification schemes, and effective communication strategies that engage diverse audiences.

Technical and logistical trade-offs also shape the feasibility of upscaling. As Paper IV showed, basement-level treatment with heat recovery offered the best environmental performance and operational manageability, while centralized systems suffered from infrastructure-related emissions and toilet-level systems demanded higher energy input. These results corroborate broader evidence that context-specific optimization is necessary, and that "one-size-fits-all" models are unsuited for urban and rural settings (Larsen et al., 2021b).

Collectively, these findings demonstrate that achieving the overall aim of enabling circular sanitation transitions requires addressing the interplay of institutional rigidity, market structures, and behavioral factors. By diagnosing where functional weaknesses constrain scaling, Objective 2 is fulfilled: the socio-technical barriers and enabling factors governing urine-recycling diffusion are now empirically identified and theoretically explained. Table 9 summarizes these barriers and their implications for scaling.

Table 9: Summary of major barriers to scaling urine recycling systems, as identified in Sweden and Switzerland (Papers II -IV)

Barrier Category	Key Barrier	Implications for Scaling
Institutional Regulatory	Lack of national strategy and product certification.	Weak guidance signals; limits investment and long-term planning
Economic Market	Centralized cost-recovery models; unclear revenue-sharing.	Low private participation; limited business innovation.
Socio-technical	Fragmented actor networks; weak market formation.	Slows knowledge translation and collective action.
Social	Hygiene concerns, low visibility, limited familiarity.	Reinforces taboos and delays normalization.
Technical Logistical	Trade-offs in system configuration and transport.	Context dependence; need for adaptive design.

Addressing these interrelated barriers requires a multi-layered approach that strengthens regulatory legitimacy, fosters viable business models, enhances service reliability, and sustains engagement with users and farmers. The next section explores how such targeted interventions can improve innovation-system functions, build market confidence, and generate the reinforcing feedback necessary for large-scale diffusion.

7.3 Transition Pathways and Practical Strategies

Building on the preceding analysis of barriers, this section addresses Objective 3 by exploring how coordinated interventions can accelerate systemic change in sanitation. Insights from the SDM and Papers (II-III) are used to identify the feedback mechanisms that govern whether urine recycling stays a niche innovation or becomes a normalized part of urban infrastructure. It then translates these insights into practical strategies for scaling.

The SDM revealed that adoption dynamics are governed by three mutually reinforcing loops: (R1) policy and legitimacy, (R2) market demand and resource mobilization, and (R3) social visibility and acceptance. When these loops operate in concert, diffusion accelerates; when any remain weak, stagnation occurs as abandonment offsets new installations. This threshold-dependent behavior– where small gains in legitimacy or visibility can trigger disproportionate growth mirrors broader diffusion dynamics described by innovation theory (Rogers, 2003) and sustainability transitions research emphasizing feedback sensitivity and tipping points (Köhler et al., 2019). In practical terms, sustainable sanitation transitions depend on aligning these reinforcing dynamics through coherent policy, credible markets, and positive user experience.

Policy support emerged as the most influential factor for long-term growth. The SDM demonstrated that the early implementation of subsidies, certification, and product standards enhanced legitimacy and market confidence, thereby reducing perceived risk for both investors and users. The Swiss case exemplifies this mechanism: approval of Aurin by the Federal Office for Agriculture transformed an experimental fertilizer into a market-validated product, demonstrating how regulatory clarity can convert niche innovation into mainstream practices. This aligns with transition literature, which suggests that stable rules and product standards reduce uncertainty, encourage new entrants, and transform environmental innovations from exceptions into normalized options (Köhler et al., 2019). The absence of national recognition in Sweden, weakened guidance of the search, discouraged investment, and fragmented coordination between municipalities and regulators. These findings highlight the importance of coherent governance – where nutrient recovery is embedded within circular-economy and agricultural policy frameworks that provide consistent standards, clear mandates, and enduring signals of state commitment (Reichardt et al., 2016).

Regulation, however, is only one aspect of the transition process. Bottom-up factors such as reliability, user experience, and social visibility determine whether policy momentum translates into sustained practice. The SDM identified a visibility threshold: once roughly half the population is exposed to urine-diverting toilets, adoption accelerates significantly. Visibility effects were influenced not only by the number of units installed but also by perceived performance and social proof, including reliable operation, positive media coverage, and public endorsement. This aligns with environmental-behavior research indicating that legitimacy and peer visibility reinforce willingness to adopt (Noppers et al., 2016). In this context, well-maintained pilot projects, transparent communication, and clear safety demonstrations are just as important as technical efficiency.

Effective scaling, therefore, requires the interaction of top-down institutional support and bottom-up social learning. Policy instruments – such as certification, fiscal incentives, and integrating urine recycling into sustainability strategies – build credibility and reduce uncertainty. Meanwhile, participatory pilots, co-design efforts, and public demonstrations build user trust and help normalize new practices. This dual strategy aligns with the principles of Strategic Niche Management and the Multi-Level Perspective, which highlight that radical innovations thrive when protected niches are in sync with the changing regime and policy frameworks (Geels & Schot, 2007; Smith & Raven, 2012).

Operationalizing these strategic dynamics involves four key areas of practical action. First, creating a strong regulatory system for urine-derived fertilizers is crucial. The lack of official recognition and certification mechanisms currently blocks environmental benefits from translating into economic and institutional gains. Establishing national or EU standards for urine-based fertilizers – with criteria for product categories, nutrient levels, safety, and liability – would reduce uncertainty and build trust among farmers, investors, and utilities. The success of Aurin shows how certification can turn a laboratory prototype into a market-ready product. Applying similar certification processes in Sweden and at the EU level could speed up policy approval, draw private funding, and support market growth.

Second, reliability and service quality must become institutionalized. The SDM showed that enhancing maintenance performance lowers abandonment rates, strengthening the feedback loop between satisfaction, legitimacy, and adoption. Municipalities and utilities can encourage long-term adoption by professionalizing service delivery through performance-based maintenance contracts, clear service standards, and coordinated training programs for technicians. Targeted outreach and education campaigns can increase social acceptance and highlight environmental benefits, thereby reinforcing the feedback loops shown in the SDM. Such arrangements help keep existing installations operational, create positive user experiences, and build trust.

Third, policy instruments should reduce risks for early adopters and promote learning at each expansion stage. The simulations show that policy support and social visibility mutually reinforce each other, suggesting that early public investments should improve both reliability and demonstration value. Targeted co-funding of pioneering basement-level systems – identified in Paper IV as environmentally and operationally beneficial – could provide high-profile demonstration sites. Short-term, output-based incentives for certified urine-derived fertilizers could encourage nutrient recovery verification and help farmers during the initial adoption phase. Municipal procurement of certified recycled fertilizers for public green spaces would create visible demand and signal product safety and performance.

Fourth, responsibilities and financial flows among actors must be clearly defined. As Paper III demonstrated, value chains remain underdeveloped, partly because responsibilities and economic roles are not well-defined. The thesis findings suggest a more transparent division of responsibilities. Developers and households share the costs of installations when benefits such as lower sewer fees, reduced water bills, or better infrastructure planning are received. Municipalities and utilities finance collection services and long-term maintenance as part of their wastewater management duties. Private producers generate value through the sales of certified fertilizers, initially supported by limited-time output premiums. Farmers benefit from affordable, verified fertilizers, along with training and support for proper use. Clarifying who is responsible for what turns diffuse responsibilities into a clear investment structure, encouraging private sector participation while ensuring public funds focus on risk reduction and public goods.

In summary, the transition pathways identified in this thesis show that scaling urine recycling requires coordinated progress across regulation, service quality, market design, and actor collaboration, reinforced by continuous social engagement. When these efforts strengthen the key feedback loops identified in the SDM – policy and legitimacy, market demand, and social visibility – urine recycling can move from pilot projects to a recognized element of circular and climate-resilient urban sanitation. These strategic pathways not only show how adoption can speed up but also how broader regime changes might happen. In the context of sustainability transitions, urine recycling is currently a niche—feasible but limited. Upscaling depends on coordinating niche innovations with regime reforms, reconfiguring systems, markets, and norms (Markard et al., 2012). Instead of complete replacement, a hybrid strategy that combines decentralized source separation with existing wastewater management is likely (McConville et al., 2017a). These hybrids enable utilities to maintain reliable services while gradually integrating nutrient recovery. Over time, hybrids act as "bridging configurations" (Smith & Raven, 2012), linking niches with institutional practices and supporting long-term regime change (Schot & Geels, 2008).

7.4 Broader Knowledge, Theoretical, and Methodological Contributions

This thesis advances discussions on sustainability transitions and the circular economy by showing how sanitation can evolve from a linear waste management approach to a circular resource system. The idea of "rethinking wastewater" aligns with similar shifts in other infrastructure sectors: the energy transition from fossil fuels to renewable sources (Geels et al., 2017) and nutrient cycling in food systems (Koppelmäki et al., 2021). However, compared to these sectors, sanitation transitions have been slower, hindered by entrenched infrastructure, fragmented institutions, and a lack of regulation, as shown in (Paper III) and highlighted by previous research, e.g., McConville et al. (2017a). Worldwide, centralized wastewater treatment remains the standard, with only a few cities adopting large-scale nutrient recovery or source separation systems. This delay underscores the need for integrated strategies, such as those developed in this thesis, that align environmental, institutional, and social capacities for change.

Broadly, the thesis places sanitation within the context of global sustainability efforts. By measuring reductions in nitrogen and phosphorus emissions via source separation, the LCA tackles two key planetary boundaries (biogeochemical flows and climate change) (Rockstrom et al., 2023). Extracting nutrients from urine not only reduces eutrophication but also replaces synthetic fertilizers, which decreases the carbon footprint of agriculture (Paper I). Hence, urine recycling acts as a local solution with global significance, helping maintain the safe operating space for humanity. Apart from technical aspects, the thesis offers a practical example of implementing circular economy principles in sanitation transitions: by integrating environmental data with institutional and behavioral insights, it transforms the idea of circularity from an abstract notion into a clear, practical process.

Methodologically, the thesis bridges the gap between sustainability assessment and transition research by developing and empirically testing a combined LCA–TIS–SDM framework. It responds to calls for approaches that integrate environmental, social, and institutional factors in sustainability transitions (Arvidsson et al., 2023; Lindfors et al., 2025; Ventura, 2022). While earlier work mainly offered conceptual links between these areas, this research advances them by sequentially combining analytical tools and applying them to a real-world circular sanitation case. The framework operationalizes sustainability transition assessment through a structured sequence: LCA evaluates environmental performance (Papers I & IV), TIS assesses institutional conditions (Papers II & III), and SDM connects these insights to explore potential upscaling trajectories.

Within this framework, several specific methodological contributions can be identified. First, the thesis demonstrated how different LCA system models, such as attributional and consequential modeling, influence interpretations of environmental benefits, highlighting the importance of methodological transparency in environmental assessments (Heimersson et al., 2019). Second, it advances TIS methodology through a new multi-criteria evaluation of the knowledge-development function and the adaptation of the Delphi process and expert visioning in TIS assessment - these additions provided a conceptual contribution to advancing transition theories. Third, integrating these tools through SDM offers a dynamic view of transitions, linking environmental benefits with institutional and behavioral mechanisms, and yields insights for targeted interventions, such as certification, incentives, and visibility, to promote adoption. Compared to broad meta-model archetypes (Gottschamer & Walters, 2023), this framework grounds feedback dynamics within a specific sector, offering a replicable approach for contexts such as bio-based materials, decentralized energy, or nutrient recycling, where institutional readiness plays a crucial role in progress..

Regarding transferability, the combined framework developed can be tailored for use in various geographical and sectoral contexts. For instance, applying the LCA outside Europe would result in different absolute environmental impacts due to variations in electricity supply and infrastructure. However, the overall pattern in which urine recycling remains superior to conventional systems is likely to remain consistent. System dynamics modeling is also adaptable: although parameters and variables may vary, the fundamental feedback loops between legitimacy, visibility, and adoption are common to socio-technical diffusion, as outlined by Rogers (2003) and Noppers et al. (2016).

Together, these theoretical and methodological advances provide a replicable foundation for analyzing and guiding sustainability transitions. The framework illustrates how integrating environmental, institutional, and behavioral perspectives yields actionable insights for accelerating circular innovation – not only in sanitation but across the broader sustainability landscape.

7.5 Limitations and Methodological Outlook

The combined LCA–TIS–SDM framework proved effective in linking environmental, institutional, and dynamic dimensions of sanitation transitions, but it is only one of several possible analytical methods. Sustainability assessment and transition research communities have developed various complementary frameworks, each highlighting different epistemological and practical views. Recognizing this methodological flexibility is crucial for understanding both the strengths and limitations of the thesis findings.

Regarding sustainability assessment, alternatives like Material Flow Analysis (MFA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA) could have expanded the framework's focus on economic and social factors. MFA provides a more detailed spatial view of nutrient flows and infrastructure connections, while LCC helps clarify the trade-offs between environmental benefits and financial costs – particularly relevant for municipal planning and private-sector investments. SLCA can examine labor conditions, gender issues related to sanitation access, and workplace safety concerns that fall outside the current environmental and institutional focus. Incorporating these methods would foster a more comprehensive understanding of "sustainability," going beyond just environmental performance and institutional readiness to include socio-economic equity and practicality.

From the perspective of transition and innovation research, other analytical approaches, such as the Multi-Level Perspective, Strategic Niche Management, or Sustainability Transitions Management, could have complemented insights into regime dynamics, actor strategies, and governance actions. Multi-Level Perspective might have situated urine recycling within wider "landscape pressures" like climate policy, agricultural nutrient security, or societal norms of cleanliness, thus broadening the explanatory scope beyond the sectoral focus of TIS. Strategic Niche Management could have emphasized niche experimentation, learning, and network development in pilot projects, while Sustainability Transitions Management might have offered a more guiding framework for managing policy portfolios and transition spaces. Although these perspectives might not have altered the fundamental findings –that legitimacy, coordination, and market formation are key –they could have reframed them in terms of multi-level alignment, rather than functional system performance.

With respect to SDM, replacing or complementing it with other dynamic or participatory methods, such as Agent-Based Modelling (ABM) or participatory scenario analysis, would shift emphasis in particular ways. ABM would allow more heterogeneous actors and localized adoption behaviors to emerge endogenously rather than through aggregate feedback. Participatory approaches could enhance stakeholder co-learning and increase the social legitimacy of model results, though possibly at the expense of generalizability and analytical precision. Future research could integrate socio-economic information from LCC or SLCA once more robust market data become available, enabling richer analyses of equity and economic viability.

Data scarcity and uncertainty remain challenges, especially for early-stage systems with limited empirical evidence. In this thesis, expert judgment was used to parameterize several institutional variables in the SDM. While suitable for exploratory analysis, these assumptions should be refined as long-term field data become available. These limitations reflect the frontier nature of circular sanitation rather than weaknesses of the approach. The framework prioritizes systemic integration and analytical clarity over micro-level social detail and participatory depth. Had alternative tools been used, the balance between generalization and contextualization would have been different.

Ultimately, no single framework can capture the full complexity of sanitation transitions. The framework developed here should therefore be seen as a structured perspective rather than a complete model – one that integrates key system dimensions while remaining open to future development through additional tools and viewpoints. Despite these limitations, the framework and findings together provide a coherent foundation for understanding how environmental performance, institutional dynamics, and social acceptance interact in shaping sustainability transitions. Future research could build on this work by using hybrid frameworks that explicitly combine environmental modeling, institutional diagnostics, and participatory foresight, thereby capturing both structural and experiential aspects of sustainability transitions.

7.6 Concluding Discussion: Synthesis and Implications

Taken together, the findings of this thesis show that advancing circular sanitation is more about aligning environmental, institutional, and social factors for change than finding a single best technology. The integrated LCA–TIS–SDM framework demonstrated how environmental benefits, institutional legitimacy, and social acceptance interact to influence the speed and direction of transition. Urine recycling emerged as a key part of this process–its environmental benefits are well-established, yet its adoption depends on effective governance, dependable service, and visible societal support.

A key insight is that sustainability transitions develop through co-evolution rather than linear substitution. Environmental benefits become transformative only when supported by institutional and social recognition. Policy tools, like certification and incentives, can legitimize new practices, while participatory pilots, service reliability, and public demonstrations help build user trust and visibility. Together, these mechanisms generate reinforcing feedback that moves sanitation transitions from niche experimentation toward mainstream adoption.

Beyond sanitation, the framework developed here illustrates a transferable approach for analyzing sustainability transitions in other sectors, such as bio-based materials, decentralized energy, or nutrient recycling, where environmental promise must be matched by institutional readiness. By empirically linking environmental performance with the dynamics of legitimacy, market formation, and feedback sensitivity, this thesis provides both conceptual clarification and practical guidance for designing transition-oriented assessments.

In doing so, the research reframes sanitation not just as waste management but as a circular resource system embedded in broader socio-technical change. It shows that combining environmental, institutional, and behavioral perspectives enables a more realistic understanding of how sustainability transitions advance and how they can be guided.

8. Conclusion

This thesis has examined how urine recycling can contribute to circular and sustainable sanitation systems and identified the institutional, social, and technical conditions required for its adoption. Using an integrated framework that combined Life Cycle Assessment (LCA), Technological Innovation Systems (TIS) analysis, and System Dynamics Modeling (SDM), the research assessed environmental performance, institutional barriers, and transition dynamics as interconnected dimensions of change.

The LCA results showed that urine recycling can substantially improve the environmental performance of both conventional and source-separating sanitation systems by reducing greenhouse gas emissions and recovering nutrients that can substitute for synthetic fertilizers. However, environmental benefits alone do not ensure adoption. Institutional weaknesses, e.g, fragmented responsibilities, limited legitimacy, and inadequate policy coordination, create barriers that hinder diffusion, even in countries with strong research capacities.

By integrating insights from TIS and SDM, the thesis demonstrates that adoption follows a threshold-dependent pattern. When credibility, reliability, and visibility reinforce each other, diffusion accelerates – suggesting that sustainability transitions are driven by feedback loops rather than gradual, linear change. The comparative analysis of Sweden and Switzerland showed that coherent regulation, financial incentives, and certification schemes can establish legitimacy, increase willingness, and attract private investment, whereas fragmented mandates slow transition. Practically, this implies that successful diffusion depends on aligning environmental performance with institutional preparedness and social trust.

Overall, the thesis shows that urine recycling is more than a sustainable alternative to conventional wastewater treatment – it represents a strategic pathway for redefining sanitation as a circular service that advances climate action, nutrient recovery, and circular economy goals. Achieving this requires institutions that can recognize new forms of value, distribute responsibilities fairly, and build public trust quickly enough to sustain transformation. When national strategies and clear legislation are combined with certifications, incentives, reliable services, and visible benefits, adoption can progress from niche experiments to mainstream markets. In doing so, urine recycling offers not only a technological solution but also a governance model for accelerating circular sanitation transitions.

9. Future Research

The findings of this thesis identify several targeted directions for future research that extend directly from the empirical and methodological insights presented here. Each recommendation builds on specific results and limitations encountered during the LCA, TIS, and SDM analyses.

1. Strengthen empirical foundations through long-term field data.

While the environmental advantages of urine are well recognized, there's still a need for more real-world data on how reliable these systems are, how they're maintained, and how well they recover nutrients. Moving forward, it will be necessary to conduct long-term studies in various types of systems – whether centralized, decentralized, or hybrid – to track nutrient flows, emissions, and the reliability of the services. Creating national monitoring programs or open databases could make a big difference by providing consistent data, enabling effective benchmarking, and helping to validate models, ultimately guiding better design choices and policies.

2. Advance governance innovations within the sanitation sector.

At the sectoral level, future studies should examine how innovative governance approaches in sanitation can help solve legitimacy and coordination challenges, especially regarding the often-unclear responsibilities among municipalities, utilities, and private actors. The TIS analysis highlighted that these institutional gaps can be significant hurdles to diffusion. Future research might consider testing different governance models like regional nutrient platforms, certification bodies, or public–private service cooperatives to see how they influence regulatory stability, market development, and collaboration among stakeholders. Comparing Nordic and other European contexts could reveal which institutional arrangements most effectively translate policy goals into real-world results and foster long-term system resilience.

3. Develop more dynamic and integrative modeling approaches.

The combined framework offered valuable explanatory insights but captured feedback primarily in one direction. Future work should focus on developing iterative or hybrid models that dynamically link environmental outcomes with institutional and behavioral change. This could involve coupling SDM with agent-based modeling or participatory scenario tools to simulate adaptive learning, behavioral feedback, and network evolution. Using parameters based on field data would reduce assumptions, lower uncertainty, and enhance model reliability, thereby enabling more effective policy testing and sensitivity analysis.

4. Integrate sanitation transitions with agriculture and climate policy systems.

At the cross-sectoral level, future research should expand the analytical scope of the framework to explore how coordination among sanitation, agricultural, and climate policy domains shapes incentives, investment priorities, and diffusion trajectories. The results of this thesis highlighted that institutional legitimacy and policy coherence are essential for scaling; however, these depend on how policy instruments from various sectors interact. Future studies could therefore use coupled modeling approaches to examine how fertilizer regulations, carbon policies, and circular economy targets collectively impact the adoption of source-separated systems. Incorporating new variables, feedback loops, and more robust quantification would enhance predictive accuracy and identify leverage points for systemic policy alignment.

Together, these directions outline a coherent research agenda linking empirical monitoring, institutional innovation, and methodological advancement. Advancing along these lines would refine the analytical tools developed here and support more effective policy, investment, and large-scale implementation of circular sanitation systems.

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ADDIN

Popular science summary

Recycling the nutrients we flush away – a pathway to circular sanitation and sustainable cities

Every day, we all contribute to a cycle where valuable nutrients like nitrogen, phosphorus, and potassium–essential for plant growth–are washed away down the drain. Instead of nourishing our soil, these nutrients often end up in wastewater systems. At the same time, agriculture depends on synthetic fertilizers made from limited resources, which can produce high greenhouse gas emissions and create disparities in global access. Addressing this broken nutrient cycle is a key part of tackling the sustainability challenges we face today.

Urine accounts for only a small part of our household wastewater, but it carries most of the nutrients. By collecting and treating urine separately, we can transform these nutrients into a safe, effective fertilizer. This idea, called urine recycling, is a practical way to close the nutrient loop, reduce pollution, and lessen the climate impact of sanitation. It's essentially a win-win: cleaner water, fewer emissions, and resource recovery. But in reality, progress has been slower than hoped. Even after years of research and pilot projects that show it's technically possible, urine recycling hasn't yet become a common part of our everyday sanitation systems.

This thesis explores the reasons behind this and offers ways to bring about change. It thoughtfully combines environmental life cycle assessment, innovation system analysis, and system dynamics modeling to not only evaluate the environmental benefits of urine recycling but also to understand the social and technical factors that influence its adoption.

The environmental assessment for a Swedish neighborhood revealed that incorporating urine recycling into an existing wastewater treatment plant can cut greenhouse gas emissions by about 20 percent. This mainly happens by avoiding nitrous oxide and methane emissions at the plant and replacing mineral fertilizers. For new developments, decentralized treatment in building basements turned out to be the most well-rounded choice, balancing climate benefits, energy efficiency, and everyday reliability. Interestingly, this basement setup can even become carbon negative when sulfuric acid replaces citric acid, with energy recovery reaching up to 52%.

But technology by itself isn't enough. The discussion then moves to the social and institutional sides: How do people share and grow knowledge about urine recycling? What challenges do we face in creating markets, policies, and gaining acceptance for these systems?

The socio-technical analysis really helps us see why promising environmental results haven't yet led to widespread adoption. Urine recycling is still facing some hurdles, like the absence of clear regulations, including proper recognition and certification of products. There's also a shortage of high-quality demonstrations, which makes it harder to gain trust from the public and professionals. All these factors together shape how willing both private and public sectors are to get involved and support this initiative.

To get a clearer picture of how adoption might grow over time, the thesis uses system dynamics modeling to simulate the interactions between technology performance, policy support, market signals, and social acceptance. The findings suggest that urine recycling tends to increase when legitimacy, reliability, and visibility support each other. Certification and targeted incentives help build trust, dependable maintenance reduces the risk of abandonment, and public demonstrations make the benefits more tangible. Without these positive reinforcing conditions, adoption plateaus at the pilot stage, even if the environmental case looks compelling.

These findings suggest some straightforward and helpful actions we can take. First, we should establish clear standards and certification processes for urine-derived fertilizers to build trust and facilitate trade. Next, investing in reliable pilot projects–especially basement-level systems in new developments–can really make a difference, especially when supported by professional maintenance, skilled technician training, and open reporting practices. Lastly, establishing steady market pathways is key: this involves clear answers on who pays for installations and services, how producers benefit from certified fertilizers, and how farmers can access affordable, verified products. Municipal procurement can play an important role in helping to create early demand.

Overall, the thesis shows that technology by itself isn't enough to achieve circular sanitation. True progress happens when environmental evidence, strong policies, and consistent practices unite. In such a supportive environment, urine recycling transforms from just an innovative idea into a real, practical solution. It helps connect sanitation with agriculture, cut emissions, and support the development of resilient, climate-smart cities. With proper certification, trusted services, and inspiring examples, the nutrients we often discard today can nourish the food of tomorrow, bringing hope and sustainability together.

Populärvetenskaplig sammanfattning

Att återvinna näringen vi spolar bort – en väg mot cirkulär sanitet och hållbara städer

Varje dag bidrar vi alla till ett flöde där värdefulla näringsämnen som kväve, fosfor och kalium – ämnen som växter behöver för att växa – spolas bort i avloppet. I stället för att återföra dessa ämnen till livsmedelsproduktionen hamnar de ofta i avloppssystemen. Samtidigt är jordbruket beroende av konstgödsel som framställs från begränsade resurser, vilka orsakar stora växthusgasutsläpp och skapar ojämlik tillgång globalt. Att åtgärda detta brutna näringskretslopp är en viktig del av arbetet med dagens hållbarhetsutmaningar.

Urin utgör bara en liten andel av hushållens avloppsvatten, men innehåller merparten av näringsämnena. Genom separat insamling och behandling av urinen kan urinens näringsämnen omvandlas till ett säkert och effektivt gödselmedel. Urinsortering eller urinåtervinning, erbjuder ett praktiskt sätt att sluta näringskretsloppet, minska föroreningar och sänka klimatpåverkan från avloppssystemet. Det är i grunden en win-win-lösning: renare vatten, färre utsläpp och återvinning av resurser. Implementeringen i samhället har gått långsammare än man kan tro utifrån systemets fördelar. Trots många års forskning och pilotprojekt som visar att tekniken fungerar har urinsortering ännu inte blivit en självklar del av våra avloppssystem.

Denna avhandling undersöker orsakerna till fördröjningen i implementeringen och visar hur förändring kan åstadkommas. Avhandlingen kombinerar livscykelanalys, innovationssystemanalys och systemdynamisk modellering för att både utvärdera de miljömässiga fördelarna med urinåtervinning och för att förstå de sociala och tekniska faktorer som påverkar systemets implementering.

Miljösystemanalysen, genomfördes för ett svenskt bostadsområde, den visar att om urinsortering integreras i ett system med befintligt reningsverk kan växthusgasutsläppen minska med cirka 20 procent. Minskningen beror främst på minskade lustgas- och metanutsläpp i reningsprocessen och att mineralgödsel ersattes i livsmedelsproduktionen. För nybyggda områden visade sig lokal behandling i byggnadens källare vara det bästa alternativet, då systemet ger en god balans mellan klimatnytta, energieffektivitet och driftsäkerhet. Systemet med installation av urinbehandling i källaren kan till och med bli koldioxidnegativ om svavelsyra används i stället för citronsyra. Systemet ger dessutom en reduktion av energianvändningen på upp till 52 %.

Men teknik i sig räcker inte, den måste också implementeras. Diskussionen går därför vidare till de sociala och institutionella dimensionerna: Hur sprids och utvecklas kunskap om urinsortering? Vilka hinder finns för att skapa fungerande marknader för systemet och den producerade gödseln?Det krävs tydliga regler och social acceptans för implementering dessa system.

Den socio-tekniska analysen visar tydligt varför lovande miljöresultat ännu inte har lett till storskalig tillämpning. Urinsortering möter fortfarande flera hinder, såsom avsaknad av tydliga regler kring systemens installation och certifieringssystem för gödselprodukterna. Det finns också en brist på välfungerande storskaliga demonstrationsprojekt, vilket gör det svårt att skapa förtroende hos både allmänhet och yrkesverksamma. Tillsammans påverkar dessa faktorer hur villiga både offentliga och privata aktörer är att engagera sig och investera i utvecklingen.

För att förstå hur implementeringen kan växa över tid används systemdynamisk modellering för att simulera samspelet mellan teknisk prestanda, politiskt stöd, marknadssignaler och social acceptans. Resultaten visar att spridningen ökar när legitimitet, tillförlitlighet och synlighet förstärker varandra. Certifiering och riktade incitament stärker förtroendet, pålitlig service minskar risken för att system överges, och offentliga demoprojekt tydliggör nyttan mer konkret. Utan dessa positiva återkopplingar fastnar utvecklingen på pilotnivå – även om miljöargumenten är starka.

Dessa resultat pekar på några tydliga och praktiskt genomförbara åtgärder. För det första bör tydliga standarder och certifieringssystem införas för urinbaserade gödselmedel, för att bygga förtroende och underlätta handel. För det andra bör satsningar göras på driftsäkra pilotprojekt, särskilt källarbaserade system i nybyggda områden, som sköts professionellt av utbildade tekniker och har öppen redovisning av resultaten. För det tredje behövs stabila marknadsstrukturer där roller och kostnadsfördelning är tydliga: vem som betalar för installation respektive drift, hur producenter får avkastning på certifierade produkter och hur lantbrukare får tillgång till prisvärda och certifierade gödselmedel. Kommunal upphandling kan här spela en viktig roll i att skapa tidig efterfrågan.

Sammantaget visar avhandlingen att teknik i sig inte räcker för att uppnå cirkulära avloppssystem. Verkliga framsteg sker när miljövetenskapliga bevis, tydlig politik och tillförlitlig praxis samverkar. I ett sådant stödjande sammanhang blir urinåtervinning mer än en innovativ idé – den blir en konkret lösning som kopplar samman sanitet och jordbruk, minskar utsläpp och bidrar till utvecklingen av uthålliga, klimatkloka städer. Med tydlig certifiering, tillförlitlig service och inspirerande exempel kan de näringsämnen vi idag spolar bort i stället bli grunden för morgondagens livsmedelsförsörjning – där hopp och hållbarhet går hand i hand.

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And finally, to my homeland, Palestine—may peace prevail and truth one day shine bright.

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Consequential life cycle assessment of urban source-separating sanitation systems complementing centralized wastewater treatment in Lund, Sweden

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ABSTRACT

This study examined various source-separating sanitation systems to evaluate their environmental performance, providing decision-makers with insights for selecting an appropriate system for a newly developed neighborhood in Sweden. A full consequential LCA was conducted to account for resource recovery and substitution. The local wastewater treatment plant WWTP was modeled as a reference. Secondly, a urine recycling system was introduced to treat 75 % of the collected urine, with the remainder piped to the WWTP. Thirdly, a black and greywater (BW&GW) treatment system handling all generated wastewater was examined. Finally, a hybrid source-separating system combining urine, black, and greywater was investigated. The results indicated that the four scenarios exhibited global warming potentials (GWP) of 78, 62, 32, and 24 kg CO2-eq per PE/ y. Recycling urine as fertilizer led to a 20 % reduction in the GWP of the reference. It also reduced other impact categories, with a 55 %, 65 %, and 45 % reduction in eutrophication, ozone depletion, and acidification, respectively. The BW&GW system achieved a 60 % reduction over the reference GWP, mainly due to fertilizer, biogas, and cleanwater recovery. Integrating urine, black, and greywater recycling in the final scenario achieved a 25 % reduction compared to the BW&GW scenario, primarily due to lowering of the ammonia stripping GWP and the additional fertilizer recovery. Based on sensitivity analyses, switching citric acid for sulfuric acid reduced the GWP of the urine stabilization unit process by 101 %, from 15.47 to -0.14 kg CO2-eq per PE/ y. Ultimately, the findings suggest that the fully decentralized source-separating sanitation system incorporating urine, blackwater, and greywater recycling, particularly when combined with 70 % energy recovery at the urine concentrator, is most favorable.

1. Introduction

Domestic wastewater is loaded with resources that can be recovered in different forms (e.g., biogas, fertilizer, and clean water) instead of being discharged into the environment, causing adverse environmental impacts (Malila et al., 2019). These pressures, such as eutrophication, climate change, acidification, and ozone depletion, are evident examples of the growing future uncertainties that threaten the well-being of our ecosystems (Rockstrom et al., 2023). To alleviate these threats and move forward to achieve sustainable development goals (SDGs) while keeping the planetary boundaries within their thresholds, today's wastewater management systems need to incorporate circularity and close resource loops (Larsen and Binz, 2021; Trimmer Jt Cusick, 2017). Various experts have examined and regarded source-separating sanitation systems (i.e., the separate collection and processing of wastewater fractions) as a potential alternative to conventional wastewater treatment for maximizing resource recovery in the sanitation sector (McConville. et al., 2017).

Several source separation methods and systems have been developed worldwide for the separate collection and treatment of different wastewater fractions (Aliahmad et al., 2022; Harder et al., 2019; Larsen et al., 2021). These systems were found to not only foster circularity and promote resource recovery (Fam and Mitchell, 2013) but also to have the potential to reduce nutrient and micropollutant emissions from wastewater treatment plants (WWTPs) (Badeti et al., 2021) and lower energy and financial costs (Igos et al., 2017). Some concrete models of

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the source-separating sanitation systems are urine and blackwater recycling (Sniatala et al., 2023). Blackwater (containing feces, urine, flush water, and toilet paper) accounts for only 15 % of the total domestic wastewater volume yet contains approximately 90 % of the nitrogen and 80 % of the phosphorus (Saliu and Oladoja, 2021). Urine, on the other hand, is even more concentrated, at about 1 % of domestic wastewater volume and containing approximately 80 % of the nitrogen and half of the phosphorus and potassium (Jönsson, 2005; Vinnerås et al., 2006). The separate collection and recycling of blackwater and/or urine thus offers the prospect of increasing nutrient recovery, meeting expected phosphorus and nitrogen recovery targets in Sweden, while at the same time reducing the carbon footprint of sanitation management in support of existing national Swedish environmental goals related to climate change (Lehtoranta et al., 2022a; McConville et al., 2017). Additionally, nutrient recovery from domestic wastewater can potentially reduce reliance on agricultural mineral fertilizers (Lehtoranta et al., 2022a; Saliu and Oladoja, 2021). Contemporary intensive farming methods rely heavily on these fertilizers, which are rich sources of phosphorus and nitrogen (Sniatala et al., 2023). Their price depends upon the cost of phosphate extraction and the natural gas used in the fixation of nitrogen in the Haber–Bosch process (Kok et al., 2018; Langergraber and Muellegger, 2005). Therefore, any volatility, such as geopolitical tensions, can create dramatic price swings. Since mineral phosphorus is also relatively scarce and the reserves of fossil fuels will soon run out, these nutrients are likely to become too expensive to capture (Cordell et al., 2009), posing a threat to the prosperity of countries susceptible to economic shock and those which rely on fertilizer imports.

While these source-separating sanitation systems have been explored from a technical perspective and optimized to maximize resource recovery (Kjerstadius et al., 2015; Mehaidli et al., 2024; Simha et al., 2018; Tarpeh et al., 2017; Udert et al., 2003), and from a socio-technical perspective to identify diffusion barriers (Abeysuriya et al., 2013; Aliahmad et al., 2023; McConville et al., 2023; Simha et al., 2021), less emphasis has been placed on exploring their comparative environmental profiles (Aliahmad et al., 2022; Mathilde Besson and Tiruta-Barna, 2021). Considering that these systems aim to improve wastewater sustainability and mitigate emerging uncertainties, their environmental profiles and foreseeable consequences must be thoroughly examined to decide whether they are sustainable alternatives.

The life cycle assessment (LCA) methodology has been employed to study and evaluate the environmental profiles of conventional wastewater treatment and source-separating sanitation systems. In turn, this has contributed to a better understanding of the environmental performance of these systems throughout their life cycle, providing insights for decision-makers involved in the strategic planning of urban infrastructure (Heimersson et al., 2019). Some of these LCA studies have focused on conventional WWTPs (Corominas et al., 2020; Raghuvanshi et al., 2017), the environmental implications of the end products (Lam et al., 2022), and the associated environmental trade-offs (Pausta et al., 2024). Some have extended their analysis beyond centralized WWTP and compared it to decentralized systems (Risch et al., 2021) or examined different spatial scenarios, including developing countries (Gallego-Schmid and Tarpani, 2019) and small communities (Garfí et al., 2017). On the other hand, fewer studies have focused on comparing source separation systems, such as blackwater systems, with conventional systems (Kjerstadius et al., 2017; Lima et al., 2023; Remy, 2010; Thibodeau et al., 2014). There has also been partial investigation into other source separation systems, including urine recycling (Ishii and Boyer, 2015), fertilizer production (Hilton et al., 2021; Martin et al., 2023), and life cycle costing (Landry and Boyer, 2016). Recent LCAs have demonstrated that source separation systems, such as urine recycling and blackwater, outperform conventional WWTPs regarding environmental impact (Besson et al., 2021). This is often attributed to the additional resources these systems recover as well as a reduction in greenhouse gas emissions such as nitrous oxide N_2O (Benetto et al., 2009; Lundin et al., 2000). However, there is a noticeable gap in large-scale comparative studies on these systems, as most studies have focused on smaller or semi-large scales (Besson et al., 2021; Spångberg et al., 2014). Existing studies, though informative, have limitations in their comparative scope; for example, none have investigated the potential benefits of a hybrid/integrated source-separating system of urine and blackwater. Ammonia stripping, for instance, was reported as a primary source of climate impact in the blackwater system (Lima et al., 2023), highlighting the need to explore whether incorporating urine recycling would mitigate this impact. Furthermore, to the best of our knowledge, most of the LCA studies reviewed are attributional, meaning they used average data in their analysis. This underscores the need for further comparative consequential LCA studies on a larger scale.

Therefore, the primary aim of this study is to address existing research gaps by performing a full consequential life cycle assessment (CLCA) on different source separation scenarios, including blackwater, urine, and a hybrid scenario of both in a large-scale newly built neighborhood of 10,000 person-equivalent in southern Sweden. Herein, the study is structured to address the following research questions: 1. *What are the foreseeable environmental impacts of conventional WWTPs compared to source separation systems throughout their life cycles? 2. What environmental hotspots are associated with each source separation scenario, and how can these be mitigated? What sets this LCA apart is the utilization of the consequential LCA approach, utilizing marginal data to model the environmental gains of substituting conventional resources with recovered products such as fertilizer, biogas, and water, details of which are further elaborated within the study. The CLCA approach aligns with the LCA's overarching goal, which is to assist decision-makers in selecting an appropriate source separation system for the newly constructed Brunnshög neighborhood in the city of Lund, located in the south of Sweden by illustrating the environmental consequences associated with these systems in comparison to a centralized WWTP. Using the CLCA methodology enables the inclusion of both direct and indirect impacts, allowing us to capture the foreseeable environmental consequences of adopting a specific sanitation system.*

2. Material and methods

2.1. Case study

The study is conducted in the city of Lund, in southern Sweden. The specific location is Brunnshög, a newly developed, under-construction neighborhood planned to house 40,000 people by 2050 (Brunnshög, Lund Kommun, 2024). The wastewater in Lund is currently being treated in the local Källby wastewater treatment plant (WWTP). However, this treatment plant is planned to shut down in the near future, and wastewater will be treated in the Sjölunda WWTP. However, Sjölunda WWTP in Malmö city has now reached a point where it would need extensive renovation to receive more wastewater. Proposing source separation sanitation systems to handle the wastewater generated in Brunnshög would potentially bring environmental benefits to the centralized WWTP and contribute to the ecological profile of the neighborhood. The proposed demo site in Brunnshög is assumed to cover 4000 apartments, hosting a total of 10,000 person-equivalent (PE).

2.1.1. Description of scenarios evaluated

In this LCA, we examined four distinct types of urban sanitation systems. The comparison revolves around centralized sewage conveyance and treatment with alternative scenarios of decentralized and semi-centralized sewage treatment that also involve different extents of source-separation of sewage. In the first scenario, a conventional WWTP serves as a baseline for comparison with other scenarios. A schematic diagram illustrating the WWTP's operation can be found in Fig. 1. In this diagram, we depict the WWTP in operation in Helsingborg City, which was selected due to its relevance and capacity size, which is similar to Lund. We have modeled the Helsingborg and the existing Sjölunda

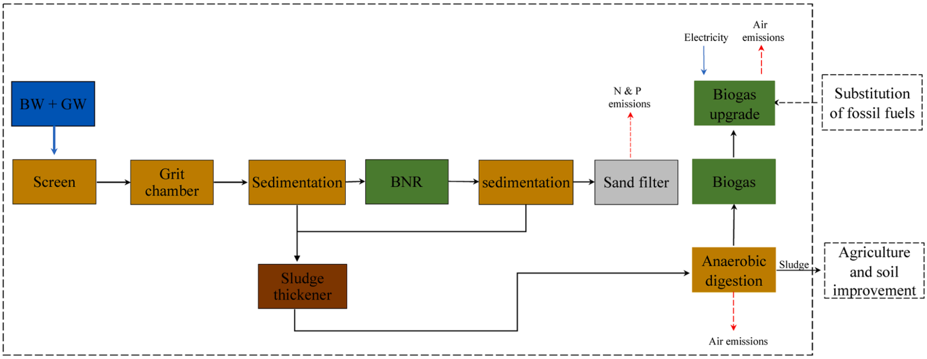

Fig. 1. Schematic diagram of Helsingborg wastewater treatment facility.

WWTPs to compare their environmental performance before proceeding with the former.

For the WWTP, blackwater and greywater (BW& GW) are mixed and collected inside the buildings in one pipe and transported through the sewer network to the facility, as shown in Fig. A.1. The influent undergoes several treatment steps, reducing and removing the biochemical oxygen demand (BOD), chemical oxygen demand (COD), and nutrients (Nitrogen and Phosphorus). Biogas is produced and upgraded to substitute diesel in buses; sludge is also produced, half of which is used in agriculture fertilizer and the other half as soil conditioner.

The second scenario incorporates the concept of urine recycling, i.e., the separate collection and treatment of urine from other wastewater fractions using a urine-diversion toilet (UDT). It is assumed that 75 % of urine is collected (the efficiency of the UDT) (Gundlach et al., 2021). To ensure comparability between the different scenarios, 25 % of the uncollected urine and the rest of the wastewater (grey and brown water) are accounted for in this scenario and assumed to be sent to the local WWTP in a second pipe. We have adjusted the WWTP to account for nitrogen and phosphorus reduction. This scenario is illustrated in Fig. A.2 for visual representation and further details. As part of this setup, urine undergoes pretreatment in the building basement in order to stabilize it, i.e., keep nitrogen as urea by inhibiting its hydrolysis into ammonia by reducing pH to $\leq$ 3.0 with the addition of an organic/inorganic acid (Simha et al., 2023). After urine is stabilized, it is concentrated to remove water and achieve a 95 % reduction in mass. The water is assumed to be recovered using a heat exchanger that also recovers 60–80 % of the heat used in concentrating the urine (Simha et al., 2020). The 60–80 % energy recovery range was selected based on the feasibility of achieving this in residential settings using well-established technologies like air-to-air heat exchangers and heat pumps. Literature on wastewater heat recovery, including (Wehbi et al., 2023), suggests a typical heat recovery of 50–60 % in residential applications. Additionally, (Larsen et al., 2021) report that the energy required for treating urine by distillation is 110 Wh·$L-1$, compared to 710 Wh·$L-1$ for water evaporation without energy recovery. Thus, the assumption of 60–80 % energy recovery is reasonable and reflects a range achievable with existing systems. The concentrated urine is subsequently transported to a factory, where it is fully dehydrated by vacuum drying and pelletized to produce solid fertilizer that can replace mineral fertilizers (as shown in the complete schematic diagram in Fig. 2).

In the third scenario, 100 % black and greywater are recycled. This system mimics the existing pilot system $H+$ in Helsingborg; for a detailed understanding of the system, readers are directed to (Kjerstadius et al., 2015). This configuration's environmental profile has been studied previously (Lima et al., 2023; Remy, 2010), though we have altered it to accommodate new population equivalents (PE) and wastewater characteristics and have chosen not to include food waste recycling, a component that was considered in their studies (see Fig. 3). An advantage of this design over the previous two is that it features a fully decentralized sanitation system, eliminating the need to pipe wastewater to a central wastewater treatment plant. This scenario is

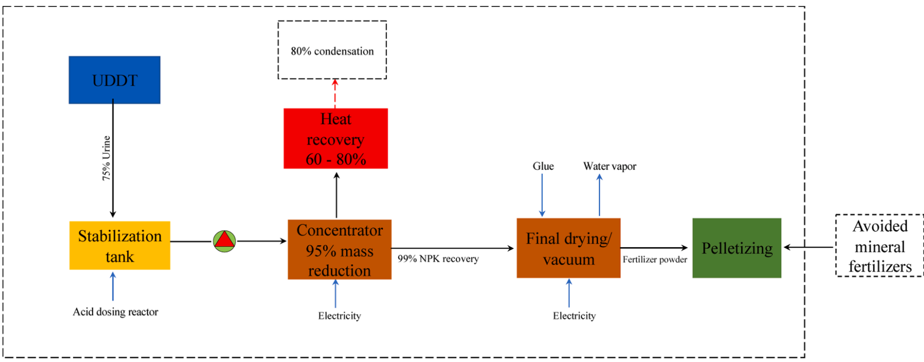

Fig. 2. Schematic diagram of the urine recycling system.

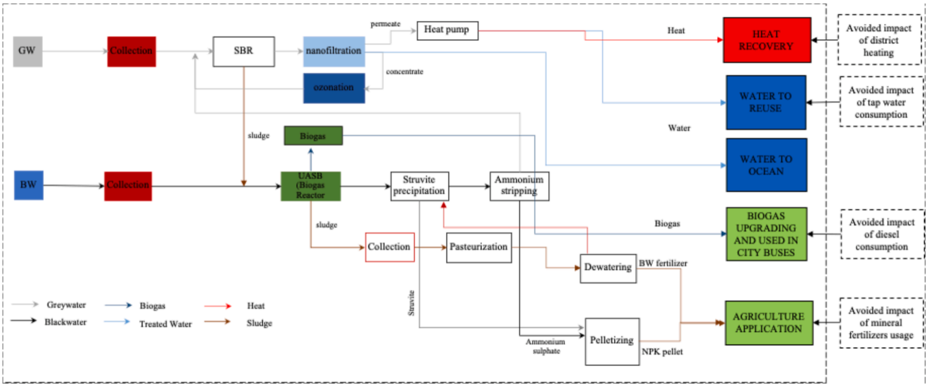

Fig. 3. Schematic diagram of the black and greywater recycling system.

illustrated graphically in Fig. A.3. The blackwater undergoes a series of treatments, including up-flow anaerobic sludge blanket digestion (UASB), which produces biogas and sludge. The UASB effluent is then further processed by struvite precipitation and ammonium stripping to recover phosphorus and nitrogen in the form of struvite and ammonium sulfate, which can be made into NPK fertilizer. In addition, after the fertilizer's recovery, the left digestate is collected and transported to be applied in farmland. The sludge from the UASB is subsequently pasteurized and then dewatered into biofertilizers, which, together with the NPK fertilizer, can replace mineral fertilizers in agriculture. The biogas is upgraded to a quality suitable for use in city buses. Concurrently, greywater is treated in a sequencing batch reactor (SBR), followed by a series of disinfection processes of nanofiltration and ozonation. The ozonation effluent is recirculated back to the SBR while the permeate passes through a heat pump, where heat and water are recovered and reused. The sludge from the SBR process joins the blackwater stream before the UASB. Despite the high quality of the reclaimed water, the regulatory restraints in Sweden and the absence of explicit permits necessitate the discharge of 20 % of the treated black and greywater into the ocean. The remaining 80 % is utilized for irrigation purposes (Lima et al., 2023).

The fourth scenario, illustrated in Fig. A.4, integrates the previously discussed urine recycling and blackwater systems. Similar to the previous scenario, this scenario also provides the advantage of treatment being fully decentralized, thereby avoiding the need for piping uncollected wastewater to a central WWTP. According to (Lima et al., 2023), ammonia stripping was a primary source of climate impact in the blackwater system in Helsingborg. In this final scenario, we examine whether the collection and treatment of urine, which contains the majority of nitrogen, helps to improve the blackwater system in terms of climate impact. Practically, as shown in the illustration, there are three separate pipes exiting the building in this scenario: one for the diverted urine, which is treated according to the method outlined in the second scenario; one for the uncollected urine, as well as the remaining blackwater; and one for greywater, which will be treated following the same procedures as the third scenario.

2.2. Life cycle assessment LCA

The International Standard 14,040 established a standardized methodology for life cycle assessment (LCA), which analyzes and quantifies the potential environmental impact of a product, from extraction to disposal ("ISO 14040," 2006). This methodology is not only a theoretical construct but is a practical tool that guides one through four main phases: defining a goal and scope, determining a life cycle inventory, assessing a life cycle impact assessment, and interpreting the results. Phases are not isolated but are interconnected, with each building upon the previous. Through this iterative process, alternatives under investigation are selected, and environmental hotspots are identified.

In general, life cycle assessment (LCA) involves two methodological alternatives: attributional and consequential. Choosing between attributional and consequential modeling is essential to the results of an LCA study because both approaches address a specific question, and an adequate choice makes the analysis and results more consistent with the decision context (Tillman, 2010; Weidema, 2003). An Attributional Life Cycle Assessment (ALCA) identifies a product's direct environmental impact (emissions). ALCA utilizes average data that is representative of the actual physical flow of products (Finnveden et al., 2009). Alternatively, the Consequential Life Cycle Assessment (CLCA) incorporates indirect emissions into the analysis, taking into account the more systematic changes caused by the product's decision (i.e., use and operation) (Curran, 2007; Ekvall, 2020). As part of a CLCA, upstream and downstream changes in supply chains are analyzed, as are market-driven factors such as changes in production, consumption, and substitution (Ekvall T, 2004; Sandén and Karlström, 2007). A CLCA utilizes marginal data to determine the additional environmental impact associated with the production and introduction of an additional unit of a product (Weidema BP, 1999; Zamagni et al., 2012).

Regarding multifunctionality—multiple outputs from a single process—the two approaches to quantifying emissions differ significantly. A specific allocation method is used in ALCA to partition the impacts based on set criteria among the outputs (Azapagic 1999), whereas system expansion avoids allocation in CLCA (Ekvall and Andrae, 2005; Wernet et al., 2016). Two approaches to system expansion may be utilized: one approach involves expanding the system boundaries to include a new function or product, harmonizing the scope of the systems being compared (Earles and Halog, 2011). An alternative to this method, the "avoided burden" method, subtracts the environmental burdens resulting from an alternative method of providing the secondary function from the overall system (Ekvall, 2020; Ekvall et al., 2016). The latter is what we used in this study as it was deemed appropriate in the context of wastewater treatment (Tillman, 2010).

2.2.1. Goal and scope definition

The primary goal of this LCA study is to evaluate and compare different source-separating sanitation systems for a newly developed neighborhood in southern Sweden against the local centralized WWTP.

The study aims to identify environmental hot spots, which will be essential for optimizing proposals and recommendations for implementation. The study is focused on a specific case area in Sweden with its current reference system where biogas is produced and upgraded to substitute diesel in buses, and sludge is also produced and used in agriculture fertilizer and soil conditioners. Therefore, this study is not meant to compare what is best going forward by either the Water Resource Recovery Facility (WRRF) or source separation but instead compare source separation to the existing local WWTP. Sanitation systems are generally designed for managing and treating incoming wastewater. Accordingly, this LCA's functional unit (FU) is the management of domestically generated wastewater per person equivalent (PE) per year, including collection, treatment, and disposal/reuse. As mentioned previously, the total population equivalent is 10,000 PE. Schematic diagrams depicting comprehensive system boundaries for each scenario are shown in Section 2.1.1. The system boundaries encompass the collection and management of wastewater (foreground processes), as well as the production and transportation of chemicals, electricity, heat, and infrastructure (background processes). Additionally, all scenarios factor in avoided processes pertaining to fertilizer, biogas, and reclaimed water production. The substitution of these resources will influence the fertilizer and biogas market in terms of production, supply, and price. For example, the demand for electricity in the studied region affects the production mix, with the same applying to the mineral fertilizer market. In consideration of these "foreseeable" impacts on energy and mineral fertilizer systems, CLCAs with marginal data are deemed most suitable.

2.2.2. Life cycle inventory (LCI)

The inventory, comprehensively detailed in the supplementary material (SM), spans a wide range of processes for each scenario. It includes a mass balance for each scenario, measuring inputs and outputs in each unit process. The inventory encompasses building collection (piping and porcelain), sewer infrastructure (piping, excavation, and backfilling), treatment facility operation (chemical and energy use), and facility construction. Furthermore, it models other unit processes such as biogas upgrading, sludge treatment, and fertilizer recovery, all of which are documented in the SM, along with the Ecoinvent processes used.

2.2.2. Life cycle impact assessment (LCIA)

We used the ReCiPe® 2016 method (Midpoint, World – Hierarchistic version) and Simapro® for modeling. We altered the impact categories and selected the five that were most significant to the assessment: Global warming potential (GWP) in kg CO2-eq, Stratospheric ozone depletion (SOD) in kgCFC11- eq, Terrestrial acidification (TAD) in kg SO2-eq, Freshwater eutrophication (FEP) in kg P-eq, and Marine eutrophication (MEP) in kg N-eq.

2.2.3. Sensitivity Analysis

Using sensitivity analysis in LCA studies allows us to determine the robustness of the results and their sensitivity to uncertainty. A common method used in LCAs is Monte Carlo, supported by software like Simapro®. However, in our case, the Monte Carlo method would not work properly due to the use of consequential system models. Hence, we carried out a sensitivity analysis in the form of scenarios on some uncertain but critical factors affecting the study's outcome. Our first scenario examined the NH_3 emissions from the urine recycling system. Initially, in line with the literature (Gao et al., 2024) (in preparation), it was assumed that NH_3 losses would not occur during concentration, and, hence, N, P, and K could be effectively concentrated up to 99 %. For the purpose of this sensitivity analysis, it was assumed that 5 % of the nitrogen may be lost as NH3 emissions during concentration. The second sensitivity scenario explored using acid agents other than citric acid for urea stabilization. (Simha et al., 2023) reported that the following acids: 1.36 g H2SO4 $L-1$, 2.86 g H3PO4 $L-1$, 2.53 g C2H2O4·2H2O $L-1$, and 5.9 g C6H8O7 $L-1$ were found to be effective for urine stabilization. Thus, this scenario will compare these alternatives in terms of their environmental performance and impact on the urine recycling system's GWP. Thirdly, we consider the use of electricity by the urine recycling system in its operation, and particularly the energy efficiency of the urine concentrator. The concentrator was assumed to recover 70 % of its energy demand (600 Wh/L) (Simha, 2021). In comparison, the sensitivity analysis considered a scenario in which no energy recovery was performed, and the system used 600 Wh per liter of urine. The fourth sensitivity scenario concerns the percentage of greywater recovered and utilized for irrigation purposes in the third and fourth systems. In line with the literature for similar studies (Lima et al., 2023), we assumed a recovery rate of 80 %, which may appear high for irrigation needs in typical urban areas, especially since the investment in storage systems is outside the scope of our study. Therefore, we proposed a sensitivity analysis that assumes a more conservative recovery rate of 40 %, with the remaining 60 % being discharged into the ocean. Finally, we considered different sources of electricity. The original scenarios accounted for the Swedish electricity mix. However, in this sensitivity scenario, we examined whether switching to the European energy mix would affect environmental impacts. These sensitivity scenarios test the robustness of the results drawn from the study and allow an understanding of how changes in these key parameters could have an impact on the overall environmental assessment.

3. Results and discussion

3.1. The comparative life cycle environmental impacts – RQ1

The characterized net results of the LCA are presented in Table 1. Upon initial examination, it is apparent that the fourth scenario, which incorporates a urine recycling system as well as a blackwater system, represents the best-performing sanitation system regarding GWP, ozone depletion, acidification and eutrophication in our study. In addition, it is evident that the inclusion of the urine recycling system in the second scenario significantly improved the WWTP's performance regarding these factors, resulting in a 20 % reduction in global warming potential, a 65 % reduction in ozone depletion, a 45 % reduction in acidification, and a 55 % reduction in marine eutrophication. It is crucial to clarify that the focus of this paper is not on predicting how WWTP managers would handle a technological system incorporating local urine recycling. Such predictions are outside the scope of this paper. WWTP managers would likely focus on meeting current demands on discharges, which will become even more manageable with local urine recycling due to lower incoming nitrogen and, thus, lower aeration requirements and chemicals in WWTPs (Kleckers, 2023). However, it is equally conceivable that stricter discharge limits could be implemented in the future to counterbalance this effect. Hence, authorities would likely seek to regulate the impact on WWTPs stemming from such technological advancements. Therefore, this paper explicitly investigates "the potential effect" of local urine recycling without considering the "potential policy or regulatory changes" necessary for a system with local treatment of urine or blackwater.

Table 1 presents the net results; each system's savings (negative emissions) from the substituted resources have not been explicitly delineated as they are already accounted for in the net. For a more comprehensive visualization of these gains and each unit process's contribution, see Fig. 4. It is evident therein that the positive emissions for the fourth scenario (92.6 and 1.3 kg CO2-eq per PE/ y) can be attributed to the treatment operation and construction, respectively. However, the system also has negative emissions, reflective of gains derived from the substitution of resources. For instance, - 54.5, −15.0, and - 0.5 kg CO2-eq per PE/ y from the NPK fertilizer, irrigation, and sludge fertilizer, respectively.

GWP values observed in the baseline scenario align with those documented in the literature (Besson et al., 2021; Diaz-Elsayed et al., 2020; Spångberg et al., 2014; Thibodeau et al., 2014). It is necessary to

Table 1
Complete characterized life cycle assessment results using the ReCiPe® method (ReCiPe-LCA) for the conventional WWTP and source-separating sanitation systems. Highlights represent the best-performing results.

Impact category	Unit	S1: Conv. WWTP	S2: Urine +WWTP	S3: BW&GW	S4: Urine +BW&GW
Global warming	kg CO2-eq per PE/y	78	62	32	24
Stratospheric ozone depletion	kg CFC11 eq per PE/y	8.2E-04	2.9E-04	6.0E-05	4.7E-05
Terrestrial acidification	kg SO2 eq per PE/y	3.3E-01	1.8E-01	7.2E-02	-1.2E-01
Freshwater eutrophication	kg P eq per PE/y	8.8E-03	7.0E-03	-2.0E-03	-1.2E-02
Marine eutrophication	kg N eq per PE/y	5.0E-01	2.2E-01	2.7E-02	2.9E-02

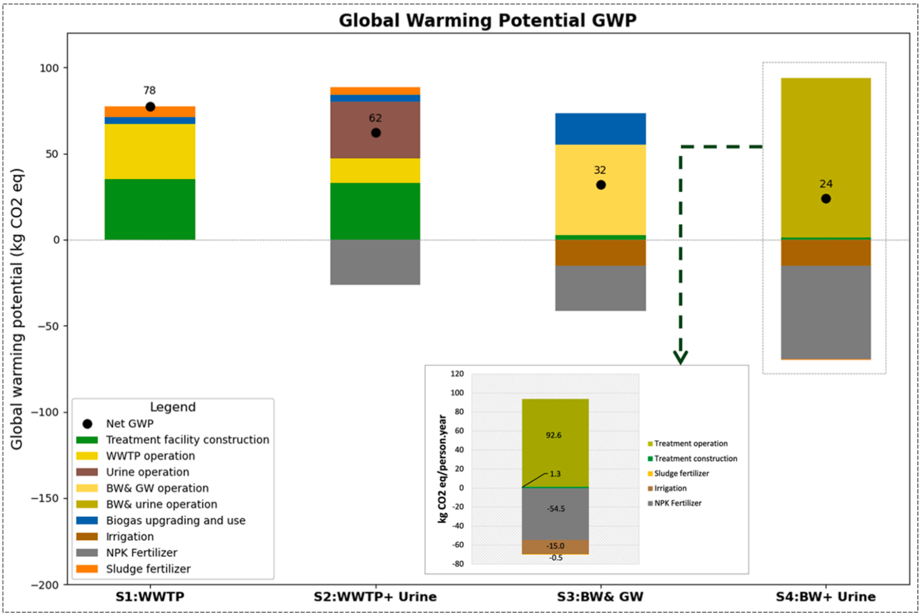

Fig. 4. The global warming potential GWP net results of the analyzed systems using the ReCiPe® method. The units are in kg CO2-eq per PE/ year. The fourth scenario has been broken down to show detailed results.

emphasize that discrepancies between LCAs may arise for several reasons. A crucial determinant is the nature of the data used, as discussed previously, where disparities may result from the utilization of marginal versus average datasets (Corominas et al., 2020). Additionally, the delineation of system boundaries within the LCA framework and the district typology exerts a significant influence on potential outcomes. Furthermore, the inclusion of recovered resources in the assessment process, the specific LCA methodology employed, the configurations of the analyzed systems—which can affect critical parameters such as N_2O emissions—and the energy sources utilized all play a significant role in shaping the assessment results (Diaz-Elsayed et al., 2019; Lehtoranta et al., 2022b). The assessment of other source-separating sanitation systems is also subject to similar considerations (Corominas et al., 2013).

To compare the four scenarios concerning the comprehensive array of other impact categories outlined in the table, the corresponding values have been plotted and illustrated in Fig. A.5. As previously indicated, the fourth scenario demonstrates the most modest impact across all categories assessed. Notably, this scenario manifests total negative values for two impact categories: acidification and freshwater eutrophication. Negative impacts are largely due to the utilization of NPK fertilizer, biogas, and reclaimed water.

3.2. *Environmental hotspot identification and mitigation recommendations*

In the initial scenario, the GWP is estimated at 78 kg CO2-equivalent per PE/ y. For a more detailed understanding of these emissions, Fig. 5 illustrates the unit processes that were modeled. It is evident from the figure that the majority of GWP is generated by the operation and construction of the WWTP. A more detailed analysis is provided within the same figure by depicting the operation unit process. In addition to electricity consumption, nitrous oxide from biological nitrogen removal in the activated sludge system and methane emissions from the anaerobic digester during biogas production also contribute significantly, accounting for 30.3 and 15.2 kg of CO2-equivalents per PE/ y, respectively. Furthermore, it is noteworthy that the integration of recovered heat, intended to replace conventional district heating, has shown positive results. This substitution has resulted in a reduction of −17.7 kg CO2-equivalent per PE/ y. The ozone depletion potential of the WWTP was calculated at 8.2E-04 kg CFC11 eq per PE/ y, the highest in comparison to the other scenarios (see Fig. A.5). A major contributor to ozone depletion is sludge management and nitrogen oxide emissions at the treatment plant. The management of sludge also contributes significantly to acidification due to emissions of ammonia (NH3), nitrous oxide (N2O), and methane (CH4). The eutrophication category is further divided into freshwater and marine, which reflect nutrient emissions (P and N, respectively) from the WWTP into the water. The results showed 0.499 kg N per PE/ y and 0.024 kg P per PE/ y, equivalent to 9.49 mg N / L and 0.45 mg P / L.

For the second scenario, integrating urine recycling with the WWTP resulted in 62 kg CO2-eq per PE/ y, which is a 20 % reduction of the WWTP GWP. To facilitate a comprehensive understanding of the scenarios, Fig. 6 illustrates the distinct stages that contribute to the GWP. It is evident from the figure that the introduction of urine recycling has significantly reduced the GWP of the WWTP operation from 32.3 (in the baseline scenario) to 14.3 kg CO2-eq per PE/ y. This is attributed mainly to a reduction in electricity required to treat the influent with lower nitrogen and phosphorus loads, consequently leading to a reduction in nitrous oxide emissions and methane emissions, similar to what was reported in (Besson et al., 2021). In addition, urine recycling led to a reduction in all other impact categories compared to the reference scenario, for example, there was a 55 % reduction in eutrophication potential caused by the decrease in nutrient discharge (N & P) into water bodies, especially the nitrate (NO_3-N) concentration, similar to what was reported in (Jimenez, 2015) . These findings align with the literature (Hilton et al., 2021), reporting that urine diversion and concentration could achieve a 29−47 % reduction in GWP and 25−64 % in eutrophication over conventional WWTP. Furthermore, there was a 65 % and 45 % reduction in ozone depletion and acidification potential, respectively (see Fig. A.5).

Moreover, the urine recycling system produces NPK fertilizer, which is assumed to replace mineral fertilizer. This substitution leads to a - 26.3 kg CO2-eq per PE/ y reduction in the scenario's GWP (Fig. 6). On the other hand, it is necessary to acknowledge that operating the urine treatment system contributes significantly to the GWP, illustrating the inherent trade-offs associated with many sanitation systems. Even though the urine recycling system brings gains, such as negative emissions via the replacement of mineral fertilizer, the operation of the urine recycling system in terms of energy demand and chemical use contributes to greenhouse gas emissions. A further investigation into the sources of GWP associated with urine recycling reveals that the urine concentrator and the stabilization tank constitute the primary contributors, contributing 16.22 and 15.48 kg CO2-eq per PE/ y, respectively. Among the main contributors is the use of citric acid as a stabilizing agent in the stabilization tank, which requires energy for the microbial fermentation and purification processes. Additionally, electricity consumption is a significant factor that affects urine concentrator performance.

For the third scenario, the black and greywater system, the total GWP was estimated to be 32 kg CO2-eq per PE/ y, a 60 % and 48 % reduction compared to the baseline scenario WWTP and the second scenario, respectively. Although these findings, i.e., a reduction in percentage from the baseline align with the literature (Kjerstadius et al., 2017; Lima et al., 2023), although the exact GWP values differed. This can be attributed to the type of system models used, the system boundaries, and the person equivalent. For a better understanding of the GWP, the different unit processes are illustrated in Fig. 7. The figure shows that the major contributors to the GWP are operation and biogas upgrading. The NPK and recovered water have negative GWP as gains (−15 and −26.3 kg CO2-eq per PE/ y) attributed to their mineral fertilizer and irrigation substitution. The operation unit process has been broken down to look at its inputs to better understand where the GWP comes from. The figure shows that ammonia stripping and struvite precipitation contribute to much of the operation GWP of 28.6 and 9.29 kg CO2-eq per PE/ y, respectively. This is attributed to the chemicals used in both processes (e.g., Sulfuric acid, Sodium hydroxide, and Magnesium chloride), which aligns with what is reported in the literature (Lima et al., 2023). Regarding other impact categories, this scenario outperforms the first two scenarios in all categories, and the system received gains, including negative emissions in acidification, ozone depletion, and eutrophication attributed to the utilization of NPK and sludge fertilizer, reclaimed water, and biogas use (see Fig. A.5).

The fourth scenario is a hybrid system that combines the urine recycling system with the black and greywater system. The total GWP has been reduced to 24 kg CO2-eq per PE/ y, which is attributed to the extra NPK recovered from the urine. This scenario achieves an almost 70 % reduction in GWP compared to the baseline scenario and a 22 % reduction compared to the BW scenario. As shown in Fig. 8, the negative GWP from NPK has increased from 26.3 for the BW without urine recycling to 54.5 kg CO2-eq per PE/ y with urine recycling. The treatment operation in this scenario contributes 92.6 kg CO2-eq per PE/ y. This includes the 33.2 kg CO2-eq per PE/ y from the urine recycling system and 18.03 kg CO2-eq per PE/ y from the biogas upgrading; thus, the BW operation is 41.4 kg CO2-eq per PE/ y, which is lower than in the

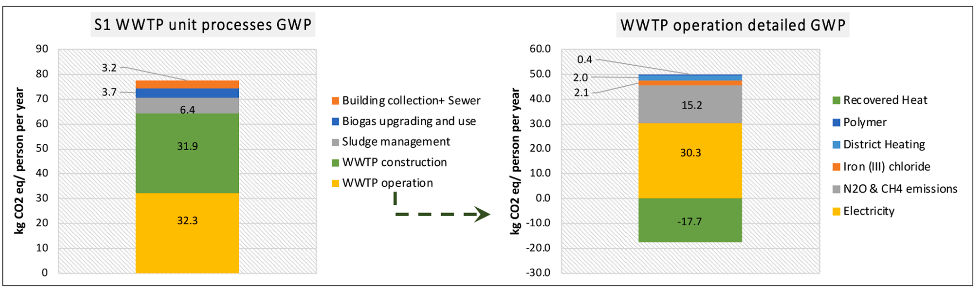

Fig. 5. Scenario 1, WWTP unit processes global warming results and the detailed WWTP operation unit process results.

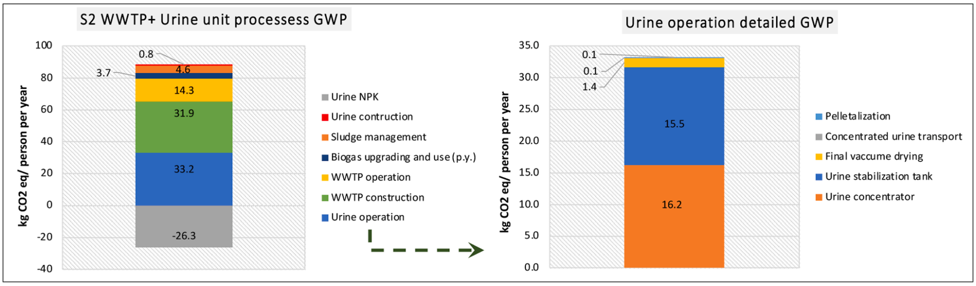

Fig. 6. Scenario 2. Urine and WWTP unit processes global warming results and the detailed Urine operation unit process results.

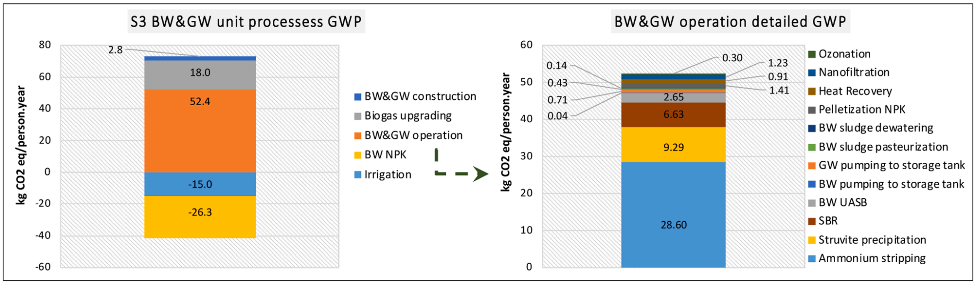

Fig. 7. Scenario 3, BW & GW unit processes global warming results and the detailed results of the operation unit process.

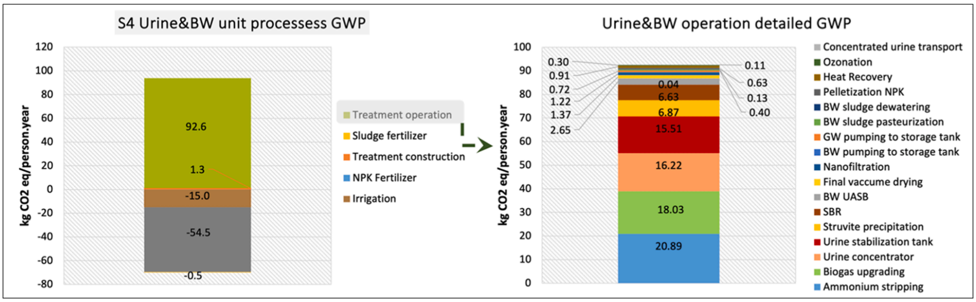

Fig. 8. Scenario 4, Urine and BW unit processes global warming results and the detailed results of the operation unit process.

third scenario without urine recycling. This is because urine recycling decreases the impact of the ammonia stripping and struvite precipitation processes, which had the highest share of the GWP in the third scenario. To better understand the treatment operation, we can see that ammonia stripping GWP is 20.89 kg CO2-eq per PE/ y compared to 28.6 kg CO2-eq per PE/ y in the third scenario. Regarding other impact categories, this scenario outperforms all scenarios in all categories, and the system received gains, including negative emissions in acidification, ozone depletion, and eutrophication attributed to the extra utilization of NPK and sludge fertilizer, reclaimed water, and biogas use (see Fig. A.5).

3.3. Sensitivity analysis

The first sensitivity scenario assumed 5 % NH_3 emissions at the urine concentrator, which is in opposition to the initial assumption of no ammonia loss. The changes exclusively affected the second and fourth scenarios, which incorporated urine recycling, while the first and third scenarios remained unchanged. The urine recycling system includes the following unit processes: urine stabilizer, concentrator, transport of concentrated urine, vacuum drying, and pelletization. The results revealed a slight (4 % and 8 %) increase in the GWP of the second and fourth scenarios. Additionally, there was a significant increase in their acidification potential by over 200 % and 300 % from 0.18 to 0.6 and −0.12 to 0.28 kg SO2 eq per PE/ y in the second and fourth scenarios, respectively. To compare these values with other scenarios, see Fig. A.5. SM contains further information regarding the impacts on other categories.

The second sensitivity analysis evaluated the environmental performance of the urine recycling systems using four different acid agents instead of citric acid. Sulfuric acid 1.36 g H2SO4 per liter of urine had the best environmental performance. Results showed that the whole GWP of the urine recycling system could be reduced by 47 % from 33.2 to 17.6 kg CO2-eq per PE/ y. The urine stabilization unit process had a 15.47 kg CO2-eq per PE/ y GWP when 10 g of citric acid was used. When sulfuric acid was used instead, the GWP was reduced by 101 % (negative savings) to −0.14 kg CO2-eq per PE/ y (see Fig. 9 for a detailed illustration). This is because sulfuric acid can be produced as a by-product in various industrial processes (e.g., copper smelting and desulfurization of crude oil), a practical and sustainable approach that improves the overall efficiency and sustainability of industrial operations. Thus, from a consequential perspective, the marginal emission factor for sulfuric acid is negative. However, there are challenges associated with the use of sulfuric acid that fall outside the scope of this LCA. Since sulfuric acid is a byproduct of fossil fuel production, transitioning to a fossil-free environment could lead to concerns about the availability of sufficient H2SO4, especially since current known minable resources are projected to last <30 years (Maslin et al., 2022).

Increasing the electricity demand in the urine recycling system to 600 Wh per liter of urine in the third sensitivity scenario resulted in a marked increase of almost 50 % in the GWP of the whole system, mainly coming from the urine concentrator unit process, which saw GWP increasing by 66 %, from 16.22 to 48.67 kg CO2-eq per PE/y. The latter sensitivity analysis made the scenarios incorporating urine (i.e., the second and fourth) look worse compared to the reference scenario and the BW.

For the fourth sensitivity analysis, we focused on the percentage of greywater GW recovered and utilized for irrigation. We used a more conservative recovery rate of 40 %, with the remaining 60 % being discharged into the ocean instead of the 80 % recovery in the initial scenario. The changes exclusively affected the third and fourth scenarios, which incorporated GW recycling, while the first and second scenarios remained unchanged. The one-unit process that was affected the most in both systems is the irrigation unit. Initially, both systems saved 15 kg CO2-eq per PE/y due to the recovered GW used for irrigation. However, when the recovery rate decreased to 40 %, the savings from irrigation also dropped to 7.5 kg CO2-eq per PE/y. Additionally, there was a slight change in the ozonation unit process due to the increased flow of GW out of the nanofiltration to the ocean, resulting in approximately 0.5 kg CO2-eq per PE/y. These two changes in the systems led to an increase in their global warming potential (GWP) to 40 and 32 kg CO2-eq per PE/y, as illustrated in Fig. A.6. Nevertheless, the two systems still outperformed the reference and second scenarios.

In the final sensitivity analysis, we examined the consequences of switching from the Swedish to the European energy mix. While all impact categories demonstrated an increase, the observed increase of approximately 10 % was less pronounced than anticipated. This deviation can be attributed to the utilization of marginal data in the consequential model (Wernet et al., 2016). When utilizing the marginal data in the consequential model, the model does not simply average out all EU power source mixes, such as coal, gas, nuclear, and renewables (Regett et al., 2018). Instead, the focus is on what power sources would actually increase production to meet the anticipated increase in demand or whether the increase would be met by imported electricity (Aliahmad et al., 2020; Vélez-Henao et al., 2019). The method used by Ecoinvent to develop marginal electricity data is to take a long-term forecast or scenario for future electricity production and define/assume the marginal electricity mix to be a mix of technologies, where the electricity is projected to increase from now until the future scenario (Ekvall, 2020; Regett et al., 2018). Supposing the trends identified for the EU marginal future electricity show a predominance of cleaner technologies (like wind or solar), the change in GWP might not be as high since these cleaner sources have lower CO2 emissions than coal (Naumann et al., 2024; Schmidt J H et al., 2011). However, this method has the drawback of ignoring declining trends; instead, it only accounts for growing ones. Based on the Ecoinvent v3 database, the average emission factor for the European electricity mix is 0,39 kg CO2-eq; however, the marginal emission factor is 0,21 kg CO2-eq, which implies that the modeled trend for the EU future electricity production and expansion is predominated by clean technologies. In conclusion, these results for the sensitivity analysis in Fig. A.6 indicate that the framework of assessment of this LCA and the data modeled in the inventories are robust and that the sensitive parameters considered are of high significance in terms of their contribution to the different impact categories.

3.4. Comparative analysis and practical insights

The conventional WWTP modeled as the reference scenario showed the highest environmental impact across all assessed impact categories. This underscores the necessity for innovations that contribute to a reduction in the environmental impacts of conventional systems, especially at the biological nitrogen removal stage. Scenario 2, which incorporates a urine recycling system, demonstrated improvements over the conventional WWTP and can thus be a coherent pathway toward sustainable improvement. In this scenario, the nitrogen and phosphorus load on the treatment plant decreased, correspondingly lowering the energy demand for biological nitrogen removal and the dosage of chemicals required for precipitating phosphate. Furthermore, fertilizer recovery from urine recycling reduced GWP and eutrophication impacts. Scenario 3, the BW&GW system, demonstrated further improvements compared to the conventional WWTP and urine recycling system. Nutrient recovery, biogas production, and reclaimed clean water significantly reduced its GWP and attained excellent results across all assessed impact categories. Additionally, treating greywater locally in this scenario reduces the load (i.e., the volume of wastewater) to the centralized WWTP, thus enhancing the treatment plant's efficiency and capacity, particularly during peak periods (Awasthi et al., 2024). In the

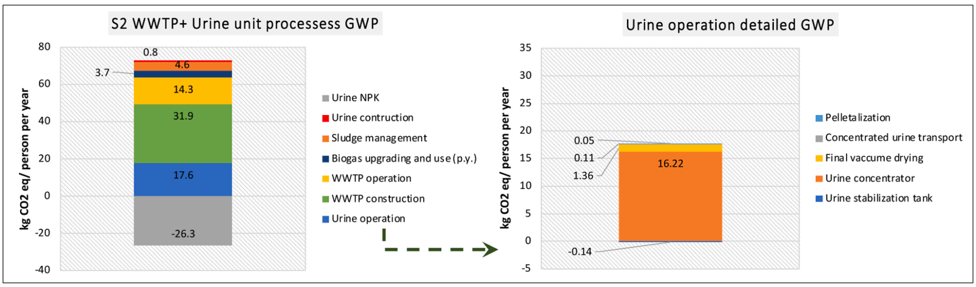

Fig. 9. Detailed analysis of the impact of using sulfuric acid instead of citric acid. The GWP of urine operation dropped from 33.23 in the second scenario to 17.61 kg CO2-eqper PE/ y. The primary reduction is in the stabilization tank (100.88% reduction), from 15.47 kg to −0,137 kg CO2-eqper PE/ y.

fourth scenario, the hybrid system, particularly when combined with 70 % heat energy recovery at the urine concentrator, showcased the best environmental performance among all other scenarios across all assessed impact categories. Integrating the urine recycling system with the BW&GW system offers a more holistic and completely decentralized approach that maximizes resource recovery, reduces the GWP of the energy-intensive ammonia stripping process, and enhances all other assessed impact categories.

In real-world applications, various factors, including infrastructure availability, resource recovery targets, social acceptance, and the environmental conditions of the local water recipients, will guide the choice of sanitation systems. Decision-making considerations are recommended to focus on the accruable long-term benefits from reduced environmental impacts, resource recovery, and energy generation when choosing appropriate sanitation systems. This paper is based on a sound framework for assessing the environmental profiles of different sanitation scenarios and, hence, forms a key instrument in guiding sustainable wastewater management practices. For already-built neighborhoods connected to sewer networks and centralized treatment plants that will undergo renovation, we recommend integrating urine recycling into the new units. This is a crucial step towards sustainability, as it promises considerable improvements to the treatment plant, including a reduction in its environmental impacts, increased capacity, and local production of bio-based fertilizers that contribute to food security and nutrient resilience. For unbuilt neighborhoods in the planning stage, we recommend a completely decentralized source-separating system like the BW&GW system, which offers a promising reduction across all investigated impact categories. To further optimize the environmental profile and sustainability of the neighborhoods, we recommend the hybrid scenario, which integrates urine recycling with 70 % energy recovery at the urine concentrator into the BW&GW system. Hence, the priority should not be deciding between urine recycling and the BW&GW system but instead integrating both for a more comprehensive decentralized source-separating sanitation solution.

4. Conclusion

This study conducted a comprehensive consequential life cycle assessment (LCA) utilizing marginal data and system expansion/substitution to compare the environmental performance of various source-separating sanitation systems to that of a centralized wastewater treatment plant (WWTP). The centralized WWTP served as the reference scenario. The second scenario included urine recycling integrated into the reference scenario. The third scenario examined the implementation of a black and greywater (BW & GW) system. Finally, the assessment featured a hybrid scenario that combined urine recycling with the BW & GW system.

Results indicated that the Global warming potential GWP of the four scenarios were estimated to be 78, 62, 32, and 24 kg CO2-eq per PE/ y, respectively. The findings suggest that integrating a urine recycling system into the WWTP could potentially reduce GWP by 20 %. This reduction is primarily attributed to the gains and savings from the recovered NPK fertilizer, which would effectively replace mineral fertilizer. The black and greywater system (BW & GW) in the third scenario achieved a significant 60 % reduction over the reference scenario and 48 % over the second. This reduction is largely attributed to the savings and gains from recovering NPK fertilizer, biogas, and clean water, which serve as alternatives to mineral fertilizer, diesel, and irrigation water. For the hybrid system in the fourth scenario, integrating the urine recycling system into the BW system reduced the GWP by almost 70 % compared to the baseline scenario and 22 % to the third scenario. The reduction in the BW system is primarily attributed to the mitigation of the GWP associated with ammonia stripping, which is due to its high energy and chemical demands. Hence, utilizing urine recycling to manage nitrogen flows instead of ammonia stripping leads to a notable decrease in the GWP of the BW system. The urine recycling system also contributed to additional gains through NPK fertilizer recovery. The potential impact of using different chemicals for urine stabilization was also examined, with results suggesting that switching from citric acid to sulfuric acid could potentially reduce the stabilization unit process GWP by 101 %, bringing the impact down from 15.47 to −0.14 kg CO2-eq per PE/ y.

It’s essential to remark that the performance of source-separating systems is largely attributed to the resources these systems recover, which translate into savings from their total GWP and give these systems an edge to outperform conventional systems. The recovery of resources is subject to assumptions and requires a thorough examination of their uncertainty and sensitivity, particularly concerning the considerable savings, such as those achieved through the recovery of fertilizer, biogas, and water, which significantly impact the overall outcomes. For instance, the sensitivity analysis revealed that lowering the recovery rate of greywater to 40 % instead of 80 % reduced the gains in the third and fourth scenarios by 7.5 kg CO2-eq per PE/ y. Although the two systems still outperformed the reference scenario, their total GWP increased to 40 and 32 kg CO2-eq per PE/y.

In conclusion, the BW & GW system in the third scenario emerged as a great environmental choice compared to the centralized WWTP. However, the additional benefits of the urine recycling system in both the BW and WWTP make it an essential component in choosing sustainable sanitation solutions. Ultimately, the findings suggest that the fully decentralized source-separating system incorporating urine, BW, and GW recycling, as demonstrated in the fourth scenario, is the most favorable environmental profile. This implies that when it comes to source separation, the critical factor is not simply a selection between urine and blackwater systems. Instead, it suggests that a hybrid or integrated source-separating system offers the most promising environmental performance and sustainability benefits, particularly when combined with 70 % energy recovery at the urine concentrator.

CRediT authorship contribution statement

Abdulhamid Aliahmad: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Priscila de Morais Lima:** Writing – review & editing, Supervision, Resources, Data curation, Conceptualization. **Hamse Kjerstadius:** Writing – review & editing, Supervision, Resources, Data curation, Conceptualization. **Prithvi Simha:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Björn Vinnerås:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Jennifer McConville:** Writing – review & editing, Validation, Supervision, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jennifer McConville reports financial support was provided by Swedish Research Council Formas. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2024.122741.

Appendices

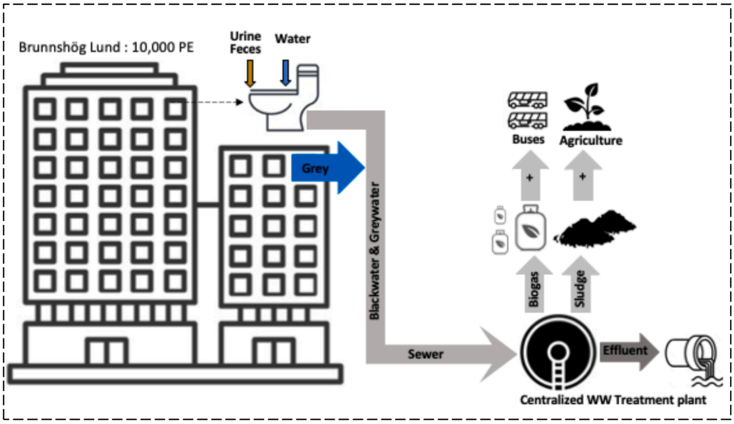

Fig. A.1. The layout of the first scenario, conventional WWTP. All wastewater fractions are mixed and transported in one pipe to the plant. The treatment plant treats influent and produces biogas and sludge that can be used in buses and agriculture. Effluent is discharged into a local water body.

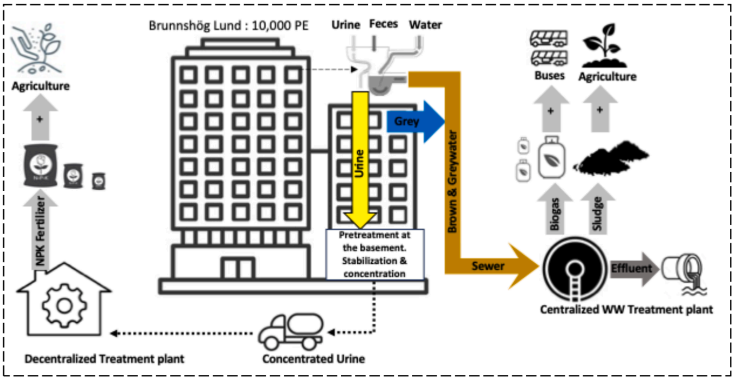

Fig. A.2. The layout of the second scenario, urine recycling + conventional WWTP. Urine is collected separately using a diversion toilet, and then the rest of the wastewater is collected, mixed, and transported in one pipe to the plant. The urine is pretreated in the basement and later treated to produce NPK fertilizer.

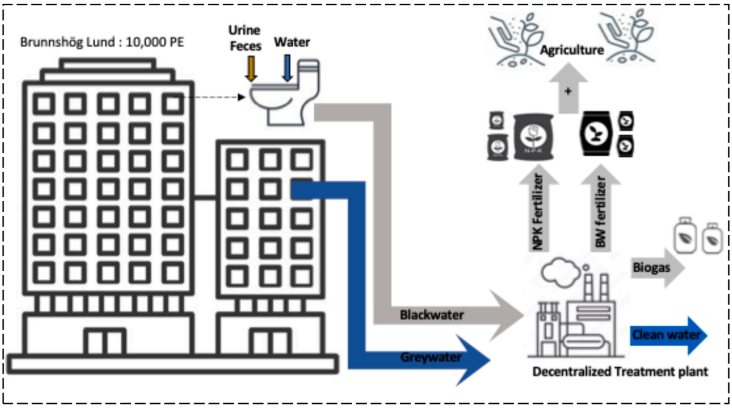

Fig. A.3. The layout of the third scenario, black and greywater. Blackwater and greywater are collected separately using two pipes. Each fraction is treated separately in the on-site treatment plant. NPK fertilizer, biogas, and clean water are produced.

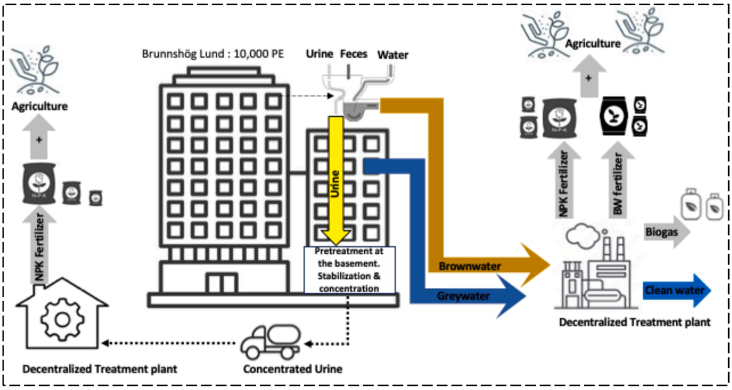

Fig. A.4. The layout of the fourth scenario, urine recycling + black and greywater. Urine (75 %) is collected separately using a diversion toilet. The brown water and the 25 % left of urine are collected separately in a second pipe; the greywater is also collected separately in a third pipe. Each fraction is treated separately, and NPK, biogas, and clean water are produced.

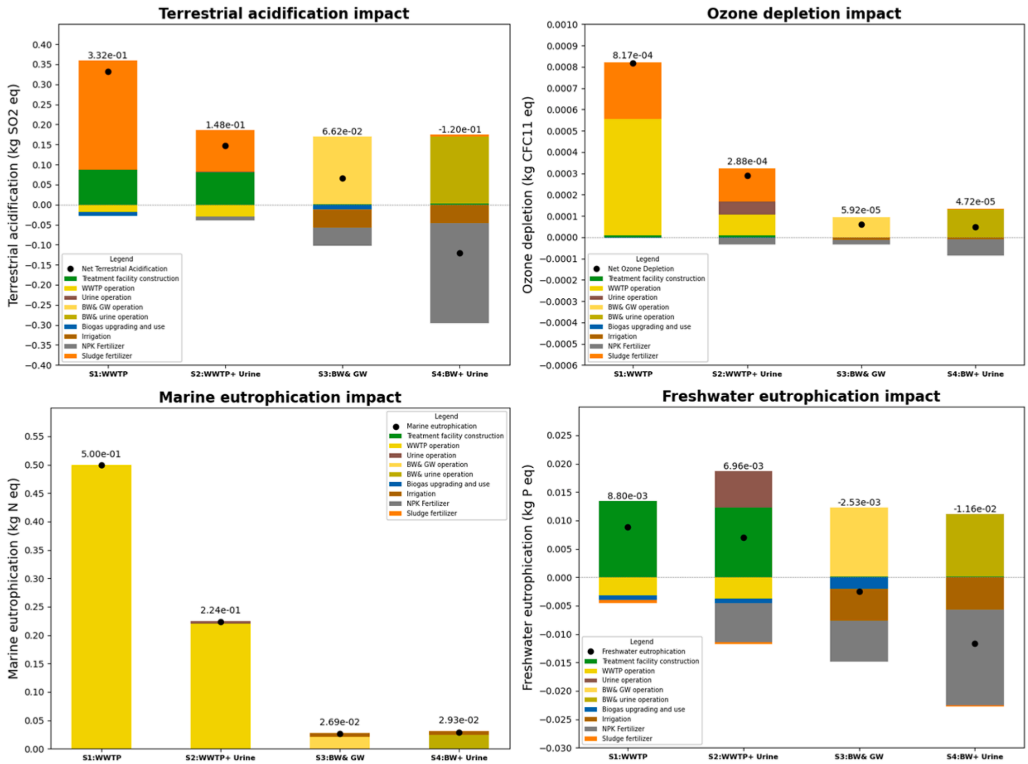

Fig. A.5. The net results of the analyzed systems using the ReCiPe® method.

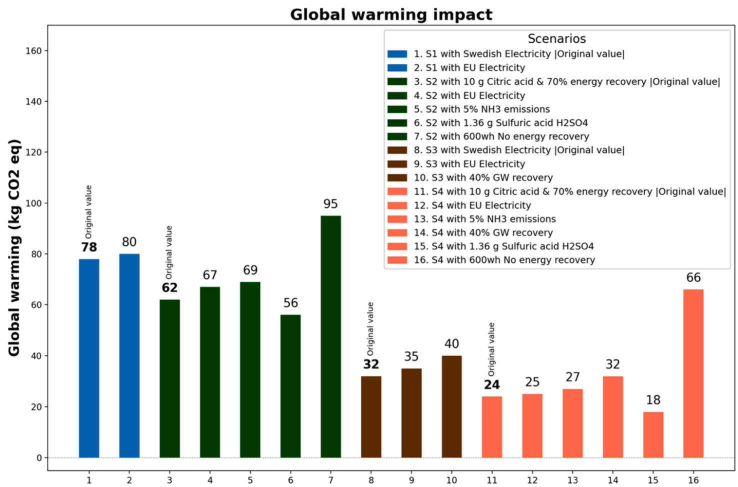

Fig. A.6. The GWP of the different sensitivity scenarios for the analyzed systems.

Data availability

All data can be found in the supplementary material submitted along with the research paper.

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Knowledge evolution within human urine recycling technological innovation system (TIS): Focus on technologies for recovering plant-essential nutrients

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ABSTRACT

Adopting urine-recycling technologies can support a transition to circular nutrient management systems. Although these technologies have been developed since the 1990s, their large-scale implementation remains limited. From a technological innovation system (TIS) perspective, "knowledge development and diffusion" is a critical function in the development phase. Yet, available methods in the literature to evaluate this function are not standardized. Hence, this study aims to fill this literature gap by developing a novel multi-criteria framework for evaluating knowledge functions. Several characteristics of emerging technologies are reflected in the criteria, including the rate of growth, novelty, diffusion, and relationship to incumbent systems. The knowledge base was measured by bibliometric analysis of publications obtained from comprehensive mapping. Results showed that the rate of publications and knowledge diffusion increased sharply in 2011–2021 compared to 1990–2010. However, the function still has insufficiency in some criteria. The lack of innovation in scientific research and the diversification of technologies were found to be impediments. The analysis also identified the lock-in of conventional technologies and centralized infrastructures in terms of publication dominance as another impediment. For the TIS to be legitimate and to grow, more pilot-scale implementations at a higher level are recommended to demonstrate that the technology works in practice.

1. Introduction

In recent decades, there have been increasing calls worldwide for a paradigm shift in global nutrient management towards circularity (Cordell et al., 2009; Robles et al., 2020). This call is a response to the biogeochemical planetary boundary being pushed beyond its threshold, mainly due to the release of anthropogenic reactive nitrogen (N) and phosphorus (P) into the environment (Rockström et al., 2009). Environmental impacts are apparent in eutrophication and algae blooms in various water bodies worldwide (Cordell et al., 2011; Sutton et al., 2011). For instance, over 90% of the Baltic Sea is eutrophied, 24% of its benthic zone suffers from anoxic conditions and 33% from hypoxia (HELCOM, 2018; Martin Hansson, 2019). These environmental impacts are frequently attributed to the use of synthetic fertilizers in agricultural fields. Although some of the N and P from agriculture are recovered in animal manure, significant amounts are released through so-called diffuse emissions (Powers et al., 2019; Tonini et al., 2019). Additionally, most nutrients that enter the human food chain ultimately end up in wastewater and are either partly removed in wastewater treatment plants or discharged directly into water bodies (Huang et al., 2017; Ramírez and Worrell, 2006). In the paradigm shift demanded in nutrient management, wastewater nutrients are perceived as resources that can be recycled into the system as fertilizer rather than being dumped in the environment (Guest et al., 2009). This perception of nutrient recovery may thus help achieve some interconnected, sustainable development goals (SDGs), such as SDGs 6 (clean water and sanitation) and 14 (life below water), and can mitigate some of the environmental implications associated with nutrient emissions to aquatic ecosystems (Larsen et al., 2021).

One approach to enable the recovery of nutrients present in wastewater is by collecting urine separately at the source (Larsen and Gujer, 1996). Urine is of particular interest because, although it only makes up 1% of total wastewater volume, it contains the majority of the plant-essential macronutrients in domestic wastewater (e.g., 80% of N, 50% of P, 60% of K) (Vinnerås et al., 2006). However, macronutrients in freshly excreted human urine are diluted since urine contains 95% water

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and only 0.7% N, 0.18% K and 0.06% P (Simha et al., 2021). Thus, to recycle these macronutrients in source-separated urine, technologies must be developed to recover and convert these macronutrients into a more concentrated urine-based fertilizer that is easier to apply and use. Recently, several nutrient-recovery technologies for urine (and other source-separated fractions of domestic wastewater) have emerged (Haddaway et al., 2019; Larsen et al., 2021; Macura et al., 2019). Some of these technologies have undergone pilot or field testing and are at technological readiness level (TRL) 5–6, yet large-scale implementation remains dispersed and challenging (Larsen et al., 2021; Maurer et al., 2006; Ohtake and Tsuneda, 2019). The evolution of technologies does not occur in isolation but rather in connection with other established systems. Thus, if nutrient recovery technologies for urine are to grow and mature, a technological innovation system (TIS) must evolve around them (Bergek et al., 2015). In TIS, an interconnected network of actors interact within an institutional structure and plays an active role in the generation, diffusion, and uptake of novel technologies (Carlsson and Stankiewicz, 1991). In recent years, TIS-analysis studies have gained popularity and credibility as an effective tool for analyzing innovation processes and understanding the embryonic phases of new industries, particularly in emerging clean-tech sectors (Markard et al., 2012; Markard and Truffer, 2008). In order to evaluate TIS performance, the concept of "innovation system functions" has been introduced (A. Bergek et al., 2008; Hekkert and Negro, 2009; Hekkert et al., 2007). These functions, which have the potential to influence the targets of newly developed and emerging innovation systems, have been identified as knowledge development and diffusion, entrepreneurial experimentation, market formation, influence on the direction of the search, resource mobilization, and creation of legitimacy. (A. Bergek et al., 2008; Hekkert et al., 2007). Literature on innovation systems and sustainability transition shows that these functions are interrelated and that a positive and active relationship between them can improve the performance of a system and foster further growth.

An essential function in developing TISs, especially early in the formative phase, is "knowledge development and diffusion" (Bergek et al., 2008; Geels, 2004; Hekkert and Negro, 2009; Jedelhauser et al., 2018). This function is considered to be the most critical system function as it reflects the breadth and depth of the knowledge base and how knowledge is diffused within the TIS; it also influences other systems functions (J. Aldersey-Williams et al., 2020; Bergek et al., 2008; Hekkert et al., 2007). For instance, the management of resources and the environment are often interconnected with governance and require institutional approval and regulatory support (Hackmann et al., 2014; McConville et al., 2017). Knowledge level plays a crucial role in influencing the engagement of regulatory and legislative frameworks by providing scientific findings illustrating the positive benefits that emerging technologies can bring to societies (Barquet et al., 2020). Therefore, emerging technologies must have an active and dynamic TIS where knowledge is generated rapidly over time and widely disseminated throughout the system (Jacobsson and Bergek, 2011). Various indicators can be used to evaluate the knowledge development and diffusion function, including R&D projects, patents, bibliometric and citation analysis of publications, learning curves, conferences, and others (Andreasen and Sovacool, 2015; Binz et al., 2014; Chung, 2018; Gruenhagen et al., 2021; Liu et al., 2018; McConville et al., 2017; Potts and Walwyn, 2020; Praetorius et al., 2010; Tigabu, 2018; Vasseur et al., 2013; Zhang et al., 2021). Analyzing the knowledge development and diffusion function can help reveal trends in research and technologies, the role and activity of different organizations, and critical actors in the context (Akbari et al., 2020; A. Bergek et al., 2008; Shiau et al., 2017).

The primary aim of this study was to evaluate whether the current knowledge base on nutrient recovery technologies is sufficient to further develop the urine recycling TIS. This evaluation was conducted using bibliometric analysis which involved tracking the evolution of these technologies, i.e., how the knowledge base has changed over time and identifying distinct trends - this required a comprehensive mapping of existing literature related to urine nutrients recovery. Despite the recent intensive increase in innovation and research concerning nutrient recovery technologies from urine, to our knowledge, no previous paper has comprehensively mapped this body of literature and analyzed research activity for distinct categories of technologies using the corresponding bibliometric data. Instead, earlier literature reviews provided an overview of available urine treatment processes (Larsen et al., 2021; Maurer et al., 2006) or recovery pathways with multiple processes (Harder et al., 2019), or have categorized technologies based on resources recovered, e.g., nutrients, energy, and water (Patel et al., 2020), or the type of fertilizer produced (Martin et al., 2020). Since there is no standardized method for evaluating the knowledge development and diffusion function, a second aim was to fill this research gap by developing a novel multi-criteria framework. This paper thus complements previous knowledge by providing a bibliometric analysis and comprehensive mapping of existing urine recycling knowledge and a novel multi-criteria framework to evaluate whether the development of such a TIS is feasible.

2. Methodology

Sections 2.1-2.4 describe how the comprehensive mapping was carried out, while section 2.5 describes the multi-criteria framework used to evaluate the knowledge development function.

2.1. Defining relevant keywords

Defining keywords is a crucial step in literature mapping. To maximize the performance of search strings in capturing relevant publications, keywords should be chosen carefully and reflect the study's objectives.

Urine and nutrients (including 'nitrogen', 'phosphorus' and 'potassium') were included as relevant keywords in our mapping. Plant-essential macronutrients (sometimes referred to simply as nutrients in this paper) can be present in urine in different forms, e.g., nitrogen can be in the form of urea, ammonia, and ammonium, and phosphorus in the form of phosphates and phosphoric acids. All these were considered relevant keywords. Outcomes of the technologies, such as fertigation, fertilizer, conditioner, amendment, char, compost, ash, biomass, struvite, and vivianite, were also considered relevant keywords in some search strings. Keywords that describe the purpose of the technologies, such as nutrient recovery, recycling, or circulation, were also considered relevant.

2.2. Bibliographic databases and search engines

Two bibliographic databases were used in this comprehensive mapping, namely Scopus and Web of Science (WOS) Core Collection (consisting of the following indices: science citation index expanded (SCI-EXPANDED), social sciences citation index (SSCI), arts & humanities citation index (A&HCI), conference proceedings citation index-science (CPCI-S), conference proceedings citation index-social science & humanities (CPCI-SSH), emerging sources citation index (ESCI), current chemical reactions (CCR-EXPANDED)). These two databases were chosen because of their accessible navigation environments and data structures, which are considered more accurate and reproducible than others. Many organizations have also adopted them as standards. Although the two databases share many of the same features, they differ in certain ways. For example, Scopus offers a more extensive list of modern sources, whereas WOS provides a large collection of scientific literature published in the past. It is, therefore, best to use these two databases in conjunction. The Google Scholar search engine was initially planned to be included in the mapping, but it was dropped before the mapping launched because, even though Google Scholar provides a broad range of information, we found that the results were often of varying quality and the search was not comprehensive. In addition, the navigation environment is not as user-friendly as the other two databases, especially regarding data exporting, citation tracking, and search limitations.

2.3. Search strings

Three strings were built for use in the comprehensive mapping to ensure that a wide range of publications was captured and that no research publications were missed. These search strings differed in terms of the number of keywords used and the query search domains, i.e., TITLE-ABS-KEY or ALL-FIELDS. For instance, string 1 used few keywords. The search domain was TITLE-ABS-KEY for the first keyword and then ALL-FIELDS for the other keywords: TITLE-ABS-KEY ((urine) AND ALL-FIELDS (nutrient*) AND ALL-FIELDS (recover*)). The results were refined after insertion of each keyword, i.e., keywords were inserted individually rather than all at once to get a notion of how many papers were eliminated for each keyword.

String 2 included more keywords than string 1, but the query search domain was limited to TITLE-ABS-KEY for all keywords: TITLE-ABS-KEY (((urine OR yellowwater OR "yellow water") AND (recover* OR circul* OR recycl*) AND (nutrient* OR nitrogen OR urea OR ammonia OR ammonium OR phosphorus OR phosphate OR potassium OR fertili* OR struvite))).

String 3 used even more keywords than the other two strings, some inspired by a recent publication (Macura et al., 2021): TITLE-ABS-KEY (((urine OR urinal OR yellowwater OR "yellow water" OR yellow-water)) AND (recover* OR *circul* OR reus* OR recycl* OR fertili* OR fertigat* OR conditioner* OR amendment* OR agricultur* OR "land application*")) AND (organic* OR nutrient* OR biosolid OR nitrogen OR urea OR ammonia OR ammonium OR phosphorus OR phosphate OR phosphoric OR potassium OR potash OR fertili* OR *char OR *compost OR ash* OR biomass OR struvite OR vivianite OR worm*))).

Although each string contained a different number of keywords, it was limited to the same subject areas as the other strings, which were primarily environmental and ecological in nature (Table A1 in Appendix A). Furthermore, all three strings covered the same period, 1990–2021.

2.4. Article screening and map's eligibility criteria

2.4.1. Screening process

Results of the bibliometric searches in Scopus & WOS were exported in research information system (RIS) format in preparation for the screening process. The screening was conducted using review management software (EPPI reviewer, version 4.12.4.0, UK). The first step of the screening process was to create three reviews on the EPPI reviewer, one for each string. For string 3, records were pre-screened using a bespoke web-based tool prior to screening in EPPI. This pre-screening consisted of filtering out papers outside the scope, primarily studies in the medical sciences. The RIS files were uploaded and checked for duplication before the screening began. Papers identified as duplicates were eliminated, and the rest entered the screening phase.

Two screening levels were performed on the three strings: 1) title & abstract and 2) full-text screening. During the screening, a set of eligibility criteria was utilized to decide on the inclusion/exclusion of papers. Potentially relevant abstracts that met the eligibility criteria were retrieved and screened on full text. Papers meeting the eligibility criteria for full text moved to the final step, coding, which primarily involved classifying and aggregating the papers into relevant synthesis categories. The search strings were primarily designed to capture technology-related papers, as the overall aim was to evaluate the emergence of these technologies. However, during the screening process, other papers not strictly related to technology were retrieved and coded into one of three synthesis categories: 1) source separation and urine diversion, 2) urine use in soil and agricultural applications, and 3) pharmaceutical and pathogen removal from urine. These categories can be expected to be incomplete, i.e., there may be other papers in the literature that were overlooked by the search strings; however, these categories were included in the analysis to represent trends within those aspects of urine. Finally, technology-related papers were coded based on: 4) named technologies for recovery of plant-essential macronutrients from urine. Papers in this category were further coded into subcategories representing one or more technologies. Note that papers in category 3 also pertained to the safe recovery of nutrients, meaning that some used technologies to remove pharmaceuticals from urine before reuse (e.g., membrane, struvite, nitrification, storage, alkaline dehydration, etc.). Although, in some countries, the removal of pharmaceuticals is mandatory in order to allow urine reuse. These papers were not included in the technologies category (4), as their contribution to the knowledge base was more niche and focused on removing pharmaceuticals as a pretreatment.

2.4.2. Eligibility criteria

Eligibility criteria form the backbone of any mapping, as they are the determinants of inclusion/exclusion during screening (Macura et al., 2019). It is, therefore, imperative to define eligibility criteria carefully to match the breadth and depth of a mapping study. If they are not carefully defined, there is a risk of increasing the breadth of the study and, therefore, including irrelevant papers. Definitions of the six criteria used in our mapping are provided below.

2.4.2.1. Eligible population(s). Source-separated urine was the primary population for our comprehensive mapping. Other wastewater fractions like brown water (e.g., faeces and flush water) or greywater (i.e., non-toilet plumbing systems, e.g., wastewater from sinks, baths, laundry, etc.) were excluded. Source-separated faeces/brown water, excreta/blackwater, and greywater were excluded. Mixed wastewater (e.g., blackwater and greywater mixed, domestic and municipal) and sludge reject water from anaerobic digesters were also excluded. Papers dealing with mixed wastewater but also including source-separated urine were included, but only if they met the other inclusion criteria. The source of urine was limited to humans; therefore, studies dealing with urine from other sources, e.g., animals, were excluded. Urine could be real or synthetic, and it could also be fresh or hydrolyzed. The sources of urine included domestic on-site systems with urine diversion toilets and centralized and decentralized systems.

2.4.2.2. Eligible intervention(s). The mapping focused on technologies for recovering plant nutrients from human urine and recycling these in the form of fertilizer (solid or liquid). Papers focusing on nutrient recovery were included in category 4. Other practices and processes that deal with human urine, but do not specifically recover and recycle nutrients in the form of fertilizer, were captured in the map by coding them into categories 1–3. Papers that did not meet the scope of the four categories were excluded.

2.4.2.3. Eligible outcome(s). The eligible outcomes of the technologies considered were nitrogen (N), phosphorus (P), and potassium (K) in the form of fertilizer. Therefore, the mapping focused solely on NPK recycling, as these nutrients are the main constituents of synthetic fertilizer, while technologies that only recover energy, carbon, salts, or other minerals and nutrients were not included. Note that the recovered nutrients from urine might not be classified as a fertilizer by legislation and regulations in some jurisdictions, but within the scope of our mapping nutrients recovered by these technologies were counted as fertilizer, regardless of the legislative standpoint. The legislation and regulations context will be examined later in a follow-up TIS study.

2.4.2.4. Eligible study type(s). Primary research publications, i.e., papers describing experimental and observational studies, were included. Book chapters describing experiments were also included. However, secondary research publications (e.g., literature, systematic and critical reviews, etc.) were excluded.

2.5. Evaluation criteria for the knowledge development function

To evaluate the knowledge development and diffusion function in the urine recycling TIS, we developed a multi-criteria evaluation framework with a rating scale of 1–5 (Table 1). The criteria are related to; the increase in the number of publications over time, technological innovation in scientific research, knowledge diversity, diffusion of knowledge between countries, knowledge volume compared with conventional systems, and actors' engagement. They were formulated based on a review of related literature and studies employing the TIS-analysis approach to analyze emerging technologies. The rationale for evaluating some of these criteria is related to the characteristics outlined by researchers for the detection of emerging technologies. For example (Cozzens et al., 2010; Rotolo et al., 2015; Small et al., 2014), unanimously reported that "fast growth in research publications" is a significant characteristic of technology emergence. Thus, the first criterion in our proposed multi-criteria framework is designed to represent the global knowledge trends on urine-recycling technologies published over the past three decades. One method used to evaluate the growth rate is the regression coefficient, i.e., the slope of the line derived from publications regression analysis. A negative slope indicates declining interest in the investigated technology. A positive slope indicates that technology is emerging. Technology is static if no slope is detected (Bengisu, 2003). The greater the growth rate in publications, the more rapid the process of technology emergence (Wang, 2018). It was assumed that for the technology to emerge, the number of publications should at least double per decade, i.e., increase by 2-folds per decade, and the higher the fold change, the better the emergence. Another highlighted attribute of emerging technologies is "radical novelty" and newness (Rotolo et al., 2015). Novelty can either be radical innovations or contributions to existing principles (Small et al., 2014). In our framework, the second and third criteria were designed to assess the novelty of the urine recycling TIS. The second criterion is pertained to the frequency of publication of research on each technology, whether the researchers built upon their

Table 1
The multi-criteria framework utilized for evaluating the knowledge development and diffusion function in the urine recycling technological innovation system (TIS). The analysis is based on the urine-recycling technologies category (category 4).

Evaluation criterion		References	(1–5) scale Evaluation		
			1-2 (Weak)	3 (Moderate)	4-5 (High)
F1- Knowledge development and diffusion	**Growth in scientific publications within the TIS per decade**	(Akbari et al., 2020; Andreasen and Sovacool, 2015; Bergek et al., 2015; Binz et al., 2014; Gruenhagen et al., 2021; Jacobsson, 2008; McConville et al., 2017; Stephan et al., 2017; Vasseur et al., 2013; Wieczorek et al., 2015; Zhang et al., 2021)	**1.** TIS publications increased zero-fold* per decade. **2.** TIS publications increased < 2-fold* per decade. (Less than double)	**3.** 2-fold*≤ TIS publications growth < 4-fold* per decade. (More than double)	**4.** 4-fold* ≤ TIS publications growth > 8-fold* per decade. **5.** TIS publications increased ≥ 8-fold*.
	Innovation in scientific research per technology within the TIS	(John Aldersey-Williams et al., 2020; Coenen and Lopez, 2010; Klitkou and Coenen, 2013; Miremadi and Baharloo, 2020; Vasseur et al., 2013; Zhang et al., 2021)	**1.** Zero pilot-scale trials, and follow-up publications per technology. **2.** < 5 pilot-scale trials, and follow-up publications per technology.	**3.** 5–10 pilot-scale trials, and follow-up publications per urine technology.	**4.** 11–30 pilot-scale trials, and follow-up publications per technology. **5.** >30 pilot-scale trials, and follow-up publications per technology.
	Diversification of emerging technologies into the TIS	(Klitkou and Coenen, 2013; Li et al., 2021; Makkonen and Inkinen, 2021; Miremadi and Baharloo, 2020; Musiolik et al., 2012; Stephan et al., 2017)	**1.** Zero new technologies entering the TIS per decade. **2.** < 5 new technologies entering the TIS per decade.	**3.** 5–10 new technologies entering the TIS per decade.	**4.** 11–30 new technologies entering the TIS per decade. **5.** >30 new technologies entering the TIS per decade.
	Diffusion of knowledge between countries	(Akbari et al., 2020; Andreasen and Sovacool, 2015; Klitkou and Coenen, 2013; McConville et al., 2017; Vasseur et al., 2013; Wieczorek et al., 2015)	**1.** Zero new countries entering the TIS per decade. **2.** < 5 new countries entering the TIS per decade.	**3.** 5–10 new countries entering the TIS per decade.	**4.** 11–30 new countries entering the TIS per decade. **5.** >30 new countries entering the TIS per decade.
	TIS knowledge volume compared with conventional systems	(Bergek et al., 2015; Frishammar et al., 2019; Jacobsson, 2008; McConville et al., 2017)	**1.** TIS publications < 1% of conventional systems & TIS conferences < 5% of total conferences/year. **2.** 1% ≤ TIS publications ≤ 2% of conventional systems & 5% ≤ TIS conferences < 8% of total conferences/year.	**3.** 3% ≤ TIS publications ≤ 5% of conventional systems & 8% ≤ TIS conferences < 10% of total conferences/year	**4.** 6% ≤ TIS publications ≤ 9% of conventional systems & 10% ≤ TIS conferences < 12% of total conferences/year. **5.** 12% ≤ TIS publications ≤ 15% of conventional systems & 12% ≤ TIS conferences ≤ 15% of total conferences/year.
	Development of urine recycling publications over time compared to conventional systems	(Bergek et al., 2015; Frishammar et al., 2019; Jacobsson, 2008; McConville et al., 2017; Rotolo et al., 2015; Wang, 2018)	Negative trend i.e., the progression of urine recycling publications compared to conventional systems is decreasing over time.	Static trend i.e., the progression of urine recycling publications compared to conventional systems is not changing over time.	Positive trend i.e., the progression of urine recycling publications compared to conventional systems is increasing over time.
	Actors' engagement in knowledge generation	(Andreasen and Sovacool, 2015; Binz et al., 2014; Frishammar et al., 2019; Gruenhagen et al., 2021; Liu et al., 2018; Musiolik et al., 2012)	Not yet defined	Not yet defined	Not yet defined

Note: The word 'fold'* in the first criterion represents the rate of growth. For instance, if one decade had 10 publications and the next decade had 50 publications, then the rate of growth was 5-fold. If the next decade had 5 publications, then the rate of growth was 0.5-fold.

previous research results and optimized their technologies, and whether pilot-scale implementations of their technologies were conducted on laboratory scale or in an operational environment. On the other hand, the third criterion assessed whether novel technologies entered urine recycling TIS in each decade and whether entrepreneurs had tested new processes. For this criterion, we also conducted a citation analysis in an attempt to discern the most dominant technologies within the TIS by locating the most frequently used keywords and cited papers. It was assumed that for the urine recycling TIS to develop to its full potential, there should be at least five new technologies, new research and pilot-scale studies emerging per decade (Akbari et al., 2020; Coenen and Lopez, 2010; McConville et al., 2017; Wieczorek et al., 2015).

The fourth criterion is related to knowledge dissemination across the globe, enabling the identification of network weaknesses in the TIS. Evaluation of this criterion entailed temporal resolution of countries' emergence in urine recycling TIS over the past three decades. It was assumed that for urine recycling TIS to develop to its full potential, at least ten new countries should emerge per decade. For the third and fourth criteria, the evaluation scale limits are largely determined by the number of countries and technologies in the conventional wastewater regime. It was assumed that for the urine recycling TIS to perform well, the number of technologies, countries, and pilots would be above 10% compared with the conventional wastewater regime (Bengisu, 2003). Through our search, we found 103 technologies within the conventional wastewater regime. Thus, if the urine recycling TIS has five to ten technologies, it is in a static phase. If there are fewer than five technologies, the TIS is performing poorly, and if there are more than ten technologies, the TIS is performing well. For the fourth criterion, we looked at the number of countries participating in conventional wastewater research publications. We chose the list of countries whose publications number is equal to or higher than the number of urine recycling publications, resulting in 99 countries. Using the same principles of the third criterion, a urine recycling TIS with five to ten countries is deemed to be in a static phase; fewer than five is weak, and more than ten is robust (see supplementary materials). The fifth criterion aimed at placing the TIS in a broader context by comparing it with the knowledge level and diffusion of conventional systems (McConville et al., 2017). Two metrics were employed to evaluate this criterion: the volume of publications and the number of conferences. First, the number of urine recycling TIS publications was compared to other conventional wastewater treatment technologies (CWWTT). Wastewater conferences, primarily those organized by the International Water Association (IWA) over the past decade, were then mapped. IWA is the largest membership association in the global water sector, and it was assumed to have an influential role in the trends at international conferences. We examined how many conferences focused on urine recycling TIS and how many were related to CWWTT. The fifth criterion gives only a quantitative description of the urine recycling publication but does not reflect the temporal changes. Therefore, the sixth criterion was defined to examine the progression of urine recycling publications over time compared to the CWWTT. The seventh criterion examines actors in the TIS involved in knowledge generation and their temporal and spatial progression. We divided urine recycling TIS actors into four subcategories: knowledge actors (universities, research institutes, and others), business actors (private firms, municipalities, wastewater treatment plants, farmers), infrastructure actors (energy infrastructure, collection systems, pipeline systems), and financial actors (banks and funding institutions). The knowledge development and diffusion function is closely tied to knowledge actors and the balance between universities, research institutes and other knowledge actors' engagement in knowledge creation (Binz et al., 2014). Dissertations, conference proceedings, unpublished manuscripts, recommendations, technical standards, public presentations, and government documents can also influence knowledge levels, but none of these sources was mapped because grey literature was not included in our mapping. As a result, this seventh criterion was not evaluated.

3. Results

3.1. String 1 results

The first keyword used for searches in Scopus and WOS was (Urine*), which resulted in 522,537 & 224,688 papers, respectively. Limiting the search to 1990–2021 reduced the number of papers to 348,270 & 202,920, respectively. Narrowing the search to predefined study areas further reduced to 64,582 and 50,626 papers for Scopus and WOS, respectively. A second keyword (Nutrient*) was then introduced, and the search was again refined, resulting in 7202 and 1023 papers for Scopus and WOS, respectively, a significant reduction from the previous step. The third keyword was a description of the technology intervention (Recovery*). This yielded a final total of 1437 and 493 papers for Scopus and WOS, respectively (Fig B1 in Appendix B).

In the first step of the screening process, testing for duplicate papers, 337 papers from the final total of 1930 were identified as duplicates and eliminated from the screening, leaving 1593 papers. These were then screened on two levels; 1): title & abstract and 2): full text. A full description of the coding process and synthesis categories for string 1 is provided in Fig. 1. This diagram, which was adapted from the *Environmental Evidence Journal* website with minor modifications, was used for all three strings.

3.2. String 2 & String 3 results

Compared with string 1, strings 2 and 3 contained more keywords, which were inserted together. Otherwise, the screening and coding processes and the synthesis categories for strings 2 and 3 were similar to those applied for string 1 (Fig. 1).

String 2 can be considered a subset of string 3, as the keywords included were also used in string 3. The results from Scopus and WOS for string 2 were 1282 and 2520 papers, respectively. Testing for duplicate papers identified 788 duplicates, which were eliminated from the screening, leaving 3014 papers. Of these, 564 papers were retrieved and included based on title & abstract, while 2450 papers were excluded. Later in the screening process, other papers were also excluded. Finally, after the full-text screening, there were 415 papers, of which 216 were technologies-related (Fig B2 in Appendix B).

String 3 had most keywords and the results from Scopus and WOS were 853 and 981 papers, respectively. Testing for duplicate papers resulted in 656 papers being identified and eliminated from the screening, leaving 1178 papers. Title & abstract screening resulted in 676 being included and 512 excluded. In the full-text screening, additional papers were excluded, resulting in a final number of 641 papers, of which 240 were technologies-related (Fig B3 in Appendix B).

All papers included after full text-screening for the three strings were coded into synthesis categories 1–4 (as shown below in Table 2). Technologies-related papers in category 4 were further coded and aggregated into relevant technologies, as shown in Table A2 in Appendix A.

3.3. Comparing string 1,2 and 3

The three strings produced different results regarding the number of papers captured. Consistency testing across the three strings showed that string 3 was able to capture many more papers than the other two strings, especially in synthesis categories 1–3. However, string 3 failed to capture a few papers that string 1 was able to capture (Fig B6 in Appendix B). As string 2 was a subset of string 3, it captured no unique papers compared with string 3. One interesting observation was that string 1 was nearly as good as string 3 for category 4 papers. In terms of mapping efficiency, using string 1 would have yielded essentially the same results as string 3, but with 20% of the effort. As a result, we merged strings 1 and 3 into one string to get an overall representation of the global knowledge level for the period 1990–2021. Papers in the

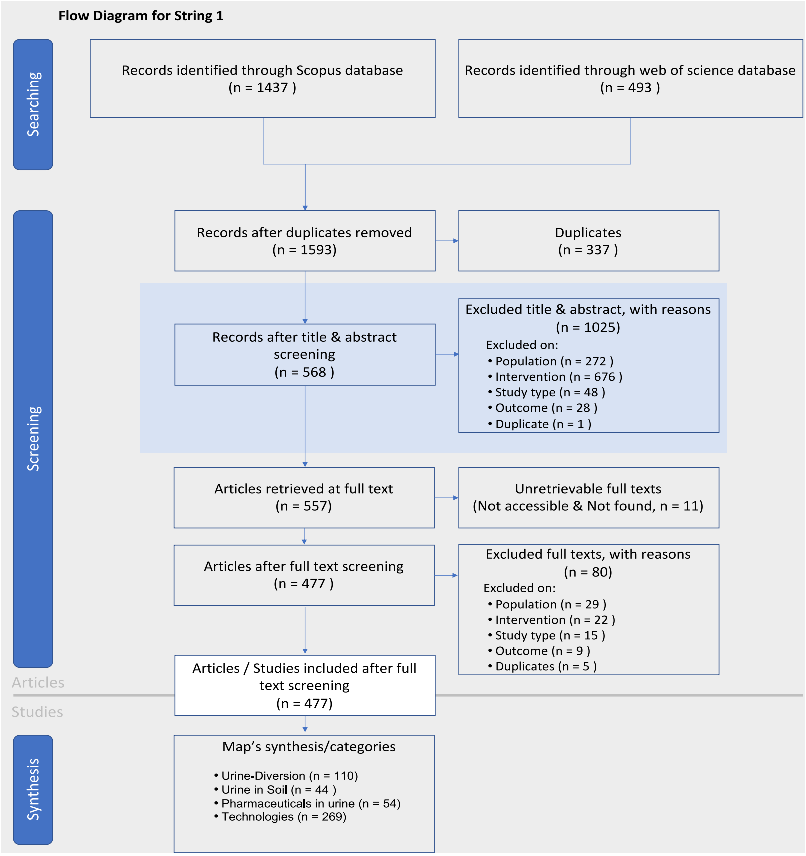

Fig. 1. Flow diagram illustrating the screening process and coding of string 1, i.e., the number of records excluded and retrieved on duplication, abstract, and full text.

Table 2
Results from search strings 1, 2, and 3 according to synthesis categories 1–4 and subcategories for the technologies-related papers (category 4). Note that some papers included multiple technologies and are thus included in more than one subcategory.

Categories for the three strings						
Category name (no.)	String 1 = 477		String 2 = 438		String 3 = 644	
	No. of papers	%	No. of papers	%	No. of papers	%
Source separation and/or urine diversion (1)	110	23%	108	25%	182	28%
Urine use in soil and agricultural applications (2)	44	9%	37	8%	105	16%
Pharmaceutical and pathogen removal from urine (3)	54	11%	35	8%	72	11%
Technologies for recovery of plant-essential macronutrients from urine (4)	269	56%	258	59%	285	44%

Table 3
Categories and subcategories for the merged string created from strings 1 and 3.

Categories for the merged string total papers = 692 papers		
Category's name	No. of papers	%
Source separation and urine diversion (1)	194	28%
Urine use in soil and agricultural applications (2)	106	15%
Pharmaceutical and pathogen removal from urine (3)	83	12%
Technologies for recovery of plant-essential macronutrients from urine (4)	309	45%
Subcategories for the technologies-related papers (category 4)		
Subcategory name	No. of papers	
P- recovery technologies	**101**	
•P-recovery (precipitation mechanism)	88	
•P-recovery (Adsorption mechanism)	13	
Ammonia stripping	12	
Alkaline dehydration	7	
Nitrification/distillation	10	
Sorption: Ion exchange, absorption, adsorption	54	
Membrane	30	
Evaporation	9	
Freezing - thaw	5	
Microalgae biotechnology	11	
Microbial electrochemical technologies METs (MFCs and MECs)	54	
Non concentrating technologies e.g., urine storage and others	16	

merged string were grouped into the same categories as the original strings. As expected, the merged string contained more papers in each category, comprising 675. Following the same process as for the original strings, these 675 papers were grouped into four categories, and technologies-related papers in category 4 were further aggregated into relevant technologies, as shown below in Table 3.

4. Analysis and discussion

This section interprets the findings in light of the main goal of the study, i.e., evaluating the knowledge development and diffusion function. To this end, we analyzed the urine technologies knowledge base for correlations, patterns, and trends throughout the three decades of the study period (1990–2021). We also measured the rate of knowledge change and attempted to visualize its temporal progression.

4.1. Interpretation of the results

We measured the level of knowledge globally on nutrient recovery technologies from urine using bibliometric analysis, i.e., the volume of global publications and citation analysis. It is imperative to emphasize that the scope of this study focuses on knowledge level rather than the effectiveness of the investigated technologies. In other words, just because one of the technologies has a higher number of publications than the others does not mean it is better or more effective. A higher number of papers can indicate interest in a field and how other functions in the TIS are performing. In the case of urine, for example, an increasing trend in one aspect of urine recycling or a specific technology would indicate the direction of the search and might influence the mobilization of resources and attract the attention of policymakers. Moreover, a wider geographical spread of publications indicates broader stakeholder interest and more entrepreneurial testing in the TIS.

Following the quantification of urine recycling publications, i.e., results gained from the search strings, temporal graphs were created to provide an understanding of the evolutionary path of the four synthesis categories. Fig. 2 shows the temporal progression per decade in the four categories during the study period. All four categories saw a marked increase in publications in the period. During 1990–2010, urine recycling publications focused on category 1 (source separation and urine diversion), with less research attention on the other three categories. However, from 2011 to 2021, publications on nutrient recovery technologies from urine (category 4) jumped to 270, which was over seven folds the number in the previous two decades. Research interest in removing unwanted substances from urine (category 3) and using urine in agricultural applications (category 2) also increased, indicating that urine recycling TIS is moving from conceptualization towards refinement of specific processes and technologies.

Looking more closely at category 4, it can be seen that urine technology-related publications went through two distinct phases during the study period, but with a gradually increasing trend (Fig. 3), confirming that urine recycling has gained more attention over the past couple of decades. Additionally, new technologies have been developed and incorporated into the system over time. For instance, from the mid-

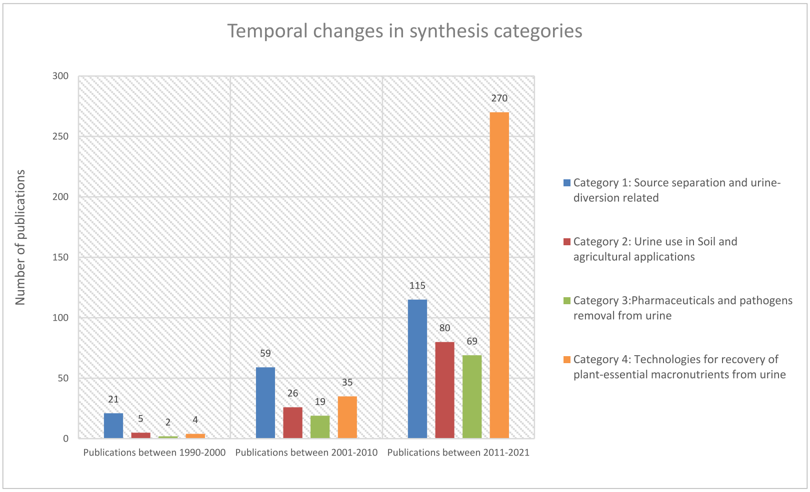

Fig. 2. Temporal changes in total number of urine recycling publications per decade within synthesis categories 1–4 during the period 1990–2021, based on searches in Scopus and WOS using a merged search string (1 and 3, see section 3.3) and a screening process (Fig. 1).

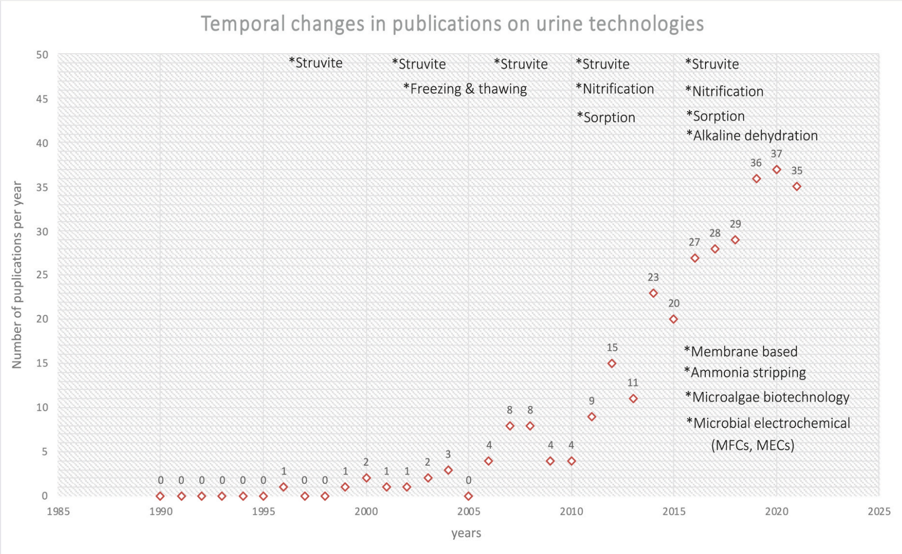

Fig. 3. Knowledge development in the periods 1990–2010 and 2011–2021 on technologies for nutrient recovery from urine (category 4). Technologies are shown based on publication year, with total number of publications for a particular technology shown above data points.

1990s to the early 2000s, P- precipitation (struvite) was widely used for nutrient recovery. From the mid-2000s onwards, new technologies that recover more nutrients (NPK), such as nitrification distillation, ion exchange, alkaline dehydration, microbial electrochemical, and membrane-based technologies, started to emerge, making the system more active. This indicates growth in entrepreneurial activity as well as knowledge development. On the other hand, experimentation and publishing related to other technologies, such as freezing & thawing, saw a decline (Fig. 3). Overall, the results indicate that more entrepreneurial testing is being initiated within the urine recycling TIS and that the level of knowledge in the field is increasing. New technologies other than struvite are being tested, but struvite still (2021) has the highest number of publications and citations. According to the citation analysis, struvite-related keywords such as precipitation & crystallization were more frequently mentioned in literature from 1990 to 2021 than keywords of other technologies (Fig B4 in Appendix B). The citation analysis also showed that struvite-related publications were most commonly cited; e.g., seven of the top 10 cited papers in the technology category were struvite-related (Fig B5 in Appendix B).

Another indication that urine technologies are gaining more attention was their increasing diffusion among countries (Fig. 4). Research on urine technologies began mainly in Sweden and Switzerland between the mid-1990s and early 2000s. Later, other countries such as Turkey, Germany, the United States, Netherlands, Australia, and India followed suit, and China is currently leading (Fig. 4). This indicates that urine technologies have become more popular, resulting in knowledge spreading internationally.

4.2. Evaluation of the knowledge development and diffusion function

Our first evaluation criterion was based on global trends in publication numbers over the past three decades (Table 1). The results showed that the rate of growth in urine recycling TIS publications was between 5 and 10 folds over the decades Fig. 2, so the first criterion was deemed high and scored 4 on the scale.

The second evaluation criterion examined the frequency of publications and pilot-scale implementations. An evaluation of the publications for each technology revealed very few pilot-scale implementations per urine technology around the globe (e.g., (Aguado et al., 2019; Fumasoli et al., 2016; Liu et al., 2010; Pronk et al., 2007; Simha et al., 2020; Tarpeh et al., 2018; Uzkurt et al., 2021; Wei et al., 2018; Xu et al., 2017; Zamora et al., 2017). Instead, some groups of researchers tended to publish frequently and build upon their previous research and investigations (see supplementary materials for information on publication frequency). This criterion was thus deemed weak and scored 2 on the scale.

From the temporal changes in publications on urine technologies in Fig. 3, it is evident that new technologies have been incorporated into the urine recycling TIS over the past three decades. Thus, our third criterion, pertaining to the emergence of new technologies in the TIS, was deemed moderate and scored 3 on the scale. Based on temporal and spatial changes in publications on urine technologies (Fig. 4), 10 to 30 countries entered the urine recycling TIS in the past two decades (2000–2021). This reflected knowledge diffusion across the globe, so the fourth criterion was deemed high and scored 4 on the scale.

For the fifth and sixth criterion, urine recycling was placed in a broader context, i.e., in relation to existing conventional systems. A similar Scopus search, limited to the same timeframe and study areas as the comprehensive mapping, was performed using the keywords of wastewater activated sludge*, oxidation process*, anaerobic filter*, UASB*, anammox*, and source separation*. This search aimed to identify the proportion of publications on these technologies compared to total publications in the wastewater sector. Results shown in (Fig B7 Appendix B) indicate that source separation made up a relatively small proportion of total wastewater publications, i.e., publications on conventional technologies, e.g., activated sludge and oxidation process. Urine recycling is a subset of source separation, meaning urine recycling-related publications are less than 1%. As regards the proportion of relevant conferences, mapping of IWA conferences (Fig B8 Appendix B) showed that urine recycling TIS conferences made up less than

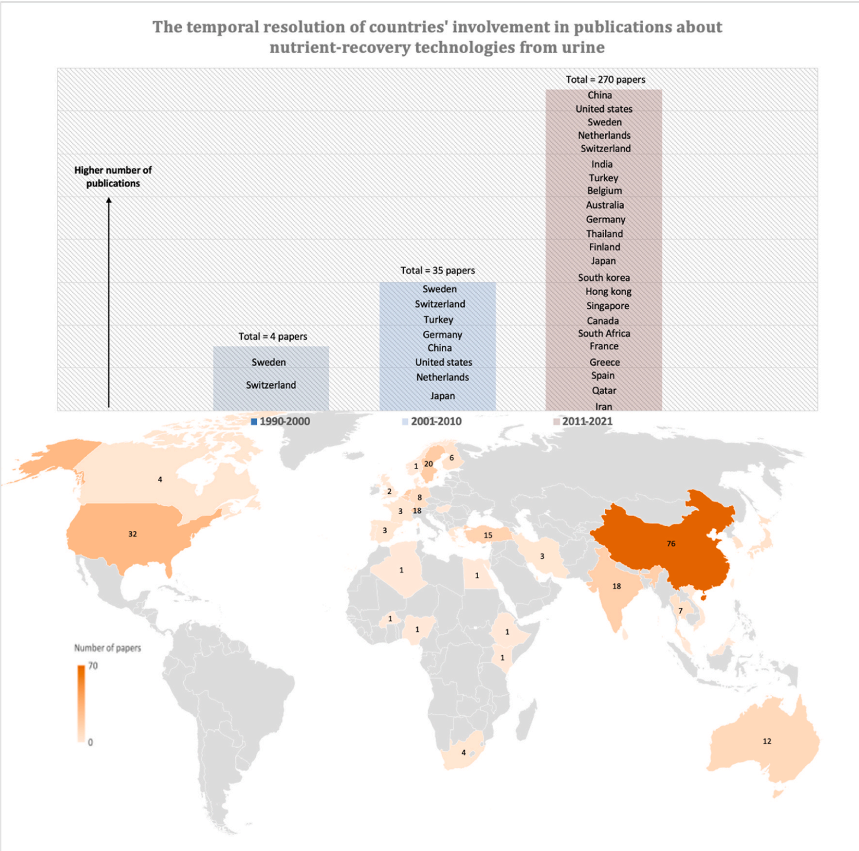

Fig. 4. Changes in the number of urine technology-related publications in different countries world-wide, 1990–2021. The top panel shows the total number of publications per decade, while the map shows total number of publications per country.

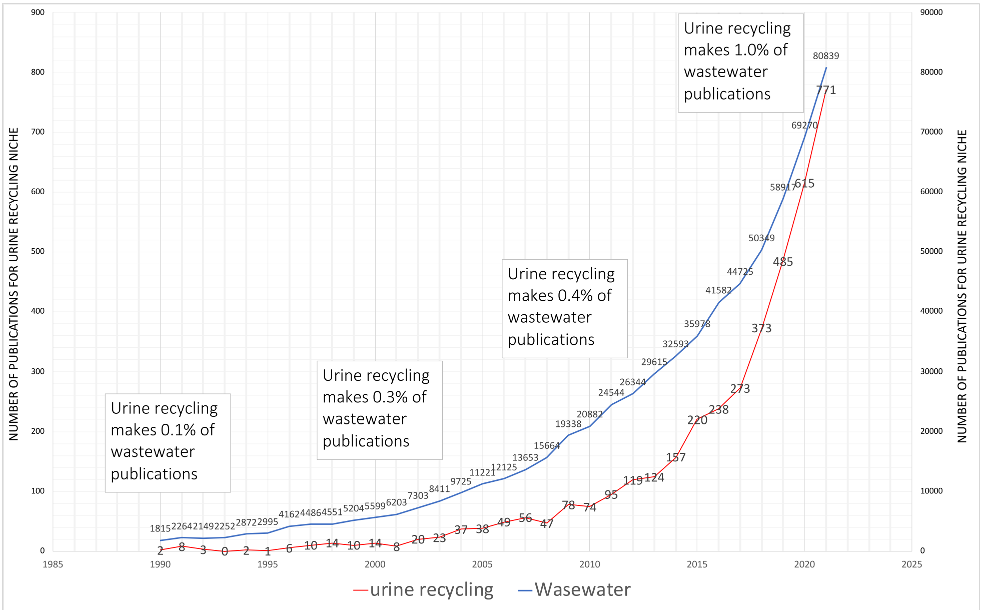

Fig. 5. Comparing the development of urine recycling research with the wastewater research over time. Each decade is highlighted and the proportion of urine recycling is presented in each decade. 0.1% in 1990, 0.3% in 2000, 0.4% in 2010 and 1% in 2021.

10% of total conferences in the wastewater sector from 1990 to 2021. The fifth criterion was therefore deemed weak and scored 1.

Despite the low proportion of urine recycling in wastewater publications, looking at the progression of urine recycling TIS over time shows an increasing trend. According to the sixth criterion, an increasing trend implies that urine recycling publications are progressing rapidly over time in relation to conventional systems. In Fig. 5, urine recycling research progression over time was compared with wastewater research. Results showed that the proportion of urine recycling research increased each decade. For instance, urine recycling made up 0.1% of total publications in the wastewater sector in 1990, which increased to 1% in 2021. The high increase in publications over time indicates the TIS is growing well, so the sixth criterion was rated high.

Overall, the knowledge development and diffusion function was rated weak to moderate in terms of innovation in scientific research and diversification of emerging technologies into the TIS, with a tendency for strong publication rate growth and diffusion between countries. For the urine recycling TIS to flourish and develop, all evaluation criteria must be moderate or higher; therefore, based on the evaluation criteria results, the current knowledge base is inadequate to develop the urine recycling TIS to its full potential. A number of factors are contributing to this, including the continuing dominance of conventional nutrient removal systems. In most cases, conventional systems are mature and optimized, while most of the technologies for nutrient recovery from urine are still in their infancy. This lock-in with conventional systems can often lead to relatively rigid technological trajectories, thereby impeding the development of urine recycling technologies (Hekkert et al., 2007). Therefore, the urine recycling TIS requires more research and attention if it is to emerge or merge with incumbent systems.

One possible approach is to involve more actors in knowledge generation (Andreasen and Sovacool, 2015; Binz et al., 2014; Liu et al., 2018; Vasseur et al., 2013). In the formative phase of the TIS, each new actor that enters the system will bring knowledge and contribute to the TIS advancement. Contributions can take the form of new experiments/combinations to fill research gaps and increase knowledge levels (Musiolik et al., 2012). Further research on large-scale implementation is also needed, as the current state of knowledge can only support small-scale (laboratory) implementations. In addition, more diversity in research and tests on technologies is needed (Klitkou and Coenen, 2013; Li et al., 2021). There is also a need for more reviews of existing knowledge on other aspects of the technologies, such as removal of pharmaceuticals and pathogens, energy consumption, collection logistics, treatment locations, and post-treatment. The latter can improve legitimization (Bergek et al., 2015) and acceptance of these technologies, thus encouraging new actors to join (Frishammar et al., 2019).

Another critical parameter is knowledge dissemination via, e.g., more conferences, workshops, and seminars dedicated to urine recycling and nutrient recovery technologies (Gruenhagen et al., 2021; McConville et al., 2017). These can be very effective means of disseminating knowledge and providing a platform for more engagement. Therefore, conferences, workshops, and seminars should be diversified in terms of their topic and geography, i.e., where they are held. It is important to note that other functions of urine recycling TIS can influence, and be influenced by, knowledge creation and diffusion (Miremadi and Baharloo, 2020). For instance, authorities can play a role in encouraging more conferences, subsidizing initiatives, mobilizing resources, and issuing companion legislation (e.g., using urine-based fertilizer) (Wieczorek et al., 2015). In addition, clear and well-defined environmental regulations (ER) are crucial in triggering and inducing the birth of new TISs. Relatively strict ER often stimulates enterprises to seek improvements in their business performance through technological innovation (van Leeuwen and Mohnen, 2016; Zhou et al., 2019). Influential organizations in the sector can also play a key role, e.g., in promoting the use of urine recycling technologies and urine-based products, which can influence the direction of research in the field and encourage new actors to invest and enter the TIS (Aldersey-Williams et al., 2020; Jacobsson and Bergek, 2011).

5. Conclusion

In this study, we conducted a bibliometric analysis to comprehensively map the current knowledge base on nutrient recovery technologies and evaluate whether it is sufficient to further develop the urine recycling TIS. Due to the lack of standardized evaluation methods in the literature, we developed a novel multi-criteria framework comprising seven criteria concerning the characteristics of emerging technologies. The analysis showed that since their introduction in the early 1990s, technologies for nutrient recovery from urine have been researched at an increasing rate, especially since 2010. New technologies have emerged, and actors in new countries have entered the urine recycling TIS. Despite the tendency for strong publication rate growth and diffusion between countries, the "knowledge development and diffusion" function still has insufficiency in some criteria, and the current knowledge base is regarded as insufficient for fully developing the urine recycling TIS to its optimal potential.

The TIS functions are entirely dependent on each other, and this interdependence is one of the key and distinctive characteristics of the TIS. As each function is interlinked to the preceding and the succeeding, a weakness in one will undoubtedly be reflected in the others. Knowledge development, as mentioned before, is considered to be the most critical system function. This is because it reflects the breadth and depth of the knowledge base and how knowledge is developed and disseminated within the urine recycling TIS. This system function may be negatively influenced by the poor performance of other system functions, such as knowledge exchange, the guidance of the search, and resource mobilization. Lack of knowledge exchange between actors within the urine recycling TIS would limit the development of the TIS knowledge base. A similar problem will occur if the direction of research in the sector is influenced by strong actors (conventional regimes). This would result in a divergence of research away from urine recycling, reducing the incentive for external actors to join the TIS and conduct research. This will ultimately negatively affect the TIS knowledge base. In addition, the inadequacy of the TIS knowledge base could lead to weak public awareness, so that actors become less motivated to join the TIS, and others might not even know it exists, which could inhibit their intention to invest in it or even participate. Lack of resources such as financial, human (competence, education, etc.) or physical (labs, etc.) can also negatively affect knowledge production and diminish abilities to do rigorous research.

Based on the analysis findings, we recommend greater emphasis to be placed on developing new innovations, i.e., technologies aimed at recovering all nutrients (NPK) from urine, and not only P. Organizing more conferences and workshops focusing on urine recycling is additionally recommended as these are effective means for diffusing knowledge and providing a platform for more engagement. In addition to the lab-scale experimentations, there should be a push for more pilot-scale implementations on the operational environment level. From a TIS perspective, measures to evaluate the seventh criterion about knowledge actors' engagement in knowledge generation should be developed as this is one of this study's limitations. Finally, a full urine recycling TIS analysis should be conducted to evaluate the system's other functions and how the other functions influence knowledge level.

CRediT authorship contribution statement

Abdulhamid Aliahmad: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Robin Harder:** Software, Validation, Writing – review & editing. **Prithvi Simha:** Writing – review & editing. **Björn Vinnerås:** Writing – review & editing. **Jennifer McConville:** Conceptualization, Supervision, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jennifer McConville reports financial support was provided by Swedish Research Council Formas.

Data availability

Data will be made available on request.

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Appendix A

Table A1
Subject areas used for the three search strings

	Limited subject areas
Scopus	Chemistry/Environmental science/agricultural & biological science/chemical engineering/engineering/multidisciplinary/material science/social science/energy/earth & planetary science/economics & finance/decision science/undefined.
WOS	Chemistry Analytical/Environmental Sciences/Engineering Environmental/Water Resources/Chemistry Multidisciplinary/Food Science Technology/Engineering Chemical/Electrochemistry/Green Sustainable Science Technology/Soil Science/Agriculture Multidisciplinary/Multidisciplinary Sciences/Public Environmental Occupational Health/Energy Fuels/Plant Sciences/Ecology/Agricultural Engineering/Engineering Civil/Engineering Electrical Electronic.

Table A2
String 1, 2, and 3 subcategories for the technologies-related papers

Subcategories for the technologies-related papers (category 4) for the three strings

Subcategory name	String 1 = 269		String 2 = 258		String 3 = 240	
	No. of papers	%	No. of papers	%	No. of papers	%
Struvite precipitation/crystallization	75	28%	77	30%	80	28%
Struvite precipitation & Adsorption	15	6%	13	5%	16	6%
Struvite precipitation & Ammonia stripping	6	2%	6	2%	6	2%
Alkaline dehydration	6	2%	6	2%	7	2%
Nitrification/distillation	10	4%	6	2%	6	2%
Sorption: Ion exchange, absorption, adsorption	50	19%	41	16%	51	18%
Ammonia/air stripping	1	0,4%	3	1%	3	1%
Ammonia stripping & Adsorption	2	1%	2	1%	2	1%
Forward/reverse osmosis	9	3%	11	4%	12	4%
Forward osmosis & Membrane distillation	3	1%	3	1%	3	1%
Membrane	13	5%	13	5%	15	5%
Evaporation	9	3%	7	3%	8	3%
Freezing and thawing	4	1%	4	2%	4	1%
Microalgae biotechnology	9	3%	9	3%	10	4%
Microbial electrochemical technologies METs (MFCs and MECs)	45	17%	44	17%	46	16%
Storage	8	2%	6		9	
Urine stabilization techniques	12	4%	7	5%	7	6%

Appendix B

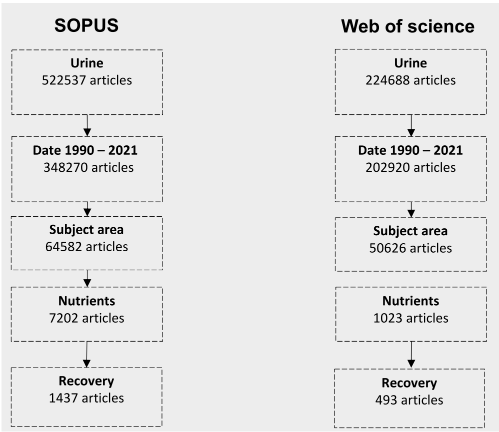

Fig. B1. Summary of the search and refinement process for string 1.

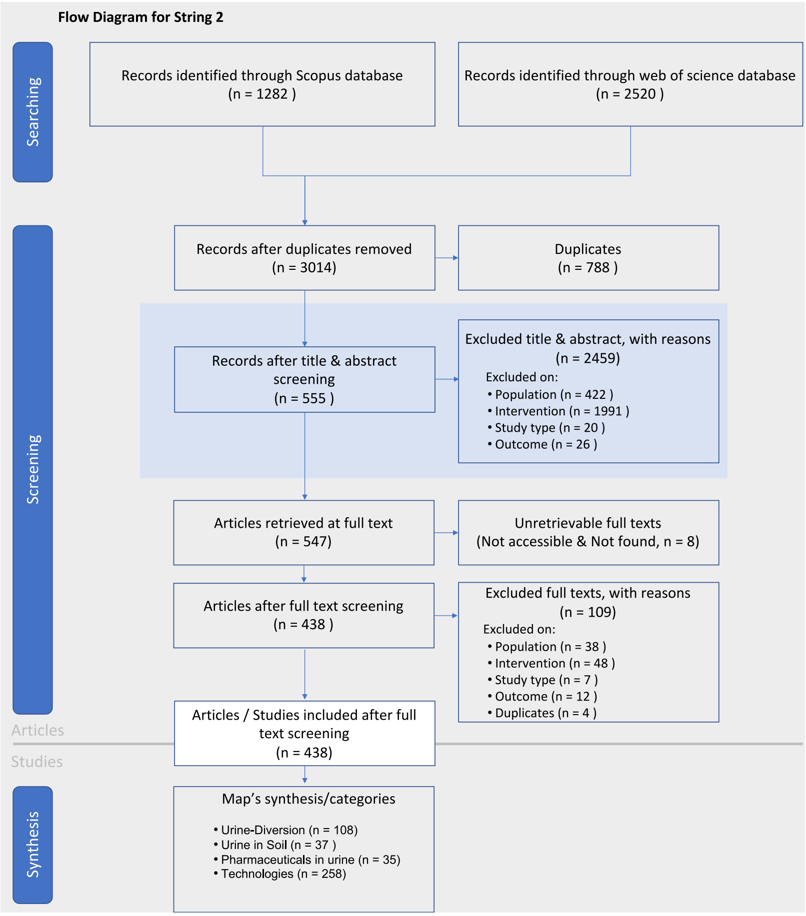

Fig. B2. Flow diagram illustrating the screening process and coding of string 2, i.e., the number of records excluded and retrieved on duplication, abstract, and full text.

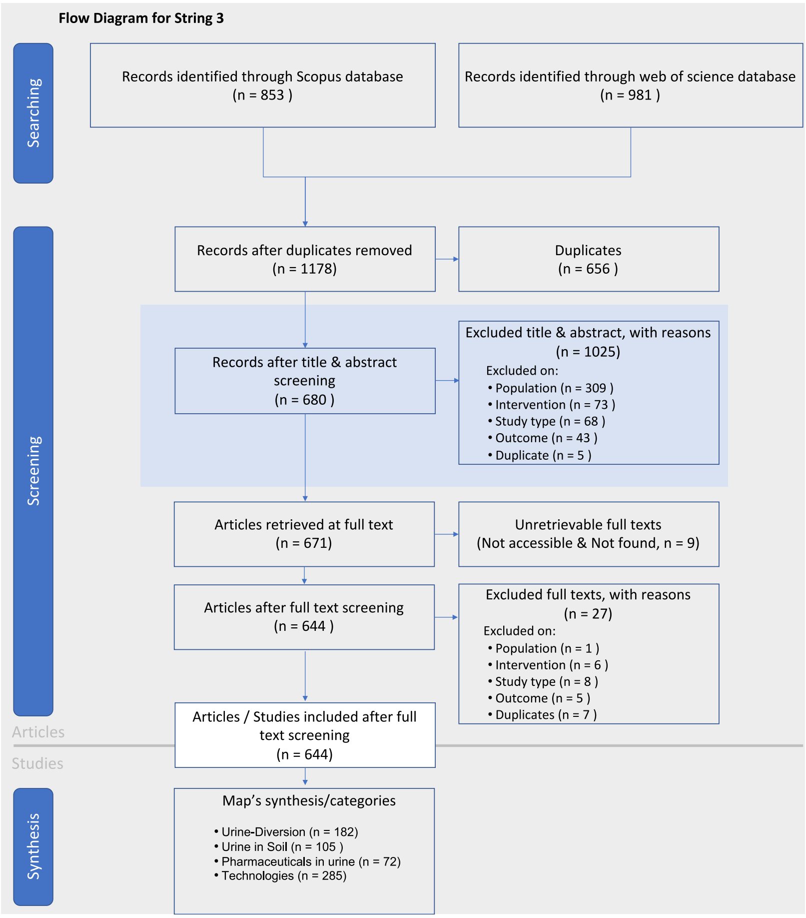

Fig. B3. Fig B2: Flow diagram illustrating the screening process and coding of string 3, i.e., the number of records excluded and retrieved on duplication, abstract, and full text.

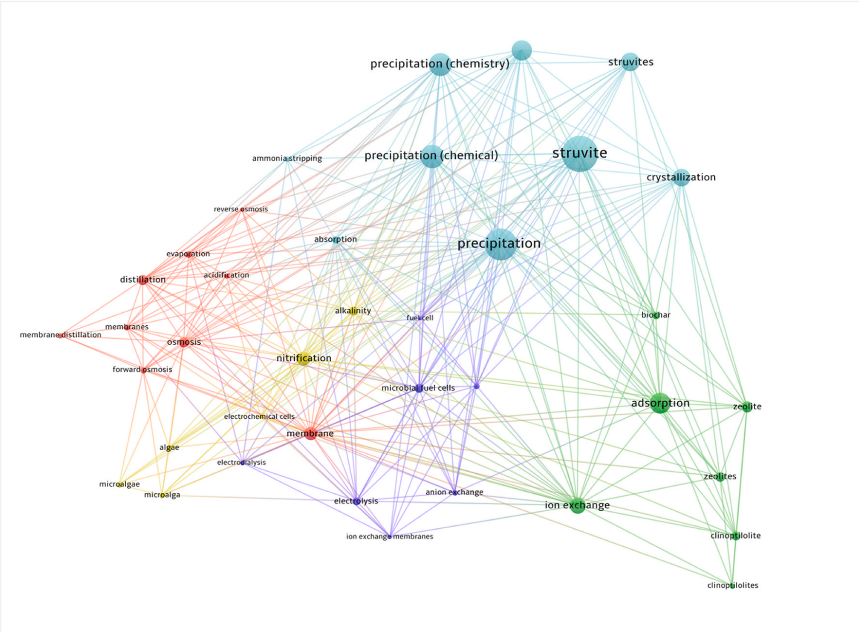

Fig. B4. Frequency of occurrence of technologies keywords within the urine technologies category, with larger circle size indicating higher frequency of occurrence. Diagram designed using VOSviewer tool. Colors represent technologies clusters, e.g., light blue

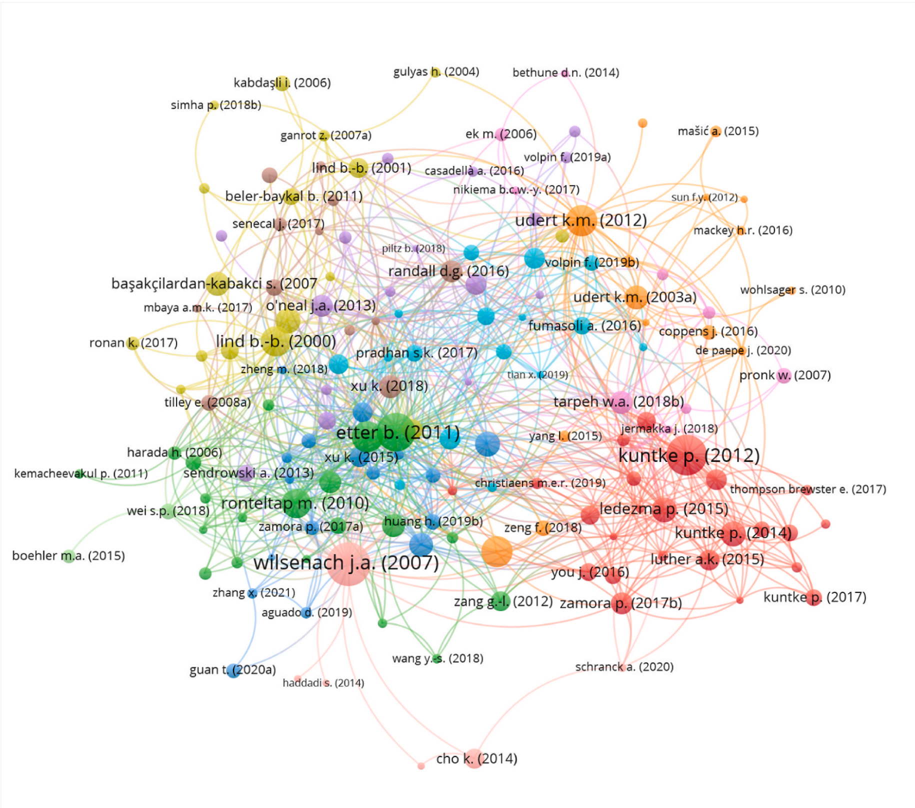

Fig. B5. Citation analysis results. Top cited papers within the urine technology subcategory are: (Etter et al., 2011; Ganrot et al., 2007; Hug and Udert, 2013; Kataki et al., 2016; Kuntke et al., 2012, 2014; Ledezma et al., 2015; Lind et al., 2000; Ronteltap et al., 2007, 2010; Udert and Wächter, 2012; Wilsenach et al., 2007; Zhang et al., 2014). Larger circle size indicates higher paper citation number. Colors in this diagram are not important.

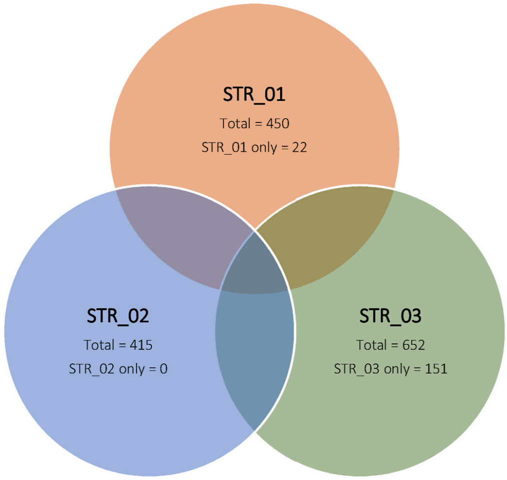

Fig. B6. Overlaps in hits between search strings (STR) 1, 2, and 3.

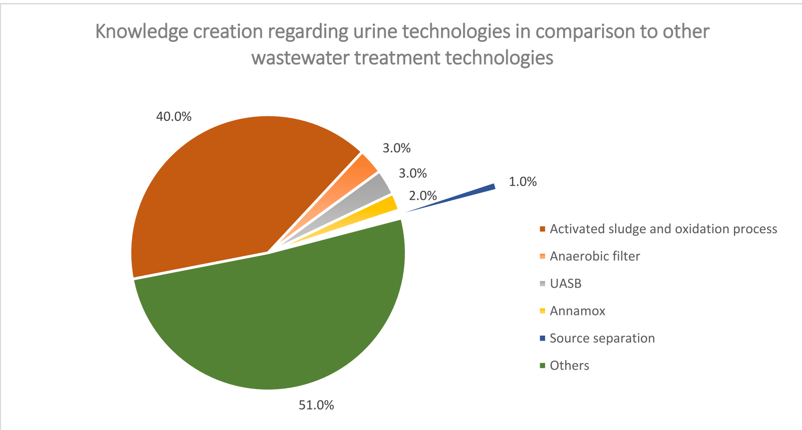

Fig. B7. Proportions of urine-related publications in the total number of wastewater publications 1990–2021.

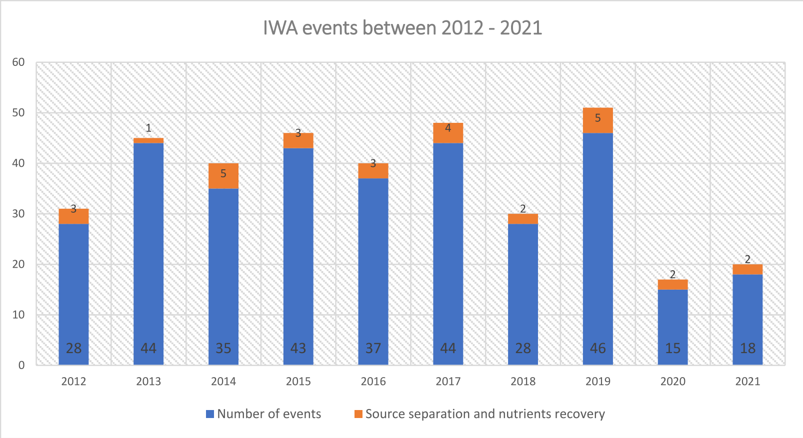

Fig. B8. Number of International Water Association (IWA) events per year, 2012–2021.

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III

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Urine recycling - Diffusion barriers and upscaling potential; case studies from Sweden and Switzerland

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A R T I C L E I N F O

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A B S T R A C T

In this study, we explored why urine recycling systems have failed to gain wide-scale expansion despite their high potential for food and fertilizer security. Additionally, we examined the future perception of urine recycling in Sweden and Switzerland, as these two countries are at the forefront of technological advancement. Along with identifying barriers, we also proposed pathways for overcoming those barriers and achieving the upscale. The analysis was conducted using the technological innovation (TIS) approach, which is technology-focused, i.e., revolves around emerging technologies. Additionally, the study provides a methodological contribution to the innovation systems research by employing the Delphi method in conjunction with urine recycling experts to enforce transparency and prevent bias in the analysis. For urine recycling to overcome its current challenges, actors must work collectively. There needs to be a combination of top-down and bottom-up efforts to achieve the upscaling pathways. Lobbying and knowledge provision are necessary to adjust the current regulatory framework in a manner that provides public and private incentives. For urine recycling to diffuse and break into the mainstream market, we must move beyond enthusiasts, innovators, and niche markets into the mass market (ordinary people); dedicated service providers can facilitate this process. Pilot projects have been found integral to urine recycling upscaling. Future work could conduct life cycle assessments on existing pilot projects to understand the environmental and economic performance of urine recycling systems when scaled up.

1. Introduction

Since the mid-19th century, centralized sanitation has been fundamental in enhancing public health by preventing water-borne diseases and improving hygiene. With time, sanitation systems have matured into intricate networks of actors, institutions, infrastructures, and sociocultural habits, leading to lock-in and path dependency (Fam and Mitchell, 2013). Consequently, they became less likely to adjust to future uncertainties such as eutrophication and resource depletion (Cordell et al., 2011). This inadequacy in adjusting to future uncertainties is also attributed to the linearity of the current management system. For instance, secondary treatment (e.g., activated sludge) in many wastewater treatment plants (WWTPs) is designed to remove biochemical oxygen demand (BOD), nutrients, and pathogens rather than recover them (Boyer and Saetta, 2019). Additionally, many of today's WWTPs cannot efficiently remove organic micropollutants, like pharmaceuticals and hormones, due to the substantial additional investment needed (Li et al., 2013), leading to considerable volumes being released into nearby water bodies (Roudbari and Rezakazemi, 2018). Hence, the lack of nutrient recovery and organic micropollutants removal poses a growing concern for urban water systems regarding food security, pollution, and undermining circularity initiatives (Pronk and Koné, 2009).

In order to meet the sustainable development goals (SDGs) and achieve food and fertilizer security, the sanitation systems of today must undergo a paradigm shift that consolidates circularity (Guest et al., 2009), resource recovery (McConville et al., 2017), and socioeconomic benefits (Öberg et al., 2020). A viable alternative solution is source separation-urine diversion (UD), i.e., separate collection and processing of urine from other wastewater fractions (Larsen et al., 2021). In practice, only about 1% of the influent volumetric flow at a wastewater treatment plant is attributed to urine, yet it contains most macronutrients (80% N, 50% P, 60% K) (Vinnerås et al., 2006). Additionally, the bulk of the organic contaminants within domestic wastewater (>70% of

Abbreviations: TIS, Technological innovation system; WWTPs, Wastewater treatment plants; UD, Urine diversion; UDT, Urine diversion toilet.

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estrogen and >60% of pharmaceuticals) reside in urine (Lienert. et al., 2007). Therefore, urine recycling systems can foster circularity by promoting nutrient recovery (Fam and Mitchell, 2013), reducing nutrient and micropollutants emissions from WWTPs (Badeti et al., 2021), and lowering energy and financial costs (Igos et al., 2017). In addition, urine recycling systems have shown in several studies to have the least impact on the environment compared to existing wastewater treatment systems (Ishii and Boyer, 2015). Furthermore, urine recycling presents a potential opportunity to achieve social gains, particularly in areas where access to sanitation is limited and advanced treatment systems are not feasible. By doing so, we are moving closer to the 'sanitation for all people' goal, in which people will have the opportunity to have sustainable sanitation systems and make use of the macronutrients for agriculture (Larsen et al., 2021b). The promising potential of urine recycling prompted the emergence of urine recycling niches in different countries, and research in this field has increased (Maurer et al., 2006). Hence, various technologies have been developed in the last two decades in different countries to concentrate macronutrients from urine into fertilizer (Larsen et al., 2021a). However, despite their high potential for advancing circularity and relieving ecological perils (Alemayehu et al., 2020), these technologies have not yet advanced into large-scale implementation/diffusion (Aliahmad et al., 2022).

A number of factors explain why new technologies, such as urine recycling technologies, with promising superior performance compared to incumbent technologies, fail to gain popularity and diffuse. One way to look at it is that a paradigm shift in today's large technical systems cannot occur solely through technological change (Fam and Mitchell, 2013; Hackmann et al., 2014). Changes in the social dimension, such as user practices (Andersson et al., 2016), regulatory changes (Zhuang et al., 2021), and industrial networks, are equally crucial (Larsen et al., 2009). Therefore, it is essential to look beyond the technical aspect and includes socio-technical elements to comprehend urine recycling holistically. For instance, certainty concerning the regulatory status was recognized as key for Swiss and German farmers to adopt urine in agriculture. This is especially true since the national laws of today only provide vague guidelines for the use of human excreta (Lienert and Larsen, 2009). Additionally, existing systems don't have the capacity to cope with the introduction of new technologies with radical innovation, as it requires an integrated transformation of all primary parameters within the system (Andersson et al., 2018; Xiao et al., 2021). As a result, conventional systems, e.g., sanitation systems, only undergo incremental changes along existing trajectories rather than radical changes (Fam and Mitchell, 2013).

Recognition of this system-level change and inclusion of the socio-technical element is key to understanding the early adoption of novel technologies and how to bridge the gap between R&D and market introduction (Markard et al., 2012). In the early stages of adoption, emerging technologies are sheltered from mainstream competition in niches (Schot and Geels, 2008). Niches represent the micro-level of innovation and are seen as protected breeding spaces for radical innovations, e.g. (labs) (Ortt and Kamp, 2022; Schot and Geels, 2008). Radical technologies are given opportunities to incubate and mature within the niches through gradual experimentation and learning by actors, researchers, users, and governmental and other organizations (Schot and Geels, 2008). Upon successful R&D, testing, demonstration, and feedback from end users within the niches, emerging technologies gain momentum and evolve through a bottom-up process into innovation systems with a more shaped structure of actors, networks, rules, and regulations (Geels, 2019). Ultimately, they enter the mainstream market as a competitor, leading to either a full or partial replacement of dominant regimes (Markard et al., 2012). Hence, to understand why the diffusion of emerging technologies is delayed, one should examine the performance of the innovation system around it (McConville et al., 2017).

Although urine recycling research has increased in recent years, most attention is devoted to the technical, engineering, and environmental aspects. A few studies have incorporated the socio-technical dimension into their analyses, but none have attempted to study why urine recycling technologies have been delayed from entering the mainstream market since their introduction in the early 1990s (Larsen et al., 2010). Instead, they looked for windows of opportunity to scale up source separation in Sweden (McConville et al., 2017), how urine recycling is being adopted (Abeysuriya et al., 2013; Fam and Mitchell, 2013), ways to promote a more sustainable phosphorus future (Jedelhauser et al., 2018), or how communication influences public acceptance of urine recycling (Cohen et al., 2020). Other studies examined the cultural aspect, e.g., how some cultures and norms impede some communities from using UD toilets (Khalid, 2018; Mugivhisa and Olowoyo, 2015; Nawab et al., 2006), how to handle norms and cultural perceptions (e.g., taboos) (Andersson, 2015), and users' perceptions of urine (Simha et al., 2021).

This study aims to fill the knowledge gap by exploring why urine recycling technologies failed to catch on and diffuse in large-scale implementation after more than two decades since their introduction. In this socio-technical investigation, we examine the state of urine recycling in Sweden and Switzerland and the fundamental processes responsible for its development and diffusion. Additionally, we explore the future perception of urine recycling in both countries since having a common vision is considered influential in the expansion of emerging technologies (Lennartsson et al., 2019). We focus on Sweden and Switzerland since they are pioneers in conducting urine research (Aliahmad et al., 2022) and are today at the forefront of technological advancement with five to six technological readiness levels for their tested technologies (Larsen et al., 2021a). Accordingly, Sweden and Switzerland can be viewed as models from which to draw lessons. Hence, countries interested in implementing urine recycling systems can benefit from the results of this socio-technical analysis.

The analysis attempts to answer the following research questions: Q1: What are the blocking mechanisms and challenges that have delayed the diffusion and expansion of urine recycling technologies? Q2: What is the future perception for urine recycling in both countries, and how different are they? Q3: What interventions are necessary to accelerate the diffusion of urine recycling to the next development stage and reach the future perception? The originality of this study is to identify barriers along the supply chain that may have hindered the expansion of urine recycling into mainstream markets. Moreover, the study provides methodological contributions regarding the conduct of socio-technical research with the assistance of subject matter experts. Further, we formulate policy recommendations targeting the corresponding actors and entities, illustrate pathways for future large-scale implementations, and pinpoint where change has the most potential for creating the most cascading/trickling-over effects.

2. Theoretical framework: socio-technical transitions

Our research examines the emergence of new technologies and the institutional and organizational changes accompanying them. Hence, we selected the technological innovation system (TIS) approach since it is technology-focused, i.e., the analysis revolves around emerging technologies (Markard and Truffer, 2008). Moreover, it emphasizes the dynamics of actors, networks, and institutions that generate and diffuse innovations; it is frequently applied to understand the technological progression of a particular technology, particularly within emerging renewable energy systems (Bergek et al., 2008; Bergek et al., 2011). TIS studies also aim to inform policymaking, which is why identifying innovation barriers is a common task in the field. Considering this study attempts to identify potential blocking mechanisms to urine recycling diffusion, the TIS method is considered the most appropriate approach (Markard and Truffer, 2008).

TIS encompasses a network of agents interacting in an economic area under an institutional infrastructure (Carlsson and Stankiewicz, 1991a). These structural components, namely actors, networks, and institutions, together form the supply chain of the TIS (Bergek et al., 2008). Actors are the core of the TIS and are spread along the supply chain segments (Hekkert and Negro, 2009). Institutions are usually viewed as the game's rules that influence actors' activities and interactions (Bergek et al., 2008). The TIS structure plays a crucial role in the development, diffusion, and application of technology, and its weaknesses adversely impact the emergence of the technology. (Carlsson and Stankiewicz, 1991b). Thus, the analysis of the TIS begins by examining its structure. There is, however, more to assessing the performance of the TIS than structural analysis, since this only gives an overview of the actors involved, but does not indicate how active they are and what they are doing (Bergek et al., 2011). Hence, function-based analysis is used to complement structural analysis and to evaluate the dynamics of the system (Bergek et al., 2008). Using this framework, TIS performance is analyzed in relation to essential functions (entrepreneurial experimentation, knowledge development, knowledge diffusion, search guidance, market formation, resource mobilization, and legitimacy creation) (Bergek et al., 2008; Bergek et al., 2011). Scholars regard these functions as critical processes within the TIS necessary for the successful emergence of emerging technologies. The analysis identifies the lagging functions along the supply chain, which actors and policymakers can then address (Stephan et al., 2017). Having a rigorous and active supply chain is essential for developing immature innovation systems (Musiolik and Markard, 2011) and facilitates the definition of the TIS's boundaries (Andersson et al., 2018). Moreover, when hindrances are narrowed down to a specific segment of the supply chain rather than addressing the entire system, it becomes easier to select the appropriate policies and responsible actors (Bergek et al., 2011).

The TIS progresses through different stages throughout its life cycle. Markard (2020) recognizes four stages of development: formative, growth, maturation, and decline (Markard, 2020). Each stage varies in terms of the number of actors involved in the TIS, the degree of uncertainty regarding the functionality of technologies in real-life applications, end-user demand, and the TIS market share (Markard, 2020). The technological change along these development stages moves into different phases (Markard, 2020). For instance, during the formative stage, a successful TIS maintains development, and technological change occurs at an increasing pace. Therefore, the formative stage can be divided into two consecutive phases; the pre-development phase and the development phase (Bergek et al., 2011). The same thing applies to the growth stage and can be divided into two phases: acceleration and market acquisition. Fig B. 1 illustrates a TIS's stages during its lifecycle, including the maturity and stabilization stages. Bergek et al., 2011 argue that not every system function is as crucial as other system functions in each phase. In each phase, different system functions play an influential role depending on the ambition of the phase. Thus, a primary function should be at the core of the analysis, and the other functions play a supporting role in developing the TIS. For instance, in the pre-development phase, also referred to as the conceptualization phase, F2 (knowledge development) is regarded as the most critical system function as it contributes significantly to building a solid foundation for experimentation and further development. While the pre-development phase is underway, this function interacts with several other secondary functions, such as knowledge exchange, searching guidance, and resource mobilization. As such, the analysis encompasses primary and secondary functions, as opposed to the remaining functions that are either missing or not yet initiated fully; for example, institutional alignment in the pre-development phase is likely to be low as the TIS has not been fully commercialized, and its market share is still narrow. The first function (entrepreneurial experimentation) is regarded as the most critical system function for the development phase as it paves the way for pilot scale implementations to prove that the technology works in practice. This function interacts with all the secondary functions; thus, the analysis encompasses all functions (Makkonen and Inkinen, 2021). Fig B. 1 illustrates the primary and secondary functions distribution for each development phase.

3. Methodological approach

The methodology employed in this study is exemplified in Fig. 1 and follows the format of Bergek et al., 2008) with some adaptations and additions. The work commenced with defining the TIS in focus, its stage of development and boundaries. This step involves specifying the type of innovation in focus and the breadth of aggregation, i.e., deciding whether to gain a global outlook of the TIS or to be more characteristic about which actors, networks, and institutions to consider, for example national scale.

In our study, we focused on innovative urine recycling TISs in Sweden and Switzerland. These TISs comprise a group of segments i.e., functional groups (urine diversion toilets, urine treatment technologies, and urine-based fertilizer) across the supply chain. Collectively, these segments contribute to the provision of the intended service, i.e., urine recycling. Supply chain segments differ according to the type of system and whether treatment takes place on-site or off-site. Fig. 2 illustrates the supply chain of the urine recycling system, starting with the user segment where urine diversion toilets (UDT) are installed. This segment involves all activities necessary to separate urine from other wastewater fractions. After that, urine is collected and transported to the treatment segment, where plant nutrients are recovered from the collected urine. During the treatment, urine is converted into fertilizer. Most of this fertilizer will end up in agricultural industries, food chains, and ultimately UDT. The breadth of aggregation, i.e., the scale of analysis, was assumed to be national for both TISs. Both TISs were assumed to be roughly at the same developmental stage, so examining roughly analogous structural schemes was more plausible. Although their structural schemes are similar, each TIS has its own actors.

The second step is the structural analysis of the focal TIS, i.e., types of actors across the supply chain. In this study, we categorized the structural components into distinct subcomponents, i.e., industry & infrastructure (*private firms, WWTP, etc.*), knowledge (*universities, research institutes, etc.*), governmental & supportive (*municipalities, NGOs, etc.*), and financiers (*banks,* funding *agencies, etc.*) as shown in Fig B. 2. In a healthy TIS, these structural components function dynamically and actively with institutional alignment and support (Bergek et al., 2008). Desk research, snowballing from our contacts in the Swedish & Swiss urine recycling communities, as well as survey and interview inputs, helped us map these structural components.

In the third step, we mapped the TIS functional pattern, i.e., which functions to consider for the analysis. The study follows the argument of Bergek et al., 2011) that the functional pattern of the TIS varies depending on its stage of development. Therefore, we should determine the current status of urine recycling TIS development in both countries. Various characteristics and features are described by Bergek et al., 2008) & Markard (2020), including target market size, the number of actors involved, articulation of demand, and institutional alignment. Both Swedish and Swiss systems exhibit the characteristics defining the development phase; few technical uncertainties, few numbers of private firms, small market shares, low demand, uncertainty regarding applications, and weak advocacy coalitions. Accordingly, we concluded that the TIS's primary function in the current phase is entrepreneur experimentation (see section 2). This is because, in the development phase, a high focus is placed on testing whether the technology works in practice. Further, other secondary functions are equally critical during this phase, and the functional analysis should take them into account, as shown in Table 1.

3.1. Data gathering for the TIS functional evaluation using the delphi method

For the fourth step, we adjusted the Delphi method to guide our evaluation process. The Delphi method is one of the most widely used expert-based methods to obtain experts' opinions about a specific issue, forecast technology emergence, or how it might affect corresponding

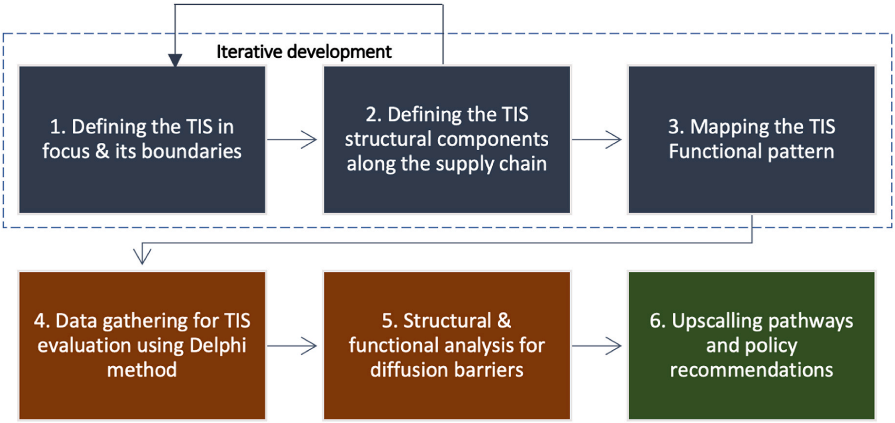

Fig. 1. This is the chain of steps utilized to conduct the TIS analysis. The first three steps blued colored depend on each other and are done iteratively. Outputs from these steps are used as a framework for steps 4 and 5. Browned colored steps are presented in the results and the green-colored step in the recommendations. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

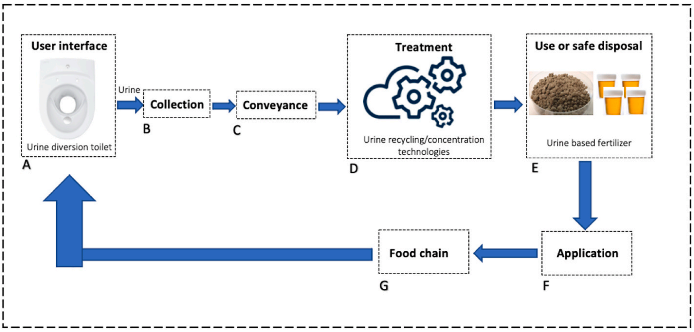

Fig. 2. Urine recycling supply chain segments. The supply chain differs between different systems depending on the type and scale of treatment but this is a general supply chain of off-grid urine recycling systems.

socio-technical systems (Gallego and Bueno, 2014). One central characteristic of the Delphi method is the anonymity of the experts' judgments and the use of iterations to reach a consensus (Gallego and Bueno, 2014). In the first round of evaluation, experts receive a list of questions for which they provide anonymous feedback. Analysts then combine experts' judgments and send an updated survey to a focused group of experts for the second round, and the process continues until a consensus is reached. Although the classic Delphi method is valid, one downside is the possibility that experts will abandon the project out of fatigue or shift their evaluations toward the mean positions to close the study (Henning and Jacobs, 2000; Landeta, 2006). Transparency of the evaluation is a significant challenge associated with TIS-function analysis, requiring sufficient and relevant information to justify each evaluation. The information and adherent references should be available for review and further development to ensure that bias was not introduced during the evaluation of TIS. One way to overcome such a challenge is by bringing together a well-represented group of experts to conduct the TIS evaluation themselves without analyst interference. If needed, expert-panel assessments can be complemented by further interviews and desk research (Feiz and Ammenberg, 2017).

In our case, the evaluation phase started with defining a few diagnostic questions in the form of indicators for each TIS function. The indicators were the outcome of desk research, literature review, and feedback from roundtable discussions between co-authors. Our initial approach was to take general indicators from Bergek and Hekkert and adapt them for wastewater (Bergek et al., 2008; Bergek et al., 2011). We reviewed studies from different contexts and adapted indicators for wastewater. Our goal was to develop indicators that would reflect urine recycling system dynamics and functionality. Additionally, we wanted to emphasize the necessity of including the cost of the urine recycling system (installation cost and treatment fees), which is closely related to users' daily behaviors, unlike other energy systems where users pay only for consumption.

Several trials later, we compiled a list of indicators. The indicators were then shared in a survey (*Qualtrics*) with urine recycling experts from different countries (Sweden, Switzerland, France, the US, China, and South Africa). After reviewing the feedback from the survey (24 responses), the indicators were further refined. We then selected a focused group of experts from the Swedish and Swiss urine recycling systems to share the modified version of the indicators for the second round of evaluation. Before sharing the modified version of the indicators, we conducted a few semi-structured interviews with experts in

Table 1
TIS functions definitions and the indicators used to evaluate the functions. Indicators with starts mean that the indicators weren't evaluated in this study but in our previous study.

Functions	Definition (Bergek et al., 2011; Bergek et al., 2008)	Indicators	References
F1- Entrepreneurial experimentation	This function represents the activities carried out within the TIS by entrepreneurs and business startups to explore & test new technologies through pioneering experiments.	♠ The diversity level of actors involved in the Swiss/Swedish urine recycling system? ♠ The level of engagement of actors within the Swiss/Swedish urine recycling system? ♠ The experimentation (lab-scale) rate in the Swiss/Swedish urine recycling system?	(Andreasen and Sovacool, 2015; Palm, 2015; Vasseur et al., 2013; Wieczorek et al., 2015)
F2- Knowledge development	This function represents the volume of the knowledge base of the TIS. How much knowledge from different aspects e.g., technical, social, and economic has been produced?	♠ The engagement level of the Swiss/ Swedish actors in knowledge generation? ♠ The growth rate in publications within urine recycling system? * ♠ The knowledge volume of urine recycling system compared with WWTP? * ♠ The development of the urine publications over time compared to WWTP? *	(Aliahmad et al., 2022; McConville et al., 2017; Wieczorek et al., 2015)
F2- Knowledge diffusion	This function represents the activities carried out by the networks within the TIS to spread and diffuse knowledge regarding the new TIS.	♠ The diffusion of knowledge regarding urine recycling between countries? * ♠ The volume of urine recycling conferences compared with conventional WWT? *	Aliahmad et al. (2022)
F3- Guidance of the search	This function gives an overview of the current regulatory framework and if it provides sufficient incentives and/or pressures for the actors to enter the TIS. It also gives an idea of actors' visions on how to use their resources and if they might be controlled by influential actors.	♠ The availability of: National strategy enabling nutrient recovery from wastewater? ♠ The availability of: National policy/ incentives enabling urine recycling? ♠ The availability of: A clear vision about the development of the sanitation system?	(Hekkert and Negro, 2009; Klitkou and Coenen, 2013; Liu et al., 2018; Ulmanen and Bergek, 2021)
F4- Market formation	This function represents the processes within the TIS that are contributing to the market creation, emergence and evolution between the different market's phases (nursing, bridging and mature market). e.g., projects installed, pilot tests outside in and out the labs.	♠ The current number of urine diversion toilets in Switzerland/Sweden? ♠ The number of pilot-scale of urine recycling in Switzerland/Sweden? ♠ The price that users in Switzerland/ Sweden need to pay for UDT? ♠ The service fees users in Switzerland/ Sweden need to pay for urine recycling? ♠ The attitude of Swiss/Swedish agricultural sector toward urine-based fertilizer?	(Akbari et al., 2020; Andreasen and Sovacool, 2015; Bergek et al., 2011; Klitkou and Coenen, 2013; Palm, 2015)
F5- Resource mobilization	This function represents the processes within the TIS contributing to mobilizing human and physical resources, and financial capital.	♠ The availability level of human resources in the urine recycling system? ♠ The availability level of infrastructure for the installation of urine recycling?	(McConville et al., 2017; Vasseur et al., 2013; Wieczorek et al., 2015)
F6- legitimacy creation	This function represents the processes within the TIS contributing to increase the social and institutional acceptance of the technology as well as the awareness.	♠ The level of lobbying activities against urine recycling? ♠ The level of lobbying activities to legitimize urine recycling? ♠ The willingness level of the conventional systems to adopt urine recycling? ♠ The level of acceptance by the users regarding urine diversion toilets?	(Andreasen and Sovacool, 2015; Esmailzadeh et al., 2020; McConville et al., 2017; Palm, 2015; Vasseur et al., 2013)

both countries. Interviews aimed to gain a better understanding of the current system and technical improvements in both countries, and in fact, the interviews led to further refinements of some indicators. We then shared the revised survey (*Menti presentation*) with the experts for evaluation, as shown in Table 1. Based on the experts' judgments, we divided the indicators into two groups: those that achieved consensus and those that did not. In the third round of evaluation, we invited experts from both countries to participate in a half-day workshop in their respective countries. Ten experts from Switzerland and thirteen from Sweden representing different actors in the urine recycling TIS (entrepreneurs, research institutions, private firms, municipalities, and associations) accepted and joined the workshops.

The workshop had three parts. During the first part, the indicators that did not receive consensus were presented to the participants. The purpose of the workshop is to engage experts in discussions that would yield a consensus. However, we wanted to ensure that the evaluation was anonymous. Thus, we gave participants an indicators template. After a brief discussion, the participants were asked to reevaluate the indicators, including their rationales for their evaluation. The printed template is intended to allow participants to state what they consider to be their valid opinion. Face-to-face discussions may lead to disagreements and bias; sometimes, participants may agree with each other's views to conclude the session. However, when they have their template, they can engage in the discussion and convey their arguments, but then write down what they believe is true. In addition, these discussions are beneficial because participants might have misinterpreted an indicator. During the discussion and brainstorming, they better understand it, which might lead to a consensus. After the first part, the facilitator collected the experts' evaluation templates for review. In the second session, the previously agreed-upon indicators were presented. Experts were asked to do the same as in the first session, i.e., discuss the indicators, reevaluate, and write down their reasoning. In the last session of the workshop, we divided the experts into groups and asked them to sketch their future perceptions of urine recycling. Future perceptions encompass scales and configurations for implementation, such as rural areas, urban areas, city scale, newly built areas, etc., the type of technology, and those involved in the supply chain. Also, the goal was to backcast how to move on to the next phase of urine recycling development. Backcasting identifies the pathways and activities deemed necessary to reach the future perceptions.

3.2. Data analysis

A key point to emphasize is that agreement and consensus do not necessarily imply that all participants selected the same rating. Typically, agreement and consensus are reached when votes are all the same, for example, all low, or when votes are split between two aligned categories, such as low and medium or medium and high. However, if votes are split between non-aligned categories, such as low and high, or spread over low, medium, and high scales, this is not considered a consensus. This study evaluated the indicators on a low, medium & high scale. Table A. 1 shows the interpretation of the scales' values regarding the corresponding indicator. Indicators with low and or low-medium values on the scale are regarded as barriers, implying that the respective function is lagging and changes are deemed necessary. Medium indicates that the indicators are insufficient, so the respective functions must be improved for the TIS to gain traction and diffuse. In contrast, if the indicator is rated between medium and high, the corresponding function is on track and is not lagging but still could be improved. Finally, indicators rated high indicate that their respective functions are performing well and that the TIS is heading in the right direction.

After all indicators were reviewed, they were linked to their corresponding functions. We then evaluated the TIS in both countries by analyzing the performance of the functions across the supply chain segments. Upon completion of the analysis, recommendations were developed to inform policymakers, decision-makers, and actors about the barriers and lagging functions in each supply chain segment hindering urine recycling upscaling.

4. Results

As of the time of the workshops, the evaluation of most of the indicators in both TISs had not reached a consensus. During the workshops, the indicators were discussed and re-evaluated anonymously. Based on the evaluation of the workshops, it was determined that all indicators met a consensus except for one indicator within the Swiss TIS: the availability of human resources. Following the workshop, the indicator was sent back to experts for re-evaluation, and an agreement was reached, as shown in Table A. 2 and Table A. 3. The evaluation of some indicators differed between the two TISs, i.e., Swiss urine recycling versus Swedish urine recycling, as shown in Table 2. For instance, the level of engagement of the actors in knowledge generation was rated as medium to high in the Swiss TIS but as low by the majority of experts in the Swedish TIS.

Table 2
Results of the Swiss and Swedish workshops on indicators evaluation. The red color highlights the barriers while the green highlights the indicators that perform well. The star indicates that the indicator is evaluated the same in both TISs. The cost, fees and lobbying against urine indicators are scored opposite from the others, e.g., high cost and fees is a barrier.

Indicator	Switzerland			Sweden		
	Low	Medium	High	Low	Medium	High
F1- The diversity level in the TIS	0	7	3	8	5	0
F1- The engagement and activeness level in the TIS*	0	2	7	0	11	2
F1- The experimentation rate in the TIS	0	6	4	12	1	0
F2- The engagement in knowledge generation in the TIS	0	3	6	12	1	0
F3- National strategy for nutrient recovery from wastewater*	10	0	0	13	0	0
F3- National policy / incentives enabling urine recycling*	9	1	0	13	0	0
F3- Vision and expectations of the sanitation system*	9	1	0	11	2	0
F4- The current number of urine diversion toilets*	9	1	0	13	0	0
F4- The number of pilot-scale projects*	6	4	0	13	0	0
F4- The price for urine diversion installation*	0	4	6	0	3	10
F4- The service fees for urine recycling*	0	0	10	0	2	11
F4- The agricultural sector attitudes toward urine-based fertilizer	3	7	0	0	13	0
F5- The availability level of human resources in the TIS*	7	3	0	11	2	0
F5- The availability level of infrastructure in the TIS	0	4	6	13	0	0
F6- The level of lobbying activities against urine recycling*	9	1	0	9	4	0
F6- The level of lobbying activities to legitimize urine recycling	0	9	1	8	5	0
F6- The willingness of conventional systems to adopt urine recycling*	10	0	0	9	4	0
F6- Users acceptance of urine recycling	0	4	6	0	13	0

4.1. Functional analysis of the Swiss and Swedish urine recycling TISs

This section entails a detailed evaluation of the indicators for Swiss and Swedish urine recycling TISs. The results are based on experts' reasoning recorded in their evaluation templates. Each subsection provides information concerning a system function, as well as results for both TISs.

4.1.1. Entrepreneurial experimentation

The evaluation of this function employed three indicators. One to gauge the level of engagement within the Swedish/Swiss urine recycling system and the second, the diversity of the actors, i.e., is the TIS inclusive of all types of actors? The third indicator assessed the degree of experimentation (lab-scale) undertaken within the Swedish/Swiss urine recycling systems to evaluate whether the actors provided adequate knowledge to foster the implementation on a large scale.

4.1.1.1. The Swiss TIS. According to the Swiss experts, engagement among actors, the diversity, and the scale of lab experiments were rated between moderate and high, indicating that the respective function (entrepreneurial experimentation) is on track and is not lagging but still could be improved.

Experts think that the Swiss urine recycling actors are from different disciplines, like process engineering, agriculture, applications, and administration. However, the number of actors per discipline is rather limited and low. Although the number of actors is relatively low, experts think that the engagement level among each other is high, and many are also internationally pioneering in the field. Experts added that the laboratory experiments are higher than pilot experiments. However, aside from Eawag/Vuna, laboratory experiments are very few and do not even exist. Experts concluded that if the urine recycling TIS is to grow and mature, the experimentation level needs to be higher, and more types of actors need to be part of the TIS and experimentation.

4.1.1.2. The Swedish TIS. According to the Swedish experts, engagement among actors is moderate, but the diversity and scale of lab experiments are low, indicating that the respective function (entrepreneurial experimentation) has some insufficiencies and, thus, changes are deemed necessary.

Experts think that there are few actors from different coalitions of the supply chain; however, some key actors for scaling up, such as infrastructure, city planners, and law legislators, are missing. Experts believe competition is needed to scale up the urine recycling system; otherwise, investors won't believe in it. Although the number of actors within the urine recycling TIS is relatively low, experts think that the engagement level is relatively moderate; " …. *researchers and some other consultants are relatively active and involved, while many other actors are not*". For instance, engagement from infrastructure owners and municipalities is relatively low; thus, end users often build their UDT by themselves, handle waste, and use the outcome as garden products. Experts think there is a difference between being engaged, communicating, and publicly debating the issue " …. *If the question is whether the actors are engaged, then the answer is yes. Do they communicate well? the answer would then be no*". Experts continue that changing people's habits and views on urine is challenging, which explains the lack of engagement from other actors in the supply chain. Experts added that only academic research, e.g., SLU and a few experiments, are currently available. To support long-term pilots, there needs to be more competition and interaction. We need more experiments to scale up and fill the gap between pilot and broad-scale applications, e.g., factories or industries. Experts concluded that for the urine recycling TIS to grow and mature, the experimentation level needs to be higher and more actors from different coalitions across the supply chain need to be part of the TIS and experimentation.

4.1.2. Guidance of the search

This function was evaluated by employing three indicators designed to gauge the breadth to which national strategies, policies, and visions were in place to enable nutrient recovery from wastewater. The Swedish and Swiss experts evaluated all three indicators as low/weak and/or low-medium; thus, the function is regarded as lagging in both TISs.

4.1.2.1. The Swiss TIS. Experts stated that no national or cantonal strategies, policies, subsidies, or incentives for implementing nitrogen (N) and potassium (K) recovery from urine. According to experts, the national approach for nutrient recovery targets only phosphorous (P); other valuable nutrients, including N and K, are not considered. The recovery of P from municipal wastewater sludge is being emphasized significantly, and this practice will soon be mandatory. Experts said, "…. *implementing such a strategy (P recovery at WWTP) would be problematic to urine recycling and diminish its chances of expansion*". Experts believe that decision-makers' vision at the national and cantonal levels is instead focused on nutrient recovery at the WWTP without changing anything upstream of the WWTP. Experts think there should be more institutional intervention and support with clearly defined strategies and policies targeting nutrient recovery from urine.

4.1.2.2. The Swedish TIS. Experts stated that " …. *despite recommendations from several committees, there are no national strategies or goals regarding nutrient recycling and urine diversion as of now. There was once a goal, but in 2012 it was abandoned*". According to experts, the national approach to nutrient recovery targets only phosphorus (P); other valuable nutrients, including N and K, are not considered. The recovery of phosphorus from municipal wastewater sludge is being greatly emphasized. Experts estimate that about 15 000-tons of nitrogen per year are released from WWTP and on-site systems, yet no one talks about it; phosphorus is more discussed. Only grassroots organizations promote recycling - no regulation has been passed at the federal level. More legislation and support for the sector at the local level and top-down support are needed to make scaling up a success. Experts concluded that there is no clear vision, as visions differ according to needs; Visby/Gotland, for instance, emphasizes water use reduction and recovery, but nutrient recovery is an afterthought. Nutrient recovery is gaining momentum, but source separation remains low-key, i.e., not so active, and nothing has happened because very few municipalities have visions and participate, and most initiatives are grassroots. Furthermore, the lack of coordination between actors in the supply chain and the participation of actors in formulating a vision are reasons for the delay of source separation upscale.

4.1.3. Market formation

A total of five indicators were employed to evaluate the market function, of which two were designed to indicate the size of the current market based on the number of existing UDTs and urine recycling technologies installed around Sweden/Switzerland. The other two focused on the cost and fee of installing and operating UDTs and treatment. The final indicator focused on the Swedish/Swiss agricultural sectors' attitude toward urine-based fertilizer. Farmers play an essential role in the formation of the urine-based fertilizer market. The willingness of farmers to use urine-based fertilizer shows possible demand articulation and future expansion. The Swedish and Swiss experts evaluated the first four indicators as weak and/or low-medium while the final as moderate; thus, the function is regarded as lagging in both TISs.

4.1.3.1. The Swiss TIS. Experts estimated that there are currently about 200–300 UDT installed in Switzerland, which according to them, is a meager number compared to conventional toilets. However, experts believe that although the number is low, it is relatively high compared to other countries. Nevertheless, experts believe that more implementations will likely be seen in the coming years as several projects are in the planning stages. The number of pilot-scale implementations of urine recycling technologies around Switzerland was also rated low. Experts stated that pilot-scale units are currently limited to Eawag, and large-scale deployments outside academic affiliations are rare. Experts estimated that around 1–3 pilots are underway in Switzerland with varying knowledge/success and scale levels. However, for the system to be proven effective in practice, there must be at least ten well-functioning units outside Eawag.

Regarding the cost of the toilets, experts stated that urine recycling systems are relatively pricey compared to conventional toilets. UDTs require additional piping for urine separation; thus, users pay extra costs for connection and installation. According to experts, high prices are also due to a lack of competition, as only a few premium brands are currently available. The same applies to the treatment fees users need to pay. Users need to pay additional fees for urine treatment and maintenance, which will be very high in real life. Experts believe that due to the high costs, individuals will not find the technology attractive and will diminish their willingness to adopt the system. Aside from that, UD systems are not yet supported by the government, but the experts believe that if they could receive incentives, users would be inclined and willing to buy them. Experts added that the government is responsible for all sanitation services; thus, users shouldn't pay extra fees for treating urine.

Regarding the final indicator, i.e., the Swiss agricultural sector's attitude. Experts stated, " …. *generally, farmers have a positive perception toward urine-based fertilizer if the cost and hygiene are convenient. However, organic farmers are less likely to adopt it*". A few experts added, " …. *prices of urine-based fertilizers today are high, so competing with chemical fertilizers and encouraging farmers to buy urine-derived fertilizers is challenging*". Experts propose that the government should subsidize urine-based fertilizer or increase chemical fertilizer prices.

4.1.3.2. The Swedish TIS. According to experts, incineration toilets dominate off-grid toilets, but UD may increase in summer houses. Experts estimate that the number of UDTs in permanent apartments is meager and that only those engaged may have them because installing one would be costly.

Experts continue, " …. *while the number is low, it is relatively high compared to other countries, but insufficient to enable scale-up and make UD a viable competitor*". In addition to the low market share, the system continues to exhibit flaws and lags, and plumbers' knowledge is limited. According to experts, the peak was earlier in the 90s when many UDTs were installed, but supply chain delays hindered their effectiveness and diffusion. Some municipalities are now exploring alternative methods of nutrient recovery, but the trend is toward black water systems, which are becoming more prevalent.

Regarding the Swedish agricultural sector's attitude, experts stated that, generally, farmers are interested. However, the food industry, which determines which fertilizers farmers can use, is uninterested and does not want to discuss using contaminated fertilizers to grow their businesses. Additionally, " …. *buyers of grains and dairy products are concerned about sewage fertilizers*". Experts believe the lack of information is the key. Furthermore, EU regulations prohibit the use of human urine and human feces as organic fertilizers or soil conditioners. Organizational certifications are thus required, but none have been issued yet. Experts concluded that " … *farmers have positive intentions and are willing, but the environment is not conducive*".

4.1.4. Resource mobilization

The evaluation of the resource mobilization function employed two indicators concerning the availability of human, and infrastructure resources.

4.1.4.1. The Swiss TIS. According to the experts, the availability of human resources in the Swiss urine recycling TIS is between low and moderate, while the availability of physical resources is moderate to high.

Experts stated, " …. *the Swiss urine recycling system encompasses a few experienced actors. Although urine recycling is an old concept, it is technically new, and only a few experts know it—a narrow team with high knowledge concentrated in a few entities and hard to replace*". Thus, experts believe that if urine recycling is to expand and grow, more human resources, competence, and experts are needed.

Regarding the physical and infrastructure, experts stated that the availability of physical and infrastructure resources for urine diversion installation in old buildings is low as it requires renovating existing infrastructure, and there is limited space for a third pipe. Unlike old buildings, newly constructed areas are much easier to adopt urine recycling. Experts concluded, " …. *Switzerland, in general, has excellent infrastructure, and the materials are available, but the artisans,* e.g., *plumbers, are missing*".

4.1.4.2. The Swedish TIS. According to Swedish experts, the availability of human and infrastructure resources in the Swedish urine recycling TIS is low.

Experts think the information is available, but one needs to ask for it. There is a good experience with black water and vacuum systems but not urine separation systems. Experts believe there are a few dedicated and well-informed people, but more knowledge and awareness must be gained. Very few professionals work daily with urine diversion. Not enough actors in each part of the supply chain, and it is difficult to recruit skilled technical expertise, e.g., plumbers.

Regarding the physical and infrastructure, experts stated, " …. *for one toilet, yes, but 1 million, no*". It would be challenging to install the new UDT for existing infrastructure, and preparations for a third pipe in the toilet can be tedious. It can be doable in new buildings but very challenging and costly in existing buildings. Experts think the entire system for urine collection, treatment, transport, and storage facilities isn't available yet. In addition, most plumbers don't know how to do it. The material is probably no problem, but the whole chain to the farmers and end users needs to be in place and to work well before that. According to the experts, the existing houses are not designed to install an extra pipe or storage tanks; therefore, the option is either in newly built or remote areas, i.e., summer houses.

Experts concluded that the human and physical resources are low because we don't have a recycling system yet; if the system starts forming, more interest will merge, and resources can be allocated. The competence nowadays is sufficient in developing the system from a technical point of view, but people working practically in the supply chain that's still unknown. Nevertheless, the current situation needs to be improved for upscaling the system.

4.1.5. Legitimacy creation

The evaluation of the legitimacy function employed four indicators. Two indicators reflect the lobbying situation in Sweden/Switzerland, both opposing and supporting urine recycling. The third indicator is concerned with the willingness of the conventional sanitation system to adopt urine recycling. The last indicator reflects the user's willingness to use urine fertilizer.

4.1.5.1. The Swiss TIS. The Swiss experts in the urine recycling TIS rated the availability of lobbying activities in Switzerland opposing, as well as the willingness of the conventional sanitation system to adopt urine recycling as low. In contrast, the availability of lobbying activities supporting urine recycling was rated as moderate. Finally, the Swiss user's willingness to use urine-based fertilizer was rated as moderate to high.

Experts stated that some actors, particularly conventional WWTP engineers, and organic farmers, are critical and hesitant about urine recycling because the technology has not yet been proven to work on large scales. However, their opposition hasn't reached the level of lobbying. Experts believe there is no lobbying against urine recycling because the system is still narrow and does not pose a threat to the current large technical systems, though this may change as it continues to evolve. Experts added that " …. *WWTP actors and Swiss authorities do not view urine recycling as an alternative. They believe that the current system works better than ever, so there is no need to change it*". Discussions in the sanitation field revolve primarily around P recovery from sludge and are very end-of-pipe oriented.

In terms of the user's acceptance, a few experts said that users are normally very accepting of urine recycling as a concept, but as soon as they have to work for it, they are no longer interested. Experts believe it greatly depends on what toilet is used. Experts added " …. generally, people will accept a system that doesn't require a great deal of behavioral change". However, if they have to change their usual behavior, it becomes a big challenge. Luckily, new UDTs are identical to conventional toilets, and users do not need to change their behaviors.

4.1.5.2. The Swedish TIS. The Swedish experts in the urine recycling TIS rated the availability of lobbying activities in Sweden opposing and supporting urine recycling as low to moderate, as well as the willingness of the conventional sanitation system to adopt urine recycling. In contrast, the Swedish user's willingness to use urine-based fertilizer was rated as moderate.

According to experts lobbying in Sweden occurs only at the individual level when people in power oppose or support such initiatives. Experts believe that people in authority do not have the time to look beyond conventional systems and consider alternatives. Municipalities, for example, recognize the benefits of source separation but are reluctant to implement it because the existing wastewater treatment plants are well-functioning and efficient. Nevertheless, experts believe many young professionals in the wastewater industry are open to source separation, and some institutions and companies actively promote urine diversion. For example, the VA Syd in Malmo is building a source separation system in a newly built neighborhood in Segepark Brunswick. Experts think that system owners want safe, tested, and used systems. Thus, if urine recycling systems are tested on a large scale, the perception of WWTP owners may change. Experts concluded, " …. *scaling up urine recycling systems isn't possible without the* support *of conventional sectors and decision-makers*".

4.1.6. Knowledge development and diffusion

The evaluation of this function utilized six indicators designed to measure the engagement level, the growth rate in publication, and its development over time compared to incumbent systems. Also, the diffusion of knowledge generation between countries and in comparison, to incumbent systems. This study considers only the level of engagement by Swiss/Swedish actors in knowledge generation, while the other five indicators were evaluated in our previous study on a global scale (Aliahmad et al., 2022). Sweden's experts rated the level of engagement as low, citing that there are only a few actors who are actively generating knowledge, whereas the Swiss experts think that actors are well engaged and thus rated it as moderate to high.

4.2. Expert's future perception of urine recycling in Switzerland and Sweden

4.2.1. The Swiss perception

According to Swiss experts, the future perception is to see urine diversion in summer houses and ecovillages, then go beyond that with time, but not at a city scale. To achieve the future perception, the urine recycling system must be cheaper, with the sanitary part and fertilizer priced in a similar range or lower than conventional methods. The urine recycling system should be articulated in the market products, i.e., fertilizers of good quality (clean and hygienic) and at a competitive price. In addition, laws and regulations need to be changed. For example, the Gewässerschutzverordnung (Water Protection Ordinance - GSchV) is quite conservative. Thus, it would be beneficial to add new regulations and strategies that can argue against existing regulations that oppose urine recycling. In order to attract the support of the public for the urine recycling system, it is necessary to break taboos and bring urine recycling to the forefront of public conversations. To facilitate this process, one way is to connect to the Schwammstadt (sponge city) concept that has already been implemented and is already being mainstreamed. This would enable us to avoid having to start from scratch again just to add additional features to something that has already gained acceptance. In the future perception, urine recycling will become an aspirational choice for architect inhabitants and an economically viable and legal alternative that users buy and install, similar to heat pumps.

4.2.2. The Swedish perception

According to Swedish experts, the long-term aim is to divert 100% of urine. In the first few years of the transition, well-functioning pilots with dedicated users are essential because things may go wrong. If people are not motivated by large in an environmental protection sense, the program will not be able to sustain itself over time. It is imperative to have a variety of technologies within a variety of contexts to achieve 100% diversion. For example, urine drying and urine storage are at the unit level, while nitrification and new technologies are at the large-scale level. But overall, there is a need for technology that works effectively and toilets that can be easily cleaned, do not smell and do not clog. To obtain this larger implementation and scale context, competitive investment or paid competition is necessary. National legislation should also be enacted to force people to recycle urine, and then local governments can provide support. Most participants agreed that the primary objectives of this project are to protect the environment, remove micropollutants, recover resources, and generate profit. Experts have observed that pitching to investors about protecting the environment has not been sufficient for them because they need a return on their investment.

5. Discussion

In this section, we compared the performance of the two-urine recycling TISs. After identifying the barriers, we projected them onto the supply chain Fig. 2 to determine lagging segments. TIS literature often gives recommendations to the entire system; in this study, we pinpointed where the intervention points along the supply chain are to enhance the lagging functions.

5.1. Why urine recycling diffusion is delayed – RQ1

5.1.1. The Swedish TIS

The Swedish urine recycling performance evaluation revealed several barriers that might have caused the delay in the system's expansion and diffusion. For instance, the first function-entrepreneurial experimentation (F1) seemed to work sufficiently only regarding actors' engagement within the TIS. However, the diversity level and experimentation rate were regarded as blocking mechanisms. The following four functions, knowledge development (F2), guidance of search (F4), market formation (F5), and resource mobilization (F6) found to be lagging as their indicators - institutional support, visions, and cost of the UD system-were evaluated as either low or low medium. Finally, the seventh function-legitimacy creation (F7) was found to be performing satisfactorily in terms of users' acceptance and the availability of lobbying against urine recycling; however, the function was lagging in terms of the availability of lobbying to legitimize urine recycling and the willingness of conventional systems to adopt urine recycling.

5.1.2. The Swiss TIS

The evaluation of the Swiss urine recycling revealed several barriers

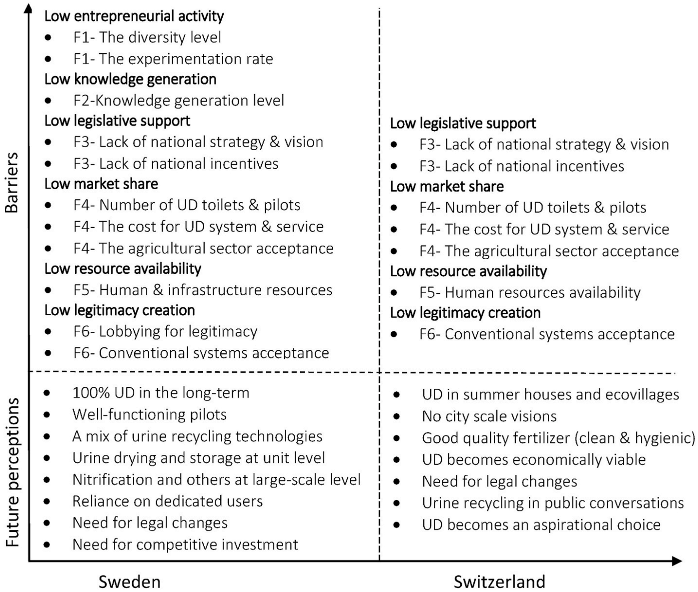

Fig. 3. An overview of the barriers and future perceptions regarding urine recycling systems in Sweden and Switzerland, according to experts in the field. The barriers are grouped under function/process headings that will be used later in this study.

that might have caused the delay in the system's expansion and diffusion. For instance, the first two functions (F1 and F2) were found to perform adequately, indicating that experts considered the entrepreneurial experimentation and the engagement of the actors in knowledge generation within the urine TIS to be effective. Unlike the guidance of the search and market (F4 & F5), the experts regarded institutional support, visions, and the cost of the UD system as blocking mechanisms. Although the sixth function-resource mobilization (F6) is performing well in terms of the infrastructure in the urine recycling TIS, it was lagging in terms of the availability of human resources. Finally, the seventh function-legitimacy creation (F7) was found to perform satisfactorily in terms of lobbying activities to legitimize urine recycling as well as user acceptance; however, the function is lagging in terms of conventional systems' willingness to adopt urine recycling.

5.1.3. Challenges urine recycling faced and the situation today

The identified blocking mechanisms (barriers) can be attributed to major challenges the urine recycling TIS has been facing, ranging from lack of technological advancement, knowledge, investment, and legal support see Fig. 3. Those challenges are dynamic, and some of today's barriers are the result of those challenges. For instance, the lack of technological advancement in the 90s certainly played a major role in market share, acceptance, and entrepreneurship. Investment and market share are also strongly correlated, as are resource availability. Similarly, the lack of investment can adversely affect acceptance and entrepreneurship. The agricultural and food industry acceptance is also affected by the level of knowledge generation. Furthermore, the lack of legal support adversely affects market share, the availability of resources, and legitimacy. Nevertheless, some of those challenges have been improved over the years, as shown below, while others still lag.

To demonstrate the challenges mentioned above, it is useful to examine the supply chain of urine recycling. Recycling urine goes beyond simply diverting urine; it encompasses the entire supply chain, from diversion and collection to post-treatment and application. This was one of the main challenges facing the industry in the 1990s when the supply chain was lagging behind (Johansson, 2001). There were issues with urine collection (segments B & C), urine technologies (segments A & D), and end users' competence in recycling urine (segments E & F). There was no robust system in place, and responsibilities between the actors were vaguely distributed, i.e., not clear who and how urine should be collected, treated, and handled. For instance, the collection and management of urine in Understenshöjden eco-village and Palsternackan housing estate projects were primarily the responsibility of the estate owners and farmers (Mats Johansson and Anna Richert, 2009). Thus, due to the investment absence and lack of resource allocation, the costs were borne by those who were not obligated to pursue the activity, and as the economic climate deteriorated, many were unable to finance such projects and lost interest (Johansson, 2001). UD technologies used in the 19990s and early 2000s, e.g., Nova Toaletta Dubbletten, Gustavsberg Nordic, Roediger No Mix, and WostMan Ecoflush, were not mature, performed poorly, and some were difficult to use (Jönsson et al., 2000). The poor performance of the old UDTs adversely affected public acceptance as well as the market share. For instance, in the Understenshöjden eco-village, the Dubbletten and Gustavsberg UDTs were used. Over the years, the system has suffered maintenance issues. The system has been clogged with acute scaling, resulting in blocked flushing and repeated problems. Moreover, one apartment suffered a serious leak that required significant and costly renovations. As a result of frustrations with the UDT, owners started replacing their toilets on their own. After contacting the project's committee, we have been informed that the board has suggested replacing all UDTs with conventional ones, and all members have approved in the fall of 2022. Such system reversal could also be linked to the fact that legal support when regarding urine recycling on all levels, e. g, R&D funds, logistics, and legislative, is rather limited (Mats Johansson and Anna Richert, 2009). Similar challenges were encountered in Switzerland; for example, the first UDT installation at the Eawag office in 1997, and four others in private apartments had to be removed later in 2003–2005 due to blockages and malfunctions. Nevertheless, Switzerland's conditions were slightly better in some respects. For example, the pilot projects under the Novaquatis project, such as private apartments, the EAWAG office, the vocational college, and the Basil-Landschaft cantonal library, were funded by either the federal, cantonal, and municipal authorities or by private actors such as universities, demonstrating the involvement of actors. Additionally, with the advent of urine recycling in Switzerland, UDT were further tested and developed compared to the situation in Sweden in the early 1990s (Larsen and Lienert, 2007).

It is, however, pertinent to cite that the legislative frameworks in both countries are rather vague and ambiguous, which has affected the national diffusion of urine recycling. The Swedish legislation, for instance, may seem to promote nutrient reuse and incorporate sustainability and green concerns, but in practice, this is not always the case. For example, the Swedish environmental code provides several opportunities to implement closed-loop sanitation solutions. However, local governing authorities do not always adhere to these principles when defining on-site sanitation system requirements (Elisabeth Kvarnström, 2006; McConville et al., 2017). According to the environmental code, household waste is under the municipality's responsibility, and urine is household waste and, therefore, should be managed by the municipality. Nevertheless, this is not the case in today's practices (Mats Johansson and Anna Richert, 2009). This lag in the implementation of closed-loop solutions by local authorities can be attributed to the paradoxical nature of the regulatory framework, coupled with contradictions in management coordination. For instance, Swedish court regulations stipulate that a municipality cannot demand, for example, source-separating systems if the end user will not utilize the collected urine, while on the other hand, farmers cannot be legally compelled to utilize specific products, e.g., source-separated urine (McConville et al., 2017). Therefore, municipalities are wary of taking the initiative in order to avoid violating the laws, particularly since these laws are vague and difficult to comprehend. Consequently, municipalities are less able to control the life cycle of waste, which weakens their position in managing it. In addition, recirculation of natural resources, including nutrients, has long been an integral part of the national objectives; nonetheless, one of the objectives that intended to recover at least 60% of phosphorus from wastewater by 2015 was dropped in 2012 when the structure of the objectives was revised and has not yet been replaced (McConville et al., 2017). There are similar issues associated with the Swiss legal framework. For instance, the Swiss Water Protection Ordinance is quite restrictive and not inclusive of urine recycling and nutrient recovery from wastewater (Fedlex, 1998). Additionally, the legal framework often fails to incorporate liquid waste into the discussions of; source separation, avoidance of waste, and resource recovery. As an example, the Environmental Protection Act limits the separate collection of waste, avoiding waste and water pollution and resource recovery to solid waste without mentioning liquid waste (Valoo, 2022). Hence, more praxis in both countries is needed regarding the interpretation of the environmental laws concerning closed-loop solutions. In addition, changes in the legal text are absolutely vital for a solid legal foundation of a circular economy in urban water management.

Today, some of the challenges faced in the 1990s have been improved; for instance, now there are new toilets that divert urine adequately. For example, "SAVE" toilet designed by EOOS-Austria and manufactured by Laufen-Switzerland, which replicates conventional toilets. The toilet uses a phenomenon known as the teapot effect, which conveys urine by the force of gravity across the inner surface of the toilet bowl into a concealed outlet, working purely by surface tension (Gundlach et al., 2021). In addition, several technologies for treating urine and producing fertilizer of high quality (e.g., nitrification/distillation, urine dehydration, membrane, etc) have been developed (Aliahmad et al., 2022). However, there remains room for improvement and optimization, particularly in the area of energy consumption and the removal of pathogens. Nevertheless, there are still lags in the supply chain, e.g., who is responsible for collection, treatment and application. In addition, the current legal system is still vague and needs to be modified to clearly targets nutrient recovery from source separated urine and other wastewater fractions.

5.2. A comparison of Switzerland and Sweden's future perception – RQ2

Comparing the future perception of the two systems in section 4.2, its noted that the two groups have different views on what it will take to scale up urine recycling and the size of the future scale. In addition, they use different definitions of successful implementation which partially explains why the Swiss evaluated the indicators differently and more positively than the Swedes. For instance, the Swiss perceive success as getting lots of summer houses to have UDTs, whereas the Swedes do not see this as a goal since it has already been achieved in the past. For Sweden the next step is to move into urban areas, which is a more challenging step.

To understand why the Swiss evaluation was more positive than the Swedes, it is useful to take a look at the Swedish experience with urine recycling. In the early 1990s, Sweden was a pioneer in UD, driven only by the ecovillage movement. The UD wave was fueled by grassroots efforts without the involvement of local governments (Mats Johansson and Anna Richert, 2009). Thousands of UDTs were installed during that time primarily in ecovillages and summerhouses (McConville et al., 2017). Later on, UD expanded in ecovillages and urban settings, e.g., Understenshöjden eco-village, Palsternackan project, Norrköping building Ekoporten, the museum Universeum, Gebers residential areas and the conference center Bommersvik (Elisabeth Kvarnström, 2006). It is not our intention to discuss the history of UD in Sweden, as it has already been extensively discussed in several reports e.g. (Johansson, 2001). Due to a backlash in the end of the 1990s, UD did not achieve the anticipated upscaling at the turn of the 21st century (Mats Johansson and Anna Richert, 2009). This might explain why Swedes do not place a high priority on ecovillages and summer houses as they already had them a few decades ago; thus, they intend to expand into urban areas and test advanced technologies. In contrast to Sweden, Switzerland carried out an interdisciplinary project called Novaquantis from 2000 to 2006, where they referred to UD as NoMix technology (Judit Lienert, 2006). The project concluded that toilet technology had not yet matured sufficiently for large-scale implementation. It was therefore recommended that in order to achieve success, future installations in Switzerland must be carefully considered, and project objectives must be clearly defined (Larsen and Lienert, 2007). Taking a closer look at the Swiss experience, it is apparent that they were more organized and envisioned the future with greater clarity, and perhaps they learned a lot from the Swedish experience.

5.3. How to accelerate the diffusion and upscale of urine recycling – RQ3

Our dialogues with experts revealed that they place a great deal of emphasis on the need for dedicated users with a solid commitment to environmental protection in order to ensure the durability of the system. Although dedicated users are crucial, we believe service providers (e.g., municipalities, estate firms, etc) are the key actors who can influence users' perceptions of the entire system. Essentially, what we need is service providers, i.e., dedicated controllers, who are passionate about the system and are able to develop urine recycling systems that function adequately so that users will not be left wondering why they purchased this peculiar toilet before moving in. In order to get the diffusion of urine recycling ongoing, we need to move beyond enthusiasts (dedicated users), innovators, and niche markets into the mass market (ordinary people). A good example is the source separation system in Helsingborg (blackwater and greywater separation), which has been well received by users due to the quality of service provided by the service providers (Kärrman et al., 2017). Users don't even need to know the entire process behind the system as it mimics the ordinary sanitary system; thus, they do not have to alter their daily habits in order to adjust to the system and still benefit the environment.

In addition, we observed a pressing need for business value chains and solutions that are fair to businesses so that they are not obligated to bear the burden of protecting the environment on their own. We, therefore, need to find a way to profit and provide incentives and subsidies, whether it's through governments (tax incentives and production subsidies) or municipalities (reduced water bills) or producers who sell fertilizer at a premium and are willing to pay more to make a profit to sustain the business. Yara, for example, has begun producing green fertilizer based on renewable resources, and reports indicate that this non-fossil nitrogen fertilizer would be sold at a premium over synthetic fertilizers (Hasler et al., 2015; Tallaksen et al., 2015); experts estimated this premium to be two to three times greater. Thus, if urine fertilizer can be classified as non-fossil nitrogen fertilizer, this could perhaps lead to a premium over the return on the price which would be sufficient to sustain business operations. It is also necessary to establish a national goal for nutrient recovery from wastewater and urine. This will allow urine benefits to be integrated into school education, thereby raising public awareness of urine recycling. We can learn from the Swedish experience in recycling solid and food waste where children were taught in schools to source separate their waste, and children then taught their parents to do the same (Mahapatra et al., 2021; Mauborgne, 2022).

5.3.1. *Pathways and scenarios for scaling up urine recycling and reaching future perceptions*

To kick off urine recycling and increase its market share and reputation, actors need to work collectively. The direction of intervention needs to be a combination of a top-down and a bottom-up movement; what matters most is that all involved actors are equally motivated. Equally engaged and motivated actors are essential to developing a robust supply chain. The absence of government intervention (top-down movement) and reliance only on grass-roots initiatives (bottom-up movement) is a major reason why the current supply chain lags behind its potential - the Swedish experience during the 1990s is a relevant example (Mats Johansson and Anna Richert, 2009).

Fig. 4 below describes pathways for upscaling urine recycling systems based on the challenges identified in both TISs and future perception. Each icon within the pathway can serve as a starting point for a top-down and/or a bottom-up movement. The current systems require national recognition where the government issues a clear national goal for nutrient recovery. To achieve policy recognition and change, lobbying at all levels is essential, coupled with knowledge provision by universities and research institutions to key policymakers and decision-makers. Lobbying can be conducted by organized formal entities that gather representatives of the urine recycling actors and aim to influence policy makers to take actions regarding urine recycling. In Switzerland, VaLoo is a good example of such a lobbying entity. In order to gain traction and momentum for urine recycling, universities and research institutions also need to generate knowledge that gets the public's attention. Another way to increase public awareness is by incorporating urine recycling into the school curriculum. Increasing public awareness could lead to a bottom-up intervention that would positively influence the government to take action. Knowledge can also be in the form of pilot projects. Pilot projects have a significant impact on the success of urine recycling systems upscaling. It is, therefore, important that universities, building companies, UDT manufacturers, and startups collaborate together to create large pilot projects that demonstrate the potential of urine recycling systems to decision makers and the general public. Universities and private sector's research and development (R&D) can also benefit from these pilots. In addition, pilot projects can pave the way for large-scale implementations.

Lobbying and knowledge provision should also aim to make adjustment to the current regulatory framework and to make federal incentives and subsidies available to both the public and private sectors. The establishment of a clear and solid regulatory framework will also provide opportunities for the private sector to invest, as urine will be perceived as a promising sustainable alternative. By engaging the private sector, competition will increase, and different types of UDTs will be produced, resulting in lower prices and increased affordability. At present, there are only a few types of UDTs available on the market, which is why they are quite pricey, and end users are reluctant to purchase them. The involvement of private investors creates the foundations for markets and influences the engagement of governments through bottom-up intervention, especially when the demand for UDTs increases. Through this two-pronged intervention, the first segment of the supply chain (A-user interface) will be enhanced, both by reducing prices and providing different optimized options of UDTs to choose from.

Public and governmental interventions need to be coupled with municipal interventions. Municipalities can facilitate the installation of UDTs in public and governmental buildings. As the backbone of the supply chain, municipalities can also coordinate the collection, treatment, and transportation; this task can be subcontracted to private companies. This coordination will enhance the second and third segments of the supply chain (B- collection & C- conveyance). National and municipal support, including state incentives and subsidies, can be sufficient to motivate UDT manufacturers and building companies to install UDTs in newly built areas. Increasing market shares can also encourage more entrepreneurship and the development of new urine treatment startups which will enhance the fourth segment of the supply

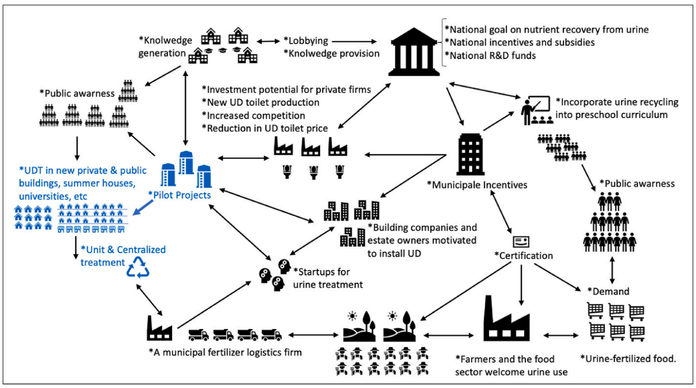

Fig. 4. Pathways on how urine recycling can be diffused. One direction arrow indicates a one-sided relationship, two directions arrow indicates a two-sided relationship. This illustration shows both bottom-up and up-bottom interventions and each icon can be a starting point. Pilot projects and scale implementations are highlighted in blue because of the referral in the conclusion. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

chain (D-treatment). As part of the urine treatment process, centralized treatment (e.g., nitrification technology) and unit treatment (e.g., dehydration technology) can be utilized. Users will be more likely to consider UDTs and accept moving into houses with UDTs when they see that the supply chain has been formed and responsibilities have been clearly defined.

In order to enhance the fifth segment of the supply chain (E−urine use), urine-based fertilizers must be monitored for quality and hygiene. As a method of controlling this, municipalities can mandate the acquisition of related certifications that demonstrate compliance with the standards. In Switzerland for example, urine fertilizer "Aurin" which is produced and marketed by Eawag-Spin-Off (VUNA Ltd) has been approved by the Federal Office for Agriculture in 2018 to be the first registered urine-based fertilizer (Vuna GmbH, 2023). Nevertheless, at present, there is no government certification in many countries including Sweden; in fact, the only EU fertilizer certification applicable to source-separated urine is SPC R178, yet it does not incorporate environmental benefits (European commission, 2019). In addition, it might soon be out of commission (in 2024) due to a lack of customers and relatively high operating costs. Accordingly, there is a need for a standardized certification framework for climate-efficient recirculated nitrogen fertilizers. In addition, it is essential to enact climate legislation that prompts the adoption of urine-based fertilizers by imposing tariffs and taxes on other fertilizer products that are more polluting (e.g., taxes on energy-intensive processes like N-fixation). Quality certification can influence the perception and demand for urine-based fertilizer and food by the general public, farmers, and the food industry. When the demand for urine-based products is high, farmers and the food industry become even more motivated and accepting. This can lead to the expansion of urine fertilizer production and increased demand for UDT installation, enhancing the sixth and seventh segments of the supply chain (F-application & G-food chain). These factors can also lead to government intervention on a bottom-up basis. In order to provide a profit source, urine fertilizer and food can be subsidized and sold at a premium as the case with organic food and the green fertilizer planned by Yara.

Lastly, Fig. 5 summarizes the results of the TIS analysis, including the identified challenges and barriers as well as policy recommendations. Note that there is a strong interplay between the functions, meaning that challenges/barriers may affect multiple functions simultaneously. As an example, a lack of investment has adversely affected several functions, such as market share, knowledge development, resource mobilization, and entrepreneurship.

6. Conclusion and recommendations

Although urine recycling offers prominent promise for food and fertilizer security and has been around since the early 1990s, the system has not yet been upscaled. In recent years, urine recycling research has increased; however, most attention has been on technical, engineering, and environmental aspects. Some studies have included the socio-technical dimension in their analyses, but none have examined why urine recycling systems haven't reached mainstream markets. In this study, we aim to fill this knowledge gap by identifying what barriers contribute to urine recycling systems falling behind. In addition to identifying potential barriers, the study offers upscaling pathways. Since Sweden and Switzerland have played a pioneering role in urine recycling research and have been at the forefront of technological advancement in recent years, we examined the status of urine recycling in these countries. This socio-technical analysis also serves as a reference point for countries interested in implementing urine recycling systems by drawing lessons from Swedish and Swiss experiences. We used the technological innovation system approach TIS to study the fundamental processes responsible for developing and diffusing urine recycling. Our study provides a methodological contribution to the innovation system domain by utilizing the Delphi method in conjunction with urine recycling experts to conduct the analysis anonymously to ensure transparency and prevent bias.

Our detailed analysis identified several blocking mechanisms (barriers) in both TISs. These barriers were attributed to major challenges urine recycling has encountered since its inception in the early 1990s, and while some of these challenges have been overcome, others remain. The challenges are summarized as: lack of technological advancements, knowledge, investment, and legal support. Our previous paper (Aliahmad et al., 2022) concluded that, despite strong publication growth, the knowledge function still lags behind in some criteria, including research innovation and technology diversification. Regarding the technical challenge, this study revealed that the UD technologies used in the 1990s and early 2000s were not mature, performed poorly, and were difficult to operate. Additionally, they experienced maintenance issues, such as acute scaling and blocked flushing. Modern UD technologies

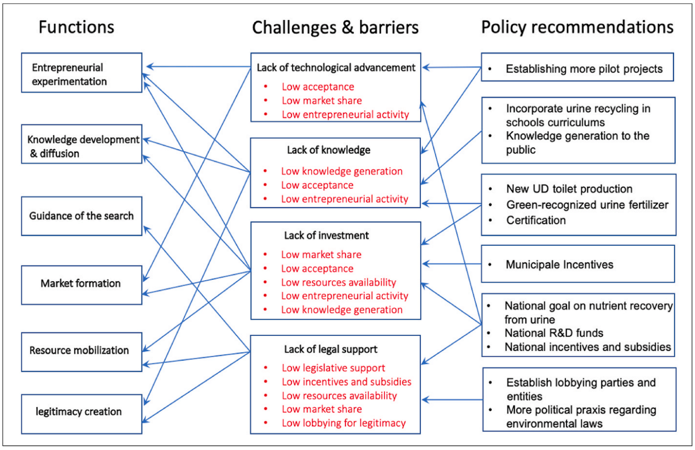

Fig. 5. Mapping challenges/barriers and potential policy recommendations for urine recycling TIS. The headings in the second column represent the challenges, whereas the red bullet points represent the barriers. These challenges/barriers are a result of the urine recycling TISs analysis conducted in Sweden and Switzerland. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

divert urine effectively and without maintenance issues, unlike their predecessors. Nevertheless, as a result of low demand and competitive conditions in the mass market, the cost of these systems remains high. The analysis also revealed that legal frameworks in both countries are quite ambiguous and vague, which hinders local authorities from taking action and discourages the private sector. Another major challenge facing the system is its lack of profit, in which costs are often borne by those who are not obligated to engage in this activity, and as the economic climate deteriorates, they are unable to finance such projects and lose interest.

To overcome the current challenges and increase the market share and reputation of urine recycling, actors need to work collectively. There needs to be a combination of top-down and bottom-up movements. Grass-roots initiatives (bottom-up movement) alone will not scale up urine recycling systems - the Swedish experience during the 1990s offers a relevant case study where top-down movement was absent, and the supply chain lags behind. There is also a need for lobbying and knowledge provision to adjust the regulatory framework, thus prompting the provision of incentives and subsidies for the public and private sectors. In addition to incentives and subsidies, we need to create a source of profit for those involved in the TIS, for instance, recognizing urine fertilizer as a green fertilizer based on renewable resources so that it can be sold at a premium. The TIS also needs dedicated service providers who are passionate about the system and can develop urine recycling systems that function adequately for users.

Pilot projects were found to play a significant role in the upscaling of urine recycling systems. Therefore, universities, building firms, UDT manufacturers, and startups for urine treatment need to collaborate to build large pilot projects to demonstrate that the system works in practice. Demonstration projects also serve as a means of bringing different actors together, allowing resources to be allocated and common visions to be reached, facilitating urine recycling diffusion. Besides demonstrating the technical performance, the demonstration should also showcase the system's environmental performance. Thus, further research must be conducted regarding the environmental performance of pilot projects and large-scale implementations (colored blue in Fig. 4). For example, at what scale of implementation does urine recycling provide the most optimal environmental performance? Decision-makers and the general public would also benefit from understanding the environmental impact of the different system scales. Additionally, economic benefits play a major role in the diffusion of urine recycling; thus, a study that examines the system's economic performance is necessary, especially for potential users. Although the scope of this study included the supply chain and attempted to narrow down the barriers to one segment of the supply chain, it did not specify how the actors should make decisions or take action to reach the objectives. Accordingly, we recommend conducting a study to investigate the structure and dynamics of urine recycling systems throughout the supply chain and how actors and decision-makers can be motivated to begin implementing the proposed pathways.

CRediT authorship contribution statement

Abdulhamid Aliahmad: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Wisdom Kanda:** Conceptualization, Methodology, Writing – review & editing. **Jennifer McConville:** Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jennifer McConville reports financial support was provided by Swedish Research Council Formas. Jennifer McConville reports financial support was provided by Stiftelsen Lantbruksforskning.

Data availability

Data will be made available on request.

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Appendics.

Appendix A

Table A. 1
Interpretation of indicators evaluation results. Bold colors indicate more voting, for example in the first raw, the color indicates that all votes were cast in the low category, but in the second raw, it indicates that the majority of votes were cast

Evaluation results	Evaluation scale		
All low = a barrier	Low	Medium	High
Low - medium = a barrier	Low	Medium	High
Low - medium = a barrier	Low	Medium	High
All medium = lagging require changes	Low	Medium	High
All high = performing well	Low	Medium	High
Medium - high = performing well	Low	Medium	High
Medium - high = performing well	Low	Medium	High

Table A. 2
Swiss indicators evaluations before and after the workshop. * This indicator was re-evaluated after the workshop and new ratings are 7- 3–0. The gray coloring in both columns is to facilitate the reading of non-zero ratings before and after the workshop.

Indicator for Switzerland TIS	Before workshop			After workshop		
	Low	Medium	High	Low	Medium	High
The diversity level of actors involved in the urine recycling system	3	4	0	0	7	3
The level of engagement of the actors within the urine recycling system	1	3	3	0	2	7
The experimentation (lab-scale) rate in the urine recycling system	0	5	2	0	6	4
The engagement level of the actors in knowledge generation	2	3	3	0	3	6
The availability of: National strategy enabling nutrient recovery from WW	4	3	0	10	0	0
The availability level of: National policy / incentives enabling urine recycling	6	1	0	9	1	0
The availability level of clear vision of source separation in the sanitation system	4	3	0	9	1	0
The current number of urine diversion toilets in Switzerland	6	0	1	9	1	0
The number of pilots of urine recycling around Switzerland	5	1	1	6	4	0
The price that home owners in need to pay for urine diversion installation	0	3	4	0	4	6
The service fees that home owners in need to pay for urine recycling	1	2	4	0	0	10
The attitudes of the agricultural sector toward the use of urine-based fertilizer	3	4	0	3	7	0
The availability level of human resources in the urine recycling system*	3	1	3	5	3	2
The availability level of infrastructure for the installation of urine recycling	0	5	2	0	4	6
The level of lobbying activities against urine recycling	3	3	1	9	1	0
The level of lobbying to legitimize & support urine recycling " alliances "	1	5	1	0	9	1
The level of willingness of conventional systems to adopt urine recycling	4	2	1	10	0	0
The level of acceptance by the users regarding urine diversion toilets	0	6	1	0	4	6

Table A. 3
Swedish indicators evaluations before and after the workshop. The gray coloring in both columns is to facilitate the reading of non-zero ratings before and after the workshop.

Indicator Sweden	Before workshop			After workshop		
	Low	Medium	High	Low	Medium	High
The diversity level of actors involved in the urine recycling system	7	5	1	8	5	0
The level of engagement of the actors within the urine recycling system	8	5	0	0	11	2
The experimentation (lab-scale) rate in the urine recycling system	12	3	0	12	1	0
The engagement level of the actors in knowledge generation	10	5	1	12	1	0
The availability of: National strategy enabling nutrient recovery from WW	9	3	1	13	0	0
The availability level of: National policy / incentives enabling urine recycling	13	0	0	13	0	0
The availability level of clear vision of source separation in the sanitation system	10	2	1	11	2	0
The current number of urine diversion toilets in Sweden	10	2	1	13	0	0
The number of pilots of urine recycling around Sweden	11	1	1	13	0	0
The price that home owners in need to pay for urine diversion installation	1	8	4	0	3	10
The service fees that home owners in need to pay for urine recycling	2	5	6	0	2	11
The attitudes of the agricultural sector toward the use of urine-based fertilizer	2	10	1	0	13	0
The availability level of human resources in the urine recycling system	6	5	2	11	2	0
The availability level of infrastructure for the installation of urine recycling	8	4	1	13	0	0
The level of lobbying activities against urine recycling	11	2	0	9	4	0
The level of lobbying to legitimize & support urine recycling " alliances "	3	7	3	8	5	0
The level of willingness of conventional systems to adopt urine recycling	7	6	0	9	4	0
The level of acceptance by the users regarding urine diversion toilets	4	7	2	0	12	1

Appendix B

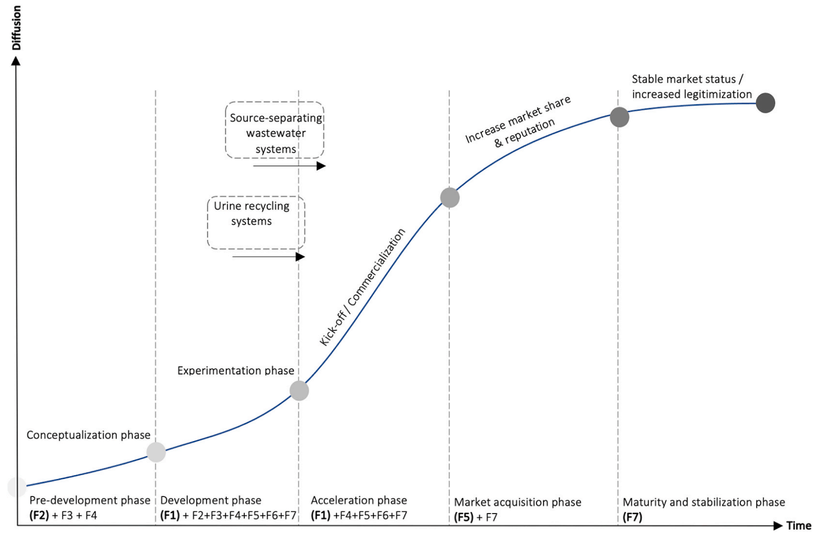

Fig. B. 1. TIS's development stages during its lifecycle with their corresponding functions. Primary functions in each development phase are highlighted with bold fonts.

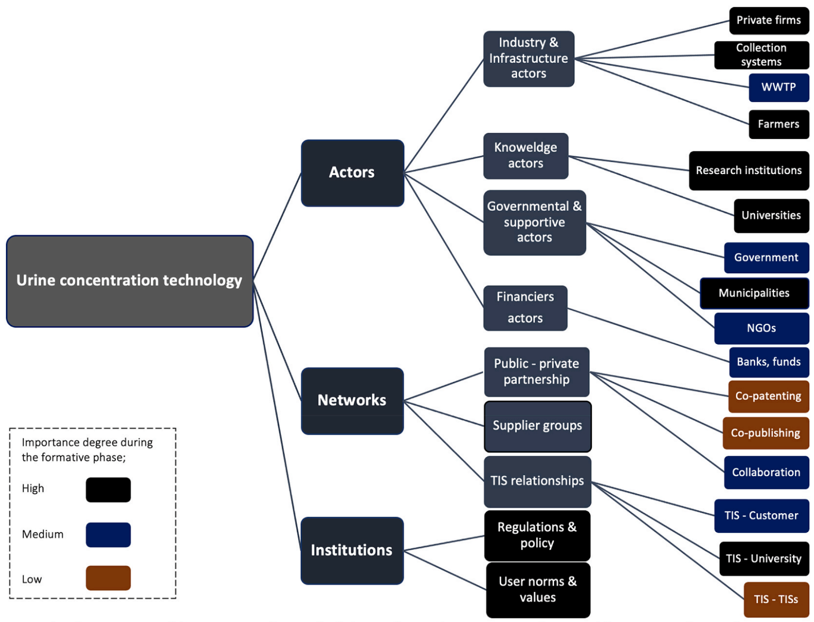

Fig. B. 2. The structure of the urine recycling TIS. Colors indicate the importance degree of these actors during the developed stage.

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IV

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Article

Comparative Environmental Assessment of Three Urine Recycling Scenarios: Influence of Treatment Configurations and Life Cycle Modeling Approaches

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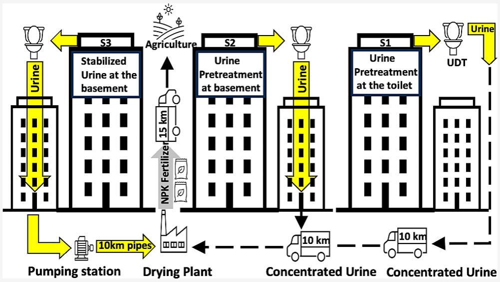

ABSTRACT: Urine recycling is an emerging promising approach for enhancing resource recovery and mitigating environmental impacts in sanitation systems. This study presents a comparative life cycle assessment (LCA) of a urine dehydration system implemented at three levels of decentralization: (i) toilet-level units within bathrooms; (ii) basement-level units serving multiple households; and (iii) centralized neighborhood-scale facilities using dedicated sewers for off-site processing. Each configuration is assessed using both consequential and attributional system models across five impact categories: global warming potential, acidification, freshwater and marine eutrophication, and cumulative energy demand. The basement-level system consistently shows the lowest impacts, with up to 50% lower global warming potential than the other configurations. Centralized treatment is the most energy-efficient per liter of urine treated, but the sewer infrastructure burden offsets this advantage. Sensitivity analysis shows that substituting sulfuric acid for citric acid and achieving >52% heat recovery can yield net-negative emissions at the basement level. The choice of the LCA system model strongly affects results: attributional with substitution yields net-negative impacts, whereas consequential provides more conservative but robust estimates. The findings underscore the need for methodological transparency in LCA and provide guidance for scaling sustainable decentralized urine recycling.

KEYWORDS: *life cycle assessment, eco technology, urine recycling, resource recovery, source separation*

1. INTRODUCTION

Urine recycling is increasingly recognized as a strategy for supporting the transition toward more circular and sustainable sanitation systems.[1] Conventional sanitation systems focus on end-of-the-pipe solutions, prioritizing pollution control over resource recovery and upstream solutions.[2] Although some modern wastewater treatment plants (WWTPs) have begun to integrate resource recovery (e.g., phosphorus and energy), they are still limited and overlook valuable nutrients like nitrogen and potassium.[3] Their effluents frequently contain some of these nutrients, which can contribute to ecological issues, such as eutrophication, when discharged into nearby aquatic ecosystems.[4] Urine stands out because it makes up only a small portion of domestic wastewater, yet it contains most of the nutrients found in wastewater.[5] Hence, source-separated urine presents a unique opportunity for nutrient recovery, specifically producing urine-based fertilizers that can serve as a substitute for synthetic fertilizers, thereby mitigating the environmental burden associated with both fertilizer production and conventional wastewater treatment. Additionally, this approach promotes a circular economy in nutrient management, enhancing sustainability in agricultural practices.[6,7]

In recent years, several innovative technologies for urine recycling have emerged.[8] These technologies enhance urine recycling practices beyond traditional urine storage methods, which encountered many logistical challenges, such as difficulties in transporting high volumes of urine and storing it at collection sites and farms.[9] The new urine recycling technologies apply alternative and advanced treatment processes that can effectively reduce volume while generating fertilizers with a higher nutrient content and reduced levels of contaminants. For instance, nitrification-distillation technologies yield concentrated urine-based liquid fertilizers,[10] whereas dehydration technologies produce solid urine-based fertilizers.[11] Solid urine-based fertilizers are particularly well suited for pelletization and can be readily integrated into agricultural

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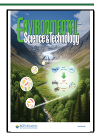

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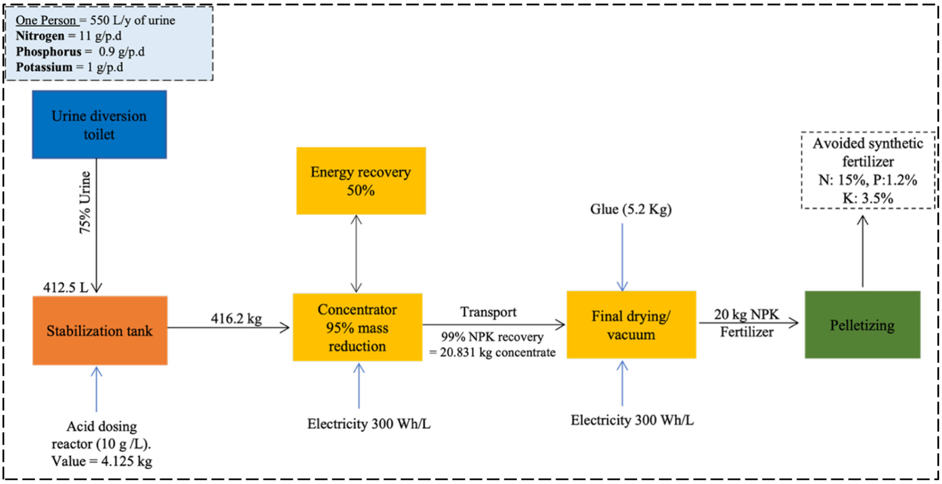

Figure 1. Schematic diagram of the primary unit process of the urine recycling system scenario (1) Energy recovery is achieved through heat recovery using a heat exchanger, which differs between the three scenarios. Each unit process is represented by a distinct color, which is used consistently throughout the study to facilitate comparison, particularly in the results.

systems that rely on existing machinery and large-scale farming practices. Consequently, they offer a highly viable solution for industrialized farming, allowing farmers to retain their current machinery and habits. Simha[12] asserts that a solid urine fertilizer requires only 900 kg per hectare, compared to 15,000 kg of unconcentrated urine, assuming cereal crops need 90 kg N ha^{-1} and dried urine contains 10% N.

Several life cycle assessments (LCAs) have evaluated the environmental performance of urine recycling systems in comparison to conventional wastewater treatment systems. The environmental benefits of the direct application of stored urine have been assessed and shown in multiple studies.[13−16] Decentralized urine diversion systems at the university scale have demonstrated environmental advantages in phosphorus recovery through struvite and potential pharmaceutical removal.[17,18] Building-scale and centralized pretreatment using struvite precipitation and microbial electrolysis cells (MEC) showed significant reductions in environmental impacts, along with high phosphorus and ammonia recovery efficiency.[19] The city-scale modeling of centralized urine treatment using struvite precipitation and ion exchange also indicated substantial reductions in greenhouse gas emissions, eutrophication, and water use.[20] Centralized blackwater and urine systems incorporating struvite precipitation and trans-membrane chemisorption (TMCS) outperformed conventional treatment in multiple environmental impact categories.[21] Most recently, hybrid systems combining decentralized urine dehydration with blackwater management have been shown to outperform centralized treatment plants and other source separation systems due to their enhanced nutrient recovery and potential for fertilizer substitution.[22] Collectively, this literature demonstrates the potential of urine recycling to mitigate the environmental burdens associated with conventional WWTPs, particularly through avoided nutrient removal processes, reduced methane and nitrous oxide emissions, and synthetic fertilizer substitution.

Despite these advances, two key gaps remain. First, little is known about how different urine treatment configurations and treatment locations, whether at the toilet, in the basement of a multistory building, or in a centralized neighborhood-scale facility, affect the environmental performance. Treatment location influences collection logistics, energy demand, emissions, and scalability, yet these context-specific trade-offs have not been systematically compared to guide decision-making and support technology scale-up. For instance, toilet-level treatment reduces the need for piping and is suitable for retrofitting older buildings[12] but may require more energy and frequent maintenance.[23,24] Basement-level treatment can process larger volumes and is generally more energy-efficient.[22] Centralized treatment may offer the highest energy efficiency per unit of urine treated; however, it involves transporting urine through the sewer infrastructure, which introduces complexity and burdens that are often underrepresented in earlier LCAs.[25,26] Second, few studies have critically examined how methodological choices in LCA—particularly the use of attributional versus consequential approaches—affect the interpretation of results for emerging sanitation technologies. These approaches are designed to answer different types of questions,[27] and the choice between them significantly influences which inputs and system boundaries are included in the analysis.[28,29] Aligning the LCA model with the study's objectives is, therefore, essential for producing credible, transparent, and policy-relevant results. Inconsistencies in methodological choices across studies hinder meaningful comparison and limit the usefulness of LCA for guiding decision-making.

This study addresses both gaps by applying LCA to compare urine dehydration systems implemented at three treatment locations (toilet, basement, and centralized facility). It further contrasts attributional cutoff and consequential system models to evaluate how methodological choices influence results and their interpretation for decision-making. Specifically, the study asks: (1) how does treatment location impact the environ-

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mental performance of urine recycling systems? (2) which configuration, if any, achieves net-negative impacts across all assessed impact categories? and (3) how do attributional cutoff versus consequential models alter the interpretation of results and conclusions drawn for decision-makers? By integrating technological and methodological perspectives, this study provides actionable insights for the sanitation system design, LCA practice, and a broader transition toward sustainable nutrient management.

2. MATERIALS AND METHODS

2.1. Study Scenarios. This LCA aims to evaluate the environmental performance of a urine recycling system under different treatment locations and modeling approaches. The case study focuses on five newly constructed residential buildings in a Swedish city, each comprising 10 apartments with an average of 2.5 capita per apartment, resulting in a total of 50 apartments and 125 capita. Three distinct urine recycling scenarios are analyzed based on the treatment location: the toilet, the basement, and a centralized treatment station. Each scenario is examined using two modeling approaches, consequential and attributional cutoff models, which are discussed in Section 2.2. The three urine recycling scenarios share several unit processes but exhibit distinct differences, particularly in urine collection, concentration, and transportation to the final drying facility. Figure 1 illustrates the unit processes involved in the three urine recycling scenarios.

Initially, urine is separately collected using a urine diversion toilet and subsequently stabilized by adding 10 g of citric acid per liter of urine to prevent enzymatic urea hydrolysis.[30] The stabilized urine undergoes a concentration process that aims at reducing its volume through dehydration. This process varies slightly based on the scale and location of the treatment system. In a toilet-level configuration, the concentration is achieved via convective evaporation, where warm air (~50 °C) is circulated over the stabilized urine using a fan and pump system. This method is compact and well suited for installation in bathrooms, as it does not require pressurized or complex equipment. It effectively removes over 90% of the water and has been validated in previous field studies (e.g., Simha[12]). In basement and centralized configurations, the bulk of the water is removed through distillation during the concentration step. This approach proves to be more energy-efficient for larger volumes and allows for the direct integration of heat exchangers for energy recovery. Once the urine is sufficiently concentrated, it is transferred to vacuum evaporation for final drying. This step is conducted under reduced pressure to lower the boiling point and preserve the nitrogen content. At this stage, organic binders are also introduced to facilitate pellet formation and to enhance product handling. Consequently, a second distillation step is not viable as the presence of these added materials alters the physical characteristics of the concentrate, making low-pressure drying a more suitable option. The dehydrated urine product generated in all three scenarios is a stable solid fertilizer containing approximately 15% N, 1.2% P, and 3.5% K (Figure 1), with ~99% nutrient recovery from the collected urine. The stabilization process prevents urea hydrolysis, ensuring that no significant nutrient losses occur during the concentration, storage, or drying. Similar urine-derived fertilizers produced via this method have been successfully field-tested in Sweden and other countries, showing agronomic performances comparable to conventional mineral fertilizers when applied on an NPK-equivalent basis.[12] Therefore, this LCA models the urine-based fertilizer as a complete substitute for synthetic fertilizers on a nutrient-equivalent basis. Readers are encouraged to review our previous LCA study for a more comprehensive understanding of the different unit processes and mechanisms involved.[22]

The first scenario, decentralized household treatment (S1—toilet-level), is illustrated in Figure S2 in the Supporting Information. In this scenario, urine is collected directly from the toilet, where it is generated, with the concentration unit installed within the same bathroom. This design allows for a direct connection from the urine-diverting toilet to the treatment unit via a short pipe. Urine is stabilized and concentrated daily, and the concentrate is stored within the unit for two months before being transported to the final drying facility. The unit is designed to accommodate urine output from a single apartment, factoring in routine inflow and allowing for a buffer volume to prevent overflow during periods of high use or unexpected inflow. Each capita produces 1.13 L of urine per day or about 550 L/year. With a capture rate of 75%,[31] this results in 413 L collected per capita per year. The concentration process achieves a 95% mass reduction, yielding about 21 kg of concentrate per capita annually. Transport occurs six times per year (once every two months), with each trip covering a 20 km round trip to the drying facility, totaling 411 kg km per capita per year; see Table S12 in the Supporting Information. Once dried, 20 kg of the urine-derived fertilizer is delivered to a local farm to substitute for synthetic fertilizers. The energy requirement for the urine concentration process is 600 W-hours per liter (Wh/L). Each urine recycling scenario in this LCA incorporates heat recovery, which recovers a portion of the thermal energy and reuses it within the system. In the toilet scenario, to reduce electricity demand, heat recovery ventilation (HRV) is assumed, which is consistent with Swedish residential systems. These systems recover thermal energy from exhaust air and typically use it for space heating. Here, a portion of that recovered heat is assumed to prewarm the air entering the urine concentration unit (to ~30−35 °C), reducing the electricity required to reach the target operating temperature (~50 °C). The urine itself is not directly heated. A 50% heat recovery efficiency is assumed based on the typical HRV performance.[32] This reduces the electricity demand for the concentration unit process from 600 to 300 Wh/L of raw urine. The drying process, which occurs separately at a centralized facility, is also modeled to demand 300 Wh/L of concentrated urine.

The second scenario, semicentralized treatment (S2—basement-level), is similar to the one examined by Aliahmad et al.[22] As illustrated in Figure S6 in the Supporting Information, urine is collected, stabilized, and concentrated in the basement of each building. Similar to the first scenario, the urine concentrate is stored onsite before being transported to the final drying facility. The basement contains a 1 m^3 tank, which takes approximately 142 days to fill at an estimated inflow of 0.007 m^3/day of concentrate, resulting in about 2.6 tank emptyings per year. Each transport trip covers a 20 km round trip to the drying facility, with each trip moving around 20,200 kg km; the total transport amounts to 416 kg km per capita per year, comparable to S1. Once dried and pelletized, the urine-derived fertilizer is delivered to a local farm to replace synthetic fertilizers, as in the other two scenarios. Mass balance calculations are detailed in Table S13 of the Supporting Information. This scenario differs from the first primarily in its urine collection system, requiring more extensive piping to transport urine from individual toilets to the basement-level treatment unit. The concentration unit process in this configuration is modeled as vacuum distillation, with energy recovery via integrated heat exchangers. This mechanism provides internal heat exchange loops that recover energy from outgoing vapor to preheat incoming urine. At this intermediate scale, we assume a thermal recovery efficiency of 60−70% based on the practical performance of air-to-air heat exchangers and small-scale heat pumps commonly used in residential applications. This assumption aligns with findings from domestic wastewater heat recovery studies, such as Wehbi et al.,[33] which report typical recovery rates in the range of 50−60%. Consequently, each of the unit processes, the concentration process and the final drying process, requires 200 Wh/L of urine.

In contrast to the other two scenarios, the third scenario, centralized treatment (S3—centralized-level), is entirely centralized and does not involve any concentration within the buildings but requires acidification for urine stabilization. As illustrated in Figure S10 in the Supporting Information, urine is collected and stabilized in the basement, similar to the second scenario; however, rather than being concentrated on site, it is transported via a sewer network over a distance of 10 km (the same distance assumed in the other scenarios) to a centralized facility, where it undergoes concentration, drying, and pelletization. This approach requires additional piping from the basement to a pumping station, followed by conveyance through the sewer network to the treatment facility. In terms of energy requirements, this scenario is the most energy-efficient, with the potential to recover up to 85% of the thermal energy. As in the basement configuration, the centralized concentration is also modeled as vacuum distillation with a full mechanical vapor recompression, enabling more efficient reuse of latent heat. To parametrize the energy demand and recovery efficiency, we refer to vendor data from KLC Cleanwater GmbH (2021)[34] as an illustrative example of commercially available evaporator systems. These systems maximize heat reuse by compressing and recycling vapor, significantly reducing the demand for an external energy input.[35] We do not assume the use of any specific proprietary unit but use these data to reflect plausible energy recovery levels in high-efficiency thermal concentration technologies. Based on KLC's published specifications, up to 85% energy recovery is achievable; we adopt this figure to represent a best-case scenario, yielding a net electricity demand of 90 Wh/L of urine for each of the unit processes, the concentration process, and the final drying process.

While the final drying facility is the same across all scenarios, the net electricity required per liter of urine differs due to variations in the moisture content and thermal characteristics of the incoming concentrate, which are determined by the upstream concentration method.[12,36] In S1 (toilet-level), the decentralized convective evaporation system has a lower dehydration efficiency, resulting in a wetter concentrate being transported to the centralized drying facility. This requires more energy for the final drying. In contrast, S2 (basement-level) uses a semicentralized distillation system with an integrated heat exchange, producing a more concentrated and drier product, which reduces the energy needed during the final drying step. In S3 (centralized-level), both the concentration and drying occur within an integrated vacuum evaporator using mechanical vapor recompression. This system recovers latent heat and operates as a continuous energy-optimized process. Based on vendor data (KLC Cleanwater GmbH, 2021), we assume up to 85% energy recovery, resulting in the lowest electricity demand. Therefore, although the same drying facility is used, the net electricity demand per liter of treated urine at the drying stage varies: 300 Wh/L in S1, 200 Wh/L in S2, and 90 Wh/L in S3, reflecting differences in the upstream moisture content and energy recovery.

2.2. Life Cycle Assessment Framework.

2.2.1. Goal and Scope Definition. This study adheres to the standardized life cycle assessment (LCA) methodology outlined in the ISO 14040/14044 framework. This methodology is designed to evaluate and quantify the potential environmental impact of a product or service throughout its entire lifecycle, encompassing raw material extraction, production, use, and end-of-life disposal, across various impact categories.

The primary objective of this LCA is to compare the environmental performance of three different urine recycling scenarios outlined in Section 2.1. The results aim to inform decision-makers, urban planners, and sanitation engineers about the trade-offs associated with decentralized, semi-centralized, and centralized approaches to urine recycling. This information supports evidence-based planning for sustainable wastewater management in urban contexts. Using a consistent mass balance and a clearly defined functional unit (the treatment of one person's annual urine excretion), this LCA examines whether the treatment location affects environmental impacts and identifies which configuration offers the most sustainable option for urine recycling and nutrient recovery. To ensure comparability across scenarios, fixed thermal energy recovery rates were applied based on the design of each configuration. Specifically, we assumed energy recovery rates of 50% for the toilet-level (S1), 60−70% for the basement-level (S2), and 85% for centralized treatment (S3). These values were used to estimate the net energy demand for the urine concentration and drying in each scenario. However, the modeling does not account for how energy demand varies with the treatment scale within a given configuration. Literature and vendor data (e.g., KLC Cleanwater GmbH[34]) suggest that the energy demand for distillation decreases with increasing throughput, particularly up to ∼500 L/h (∼10,600 PE/day), beyond which additional gains are marginal. As a result, the centralized scenario may be even more energy-efficient at larger scales than our assessment reflects.

Two primary LCA approaches exist: attributional (ALCA) and consequential (CLCA). Each serves a distinct purpose and is designed to answer different types of questions regarding the environmental performance of products or services. ALCA functions as an environmental accounting tool, estimating the share of the global environmental burden attributable to a specific product, i.e., how much of the global footprint can be assigned to the product under study. It assumes that the sum of environmental burdens from all final consumption activities equals the total anthropogenic impact.[27,37] In the case of multifunctionality, where multiple valuable coproducts are produced, ALCA applies allocation methods to partition the impacts among outputs based on predefined criteria.[38] CLCA, on the other hand, evaluates changes in the global environmental impact caused by decisions or interventions. It considers indirect market effects and system-wide consequences, i.e., how the global footprint is affected by the production and utilization of a product.[27,39] In cases of coproduction, CLCA avoids allocation by assigning all impacts to the primary

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product and accounting for the avoided burden of the substituted coproducts.[29,40] Despite the broader system perspective of CLCA, most published LCA studies still favor the attributional approach, with reviews indicating that 94% of examined papers adopted this method.[41] The debate over the choice between ALCA and CLCA remains among the most prominent in the LCA community, particularly in relation to multifunctionality and the implications for decision-making.[42] A key methodological distinction is that ALCA (cutoff system model) typically relies on average data, while CLCA utilizes marginal data to reflect system-level changes.[43] This LCA study adopts a consequential approach, as the substitution of synthetic fertilizers with urine-derived alternatives aligns with the CLCA framework. However, this study also has a secondary objective: to investigate how the choice of modeling approach, consequential versus cutoff system models, impacts the study's results, conclusions, and their interpretation for decision-makers.

The three scenarios examined in this study maintain consistent system boundaries in terms of which unit processes are included or excluded. While some of these processes are shared across scenarios, others are unique to individual scenarios; e.g., the sewer network is present only in the centralized scenario (S3). In general, the system boundary begins with the collection of urine, either through direct transport from the urine-diverting toilet to the treatment unit or via a pumping system through the sewer network. The urine then undergoes stabilization, concentration, final drying, and pelletization to produce a solid urine-based fertilizer, which is assumed to replace conventional synthetic fertilizers. It should be noted that the potential impacts on the downstream wastewater treatment plant, such as reduced hydraulic or nutrient load due to urine diversion, are not taken into account in this study.

2.2.2. Life Cycle Inventory. The life cycle inventory (LCI) structure is based on the mapping material, energy, and emission flows within the system. The boundary conditions for each scenario were established through round table discussions involving coauthors and developers of urine recycling systems. Utilizing these established parameters, we developed the corresponding LCI, which encompasses a wide array of processes for each scenario and features a mass balance that assesses the inputs and outputs for each unit process. This includes collection systems (such as piping), sewer infrastructure (including piping, excavation, and backfilling), and operation of the treatment unit (covering chemical and energy consumption). Additionally, the LCI models the production of urine-based fertilizers and the replacement of synthetic fertilizers. The material used for the system's construction has not been accounted for due to a lack of data on some scenarios. The Ecoinvent v3.8 consequential database (marginal inputs) was used for the foreground and background systems. It should be noted that while the Ecoinvent consequential model identifies marginal suppliers consistently across sectors, its precision varies. Marginal mixes for electricity are based on dispatch modeling and long-term projections, whereas for many materials (e.g., polypropylene pipes, gravel, steel) and transport services, the marginal suppliers are determined from broader market assumptions. These assumptions may not fully capture national- or sector-specific dynamics and thus introduce a greater uncertainty for infrastructure components than for energy use. Detailed procedures for establishing the LCIs are provided in the Supporting Information, and information regarding the composition of the marginal electricity and fertilizer market is found in Section 1.5 of the Supporting Information.

The urine dehydration technology assessed in this work has been demonstrated at a pilot scale and has shown proof of concept and feasibility under controlled conditions.[12,24] Scaling up to centralized systems with energy recovery remains conceptual, relying on performance extrapolations from smaller scale data. Accordingly, our energy and mass balance assumptions are based on a combination of experimental pilot data and engineering-scale modeling.

2.2.3. Life Cycle Impact Assessment. Our assessment used the ReCiPe 2016 method, explicitly utilizing the Midpoint version alongside Simapro software for modeling. We selected four impact categories that were considered most significant for our analysis; the rest of the impact categories are shown in Table S14 in the Supporting Information. These categories include global warming potential (GWP) expressed in kg CO_2-equivalent, acidification in kg SO_2-equivalent, freshwater eutrophication in kg P-equivalent, and marine eutrophication in kg N-equivalent. In addition to these environmental indicators, we applied the cumulative energy demand (CED) method to quantify the total primary energy consumed across the life cycle of the urine recycling system, reported in megajoules (MJ). This method estimates the total amount of primary energy, both renewable and nonrenewable, required to deliver the system's function. It includes direct energy use (e.g., electricity for urine evaporation) as well as indirect energy inputs (e.g., energy used to manufacture equipment or transport materials). While CED does not reflect the environmental impact on its own, it serves as a complementary indicator by capturing the overall energy intensity of each recycling system. This is particularly valuable for comparing the resource efficiency of different treatment configurations.

2.2.4. Sensitivity Analysis. Sensitivity analysis is a crucial method used in LCA studies to evaluate the robustness of the results. The results of these analyses provide insights into how variations in key parameters can influence not only the overall environmental assessment but also the conclusions drawn and their interpretations for stakeholders. Our previous study, Aliahmad et al.,[22] identified several parameters within the urine recycling system that influenced the environmental impact. For instance, assuming 5% NH_3 emission from the urine concentrator instead of no emissions leads to a significant increase in the acidification potential. Similarly, substituting sulfuric acid for citric acid as the stabilizing agent nearly halved the GWP. Another key finding was that applying 600 Wh/L of urine for the concentration without energy recovery increased GWP by almost 50%. Because these parameters are integral to unit processes that are common across all three treatment scenarios in this study, we assume the trends remain consistent and do not retest them here.

Instead, this LCA focuses on new sensitivity parameters specific to this study as well as one additional energy-related parameter for broader applicability. The first set of analyses evaluates the impact of the location of the final drying facility, which is assumed to be 10 km from the buildings in the baseline scenario. In particular, we examine how variations in the sewer network length affect the environmental performance of the centralized scenario (S3), identifying thresholds beyond which this configuration may become environmentally unsustainable. We also assess whether relocating the drying facility influences the decentralized (S1) and semicentralized

Table 1. Characterized Life Cycle Assessment Results for Three Urine Recycling Scenarios with Different Treatment Locations, Calculated Using the ReCiPe Method (ReCiPe-LCA)[a]

impact category	unit	toilet (S1)	basement (S2)	centralized (S3)
global warming	kg CO_2 eq/capita y	17	8	16
acidification	kg SO_2 eq/capita y	6.7×10^{-2}	5.0×10^{-2}	8.0×10^{-2}
eutrophication (P)	kg P eq/capita y	1.9×10^{-3}	1.0×10^{-3}	5.1×10^{-3}
eutrophication (N)	kg N eq/capita y	3.0×10^{-3}	3.0×10^{-3}	3.2×10^{-3}

[a]Results are reported per capita per year (capita y). All scenarios include synthetic fertilizer substitution benefits, which are integrated into the net impact values shown.

(S2) scenarios by reducing the transport distance for the urine concentrate. Although sulfuric acid was previously shown to reduce GWP, a second sensitivity analysis will explore what combination of configuration adjustments (including stabilizing chemical choice and treatment location) could result in net-negative impacts across all assessed impact categories. Finally, to examine the influence of regional energy supply characteristics, we replaced the Swedish marginal electricity mix (baseline) with the EU marginal mix. This allows the assessment of result robustness in regions with a higher average grid carbon intensity. These sensitivity analyses help identify how changes in the infrastructure, chemical use, and electricity supply affect the three treatment configurations and whether they alter the comparative ranking.

3. RESULTS AND DISCUSSION

3.1. Environmental Impact of Different Treatment Locations. The primary research question that this study aimed to address is how the location of urine treatment affects the environmental performance of urine recycling systems. The net characterized results using the consequential system model shown in Table 1 indicate that the basement-level scenario has the most favorable environmental performance across all investigated impact categories, outperforming both the toilet-level and centralized treatment configurations. Notably, the basement scenario has a Global Warming Potential (GWP) of 8 kg CO_2-eq/capita y, which is approximately half the GWP of the other two scenarios. For a more straightforward interpretation, Figure 2 illustrates the contributions of individual unit processes to the overall impact in each scenario. It is important to note that some unit processes are unique to specific configurations; for example, the sewer network is present only in the centralized scenario. The figure also highlights the net environmental savings (negative emissions) from substituting the synthetic fertilizer with a urine-derived fertilizer, which are not explicitly detailed in Table 1, as they are integrated into the net results shown. All three scenarios are assumed to recover an equal quantity of nutrients and, therefore, yield identical climate benefits from fertilizer substitution, contributing −26 kg CO_2-eq/capita y to the net GWP in each case.

3.2. Environmental Hotspots across the Three Scenarios. *3.2.1. Decentralized Household Treatment (S1—Toilet-Level).* The first scenario (S1—toilet-level) exhibited the highest GWP among the three configurations, with a net impact of 17 kg of CO_2-eq/capita y. The primary hotspot in this scenario is the urine concentration unit process, which accounts for 24 kg of CO_2-eq/capita y. The second major contributor is urine stabilization, with a GWP of 16 kg of CO_2-eq/capita y, largely due to the use of citric acid. Because the same amount of citric acid is applied per liter of urine in all three scenarios, the stabilization-related GWP remains consistent across them. Other unit processes, including urine collection, dehydration, and pelletization, contribute minimally, with respective values of 0.64, 1.7, and 0.05 kg CO_2-eq/capita y. The transport of the urine concentrate (411 kg km/capita y) contributes 0.22 kg CO_2-eq/capita y to GWP, which is small compared to the concentration and stabilization processes. Results across other impact categories, including acidification and eutrophication, show similarly higher values compared with the basement scenario. These are primarily attributed to the higher energy consumption associated with toilet-level treatment. A detailed breakdown of environmental contributions by unit processes is provided in Figure S12 in the Supporting Information.

3.2.2. Semicentralized Treatment (S2—Basement-Level System). The second scenario (S2—basement-level) results in a GWP of 8.0 kg CO_2-CO_2-equivalent/capita y, which is 53% lower than the toilet-level scenario. This reduction primarily arises from the decreased energy consumption in the concentration unit process, which consumes approximately 83 kWh/capita y and contributes 16 kg CO_2-equivalent/capita y, a 32% reduction compared to S1. The second largest contributor to GWP is the urine stabilization unit process, which, as in the other scenarios, relies on citric acid dosing and contributes around 16 kg of CO_2-equivalent/capita y. The remaining unit processes of urine collection, dehydration, and pelletization contribute less to GWP, with respective values of 0.8, 1.2, and 0.05 kg of CO_2-equivalent/capita y. Notably, urine collection in this scenario has a 25% higher GWP than in the toilet-level scenario, attributed to the need for additional piping to convey urine from each toilet to a shared basement-level tank, unlike in S1, where each toilet is directly connected to a nearby treatment unit placed in the same room. Transport-related GWP is similar to S1, reflecting comparable annual transport work (416 kg km/capita y), despite fewer trips per year from a larger tank capacity. Across all investigated impact categories, the basement scenario consistently shows a more favorable environmental performance. A detailed breakdown of contributions by unit processes is shown in Figure S13 in the Supporting Information.

3.2.3. Centralized Treatment (S3—Centralized-Level System). The third scenario (S3—centralized-level) has a GWP of 16 kg CO_2-equivalent/capita y, nearly identical to the toilet-level scenario and about 50% higher than the basement-level scenario. Although this system is the most energy-efficient in the concentration unit process, consuming only 37 kWh/capita y and contributing 7.3 kg CO_2-equivalent/capita y (a reduction of 55% and 70% compared to the toilet and basement scenarios, respectively), its overall GWP is high. This is primarily due to the emissions associated with the sewer network, which contributes approximately 16 kg CO_2-equivalent/capita y to the total impact. A breakdown of the sewer unit process shows that the main contributors to its

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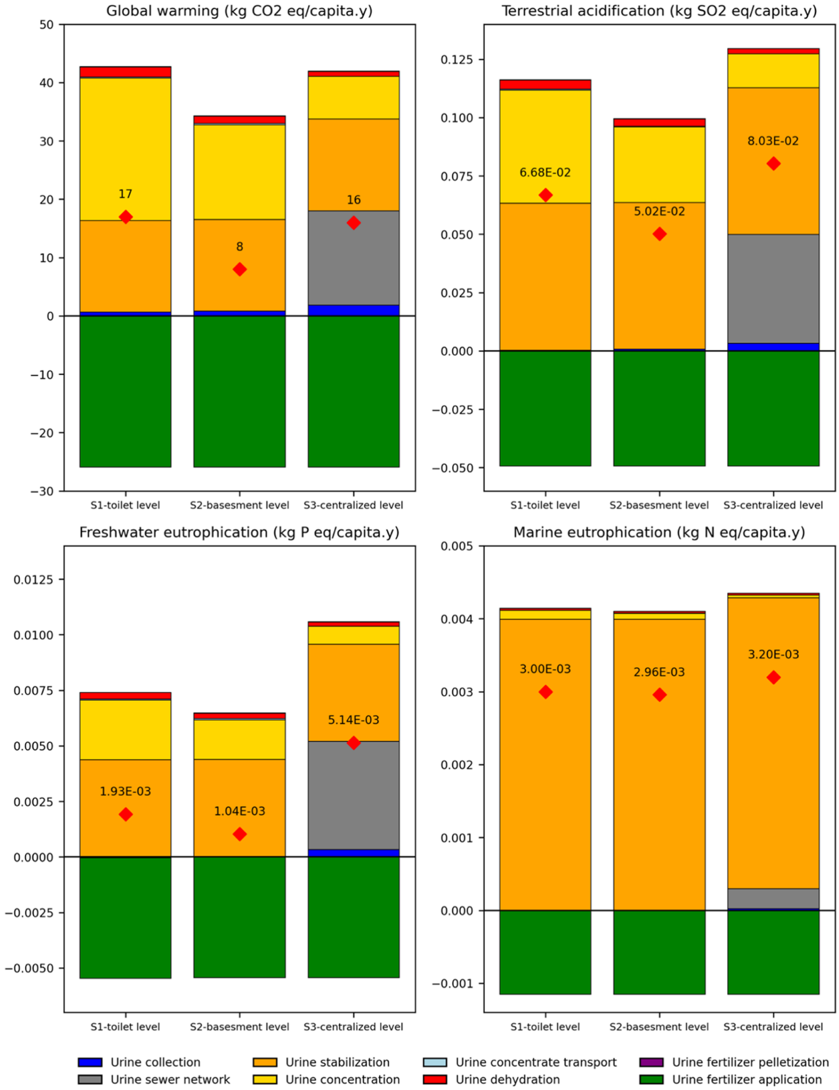

Figure 2. Net environmental impacts of the three urine recycling scenarios (S1: toilet-level, S2: basement-level, and S3: centralized-level), evaluated using the ReCiPe method. Results are presented across four impact categories: global warming (kg CO_2-eq), terrestrial acidification (kg SO_2-eq), freshwater eutrophication (kg P-eq), and marine eutrophication (kg N-eq), normalized per capita per year (PE/y). Colored bars represent contributions from individual unit processes, while red diamonds indicate net impact values after accounting for avoided impacts from the synthetic fertilizer substitution.

GWP are the polypropylene pipes (10.51 kg of CO_2-eq/capita year) and the gravel used for trench bedding and backfilling (4.99 kg of CO_2-eq/capita year). Other contributors, such as excavation with hydraulic diggers (0.58 kg CO_2-eq/capita year), chromium steel components for pumps (0.05 kg CO_2-eq/capita year), and transport (0.05 kg CO_2-eq/capita year), are comparatively minor, see Figure S16 in the Supporting Information. In this scenario, the urine is pumped through a dedicated sewer network from the basement of each building to a centralized treatment plant. This contrasts with the other two systems, where urine concentrate is directly transported by a vehicle. The stabilization unit process using citric acid also has a notable GWP estimated at 16 kg of CO_2-equivalent/capita y. Other unit processes, such as urine collection, dehydration, and pelletization, contribute minimal amounts to GWP, with respective values of 1.85, 0.84, and 0.05 kg of CO_2-equivalent/capita y. Although marginal, the urine collection process in this scenario has a 65% and 57% higher GWP than

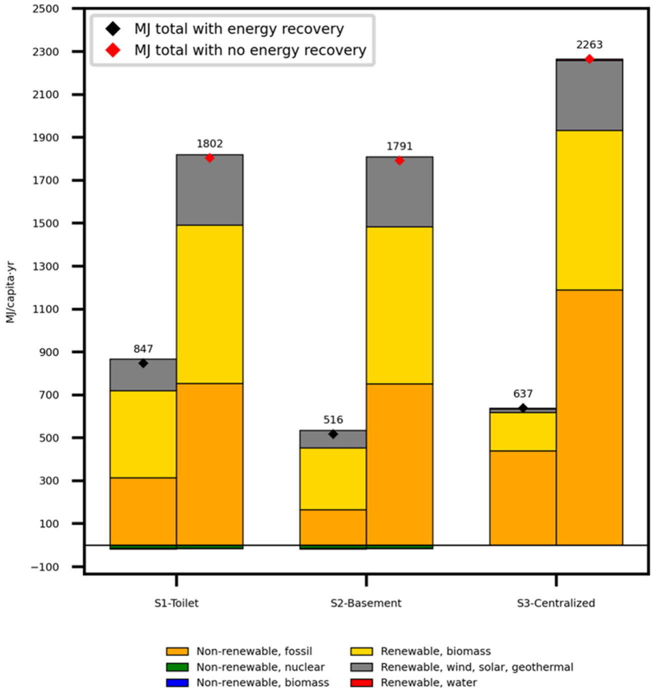

Figure 3. Cumulative energy demand (CED) per capita per year (capita/y) for the three urine recycling scenarios (S1: toilet-level, S2: basement-level, and S3: centralized-level). Results are disaggregated by the energy source and presented with and without heat energy recovery. Red diamonds indicate CED values without energy recovery, while black diamonds show values with energy recovery.

that of the first and second scenarios. This increase stems from the requirement for additional piping infrastructure to convey urine from each toilet to the basement and then through a trunk sewer line to a central pumping station. In contrast, the other systems carry out urine pretreatment locally within the buildings and only transport the concentrate. It is worth noting that the high sewer-related GWP in this configuration is partly due to the assumption of entirely new trench installation. While the largest share of emissions comes from the polypropylene pipes, which would still be required, reusing existing utility trenches could avoid most excavation and gravel bedding impacts, lowering sewer-related GWP by roughly one-third. Such a change could reduce the carbon footprints of the centralized configuration and make it more competitive with that of the basement-level system. Across the other impact categories, the centralized scenario performs poorly compared with the other systems, particularly for acidification and freshwater eutrophication, again largely due to the sewer infrastructure needs. A detailed breakdown of contributions by unit processes is provided in Figure S14 in the Supporting Information.

3.2.4. Cumulative Energy Demand. The cumulative energy demand (CED) using the consequential model for the three urine recycling scenarios is shown in Figure 3. Among them, the second scenario (S2-basement level) has the lowest overall energy demand at 516 MJ/capita·y (≈143 kWh/capita y, given 1 kWh = 3.6 MJ). Notably, this scenario has the lowest energy demand, even when the thermal energy recovery is excluded from the analysis. To contextualize these values, consider that a typical European household consumes approximately 1.3 tons of oil equivalent (toe) annually (≈15,119 kWh, given one toe = 11,630 kWh).[44] In comparison, treating one person's annual urine production in Scenario 2 requires only 0.8% of this total annual energy consumption. Relative to Sweden's national average electricity use, approximately 12,000 kWh per capita per year across all sectors, Scenario 2 represents about 1% of a person's annual electricity footprint.[45] For further perspective, 516 MJ/PE/y is roughly equivalent to 15 L of gasoline per year (1 L ≈ 34 MJ), enough to fuel an average passenger car for around 200 km/y. This comparison illustrates the relatively modest energy demand required to process urine using acid stabilization and evaporation in a basement-level urine recycling system, particularly when paired with thermal energy recovery systems.

The CED per unit process is illustrated in Figure S15 in the Supporting Information, highlighting that the urine concentration (largely due to electricity use) and stabilization (due to citric acid production) significantly contribute to CED in the first two scenarios, whereas the sewer network is the dominant contributor in the third scenario. Notably, a urine-based fertilizer shows a negative CED, indicating that it offsets more energy use than it consumes. This credit arises from avoiding the energy-intensive production of synthetic fertilizers through the Haber−Bosch process and the extraction of mineral phosphate fertilizers. However, CED does not account for the additional energy that would have been required to remove

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urine-derived nitrogen and phosphorus from conventional wastewater treatment plants.

3.3. Impact of Life Cycle Assessment System Models on the Global Warming Potential Results.

As stated in Section 3.2.1, ALCA is based on average data, whereas CLCA models are based on marginal suppliers who can adjust production in response to changes in demand and market requirements.[29] Initially, when this LCA was first conducted, all inputs were modeled using a consequential system perspective. Under this model, the first scenario (S1—Toilet) exhibited the highest GWP of 17 kg of CO_2 equiv/capita y, which was comparable to the centralized scenario (S3) and 50% higher than the basement-level scenario (S2). However, when the system modeling approach was switched to a cutoff model under ALCA, the results changed markedly. In the ALCA model, the first scenario (S1—Toilet) now resulted in a net negative GWP of −8 kg of CO_2 equiv/capita y. This value was comparable to the second scenario (S2—basement) and lower than the third scenario (S3—centralized), as illustrated in Figure 4. These discrepancies primarily arise from two methodological factors: the use of average and marginal factors and the inclusion of substitution in ALCA.[46] In the cutoff ALCA model, average emission factors are applied, which may, in certain instances, result in lower calculated emissions compared to the marginal approach, particularly in contexts like Sweden, where low-carbon renewable energy sources dominate the national energy mix. As a result, the climate impact of electricity use in processes, such as the urine concentration, is relatively small. In contrast, the CLCA model assumes that the increased electricity demand is met by marginal energy suppliers, which typically are fossil-fuel-based, leading to higher associated emissions.

The second key factor contributing to the discrepancy and the net negative GWP values in the first and second scenarios is the use of substitution (i.e., accounting for the replacement of the synthetic fertilizer with a urine-derived fertilizer) within ALCA. One of the most persistent critiques of LCA studies in wastewater treatment is the lack of methodological transparency, particularly concerning the choice of the LCA framework. Many studies do not disclose whether they use attributional or consequential LCA.[47] For example, Heimersson et al.[48] reviewed 62 wastewater-related LCA studies and found that most did not explicitly state the type of LCA employed. Additionally, many studies appear to adopt hybrid approaches, such as avoiding allocation through substitution in ALCA and/or modeling-substituted products using average data in CLCA. Although substitution is mathematically feasible in ALCA, its application often lacks an internal logic when based on average data. ALCA is inherently designed to reflect an accounting perspective, which contradicts the substitution method that benefits from avoided burdens outside the physical system. ALCA provides a representation of the current status quo and the actual physical burdens,[49] offering a snapshot of static impacts without considering future effects.[50]

Multiple studies recommend that substitution is more suitable within a CLCA framework and should be avoided in ALCA.[27,49,51,52] As noted in Section 2.2.1, the two LCA approaches are designed to answer fundamentally different questions.[29] Hence, merging divergent methodological elements can introduce inconsistencies and result in uncertain and even misleading results.[53] However, these recommendations are often overlooked in practice, as most ALCAs appear to use substitution to resolve multifunctionality problems.[42]

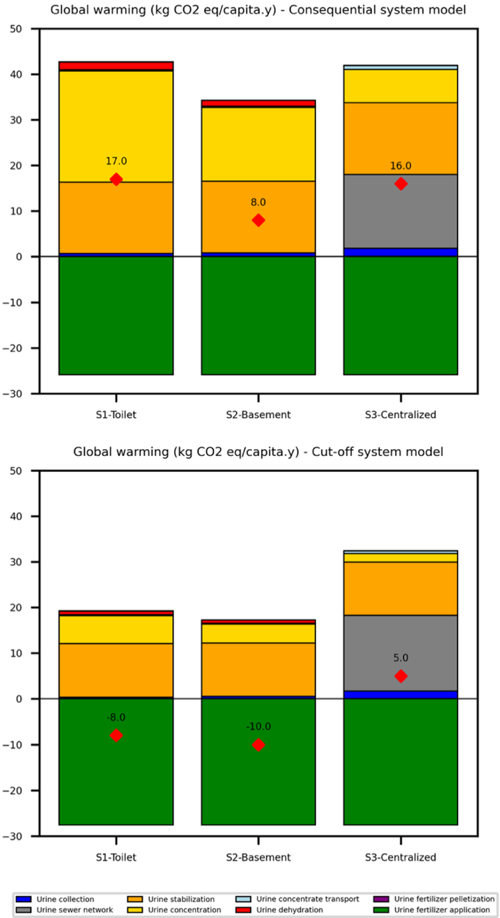

Figure 4. Impact of the LCA system modeling approach (cutoff versus consequential) on the Global Warming Potential (GWP) results for three urine recycling scenarios (S1—toilet, S2—basement, and S3—centralized). The top panel presents GWP outcomes using a consequential system model, while the bottom panel shows results under a cutoff attributional model. Bars indicate the contribution of individual unit processes, while red diamonds mark the total net GWP (kg CO_2-eq per capita per year).

Applying substitution with average data can lead to the underestimation of environmental burdens, as it credits systems for avoided impacts that do not, in reality, occur.[49] Hence, the LCA results may neither reflect the true share of the global environmental load attributable to the studied system nor accurately capture the changes that would result from the system's introduction.[47]

This inconsistency is evident in our study. When substitution was applied in ALCA (Figure 4), the net GWP values for all three scenarios decreased significantly, resulting in negative values for the first two scenarios. However, this outcome hinges on problematic assumptions. For example, if a region's nitrogen fertilizer mix includes both unconstrained synthetic fertilizer (e.g., urea) and constrained organic fertilizer

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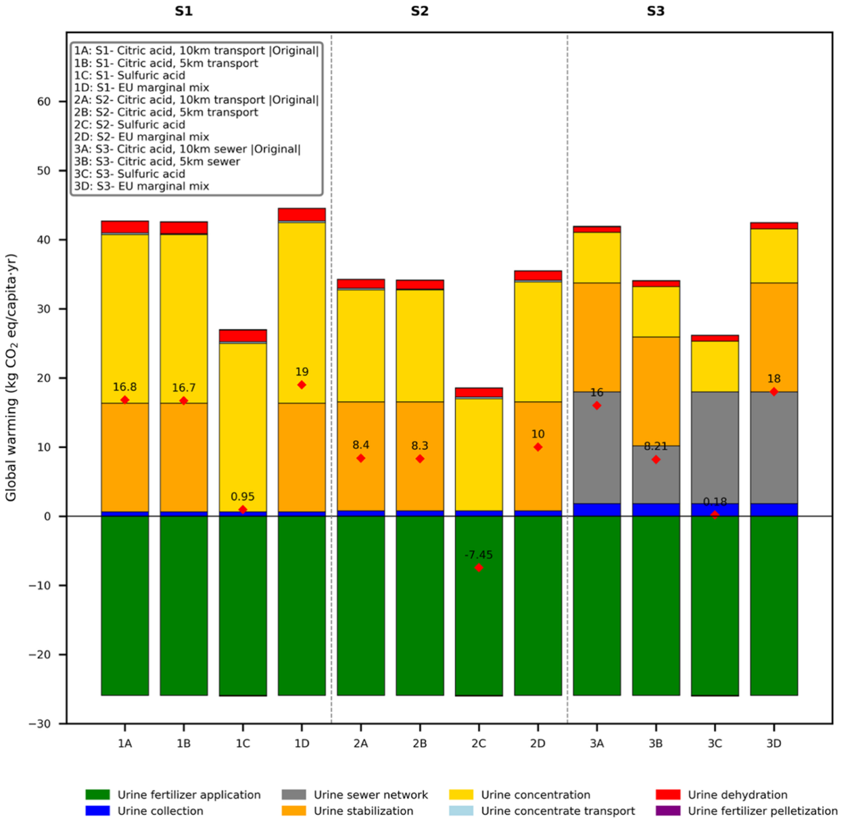

Figure 5. Impact of sensitivity analysis scenarios on the global warming potential (GWP) of the three urine recycling scenarios (S1—toilet, S2—basement, S3—centralized). The analysis includes two parameters: (i) reducing transport or sewer distances from 10 km to 5 km (scenarios S1, S2, S3), and (ii) substituting citric acid with 1.36 g/L sulfuric acid (scenarios S1, S2, S3). The red diamonds indicate net GWP (kg CO_2-eq/capita y).

(e.g., manure from local livestock farms), claiming that the urine-based fertilizer offsets the entire nitrogen mix is inaccurate. Manure, as a constrained byproduct of livestock production, cannot simply be scaled up or down. Even if it is not applied locally, it will likely be utilized elsewhere. Thus, only unconstrained inputs, such as urea, can be legitimately displaced by a urine-derived fertilizer. Even studies that tolerate substitution in ALCA argue that, if applied, it should be based on unconstrained marginal technologies that can respond to market dynamics.[54]

3.4. Sensitivity Analysis Results. The results of the sensitivity analysis are listed in Figure 5. The first analysis examined the effect of reducing the transport distance to the final drying plant from 10 km to 5 km on the GWP across the three urine recycling scenarios. This relocation had a marginal effect on the first two scenarios but a significant effect on the third. This disparity stems from the relative contribution of the sewer network to the third scenario's overall GWP. Specifically, reducing the transport distance to 5 km led to a GWP reduction of only 1% for the first two scenarios, from 16.8 to 16.7 for S1 and 8.4 to 8.3 kg CO_2-eq/capita y for S2, respectively. The minor change is attributable to a small reduction in emissions from the concentrate transport, from 0.22 to 0.11 kg CO_2-eq/capita y. In contrast, for S3, the shorter sewer distance significantly reduced GWP, from 16 to 8.2 kg CO_2-eq/capita y, representing a 49% decrease. The decline is due to the decrease in sewer network GWP, which dropped from 16.17 to 8.34 kg CO_2-eq/capita y. Thus, the net GWP of the third scenario became comparable to that of the basement-level scenario. Nevertheless, S3 still exhibited higher impacts in other categories, as described in the Supporting Information.

The second sensitivity analysis explored alternative chemical inputs and energy recovery assumptions to identify the most environmentally favorable configuration capable of achieving net-negative impacts across all categories. The literature suggests that sulfuric acid has a lower GWP than citric acid, as it is often produced as a byproduct in industrial processes such as copper smelting and crude oil desulfurization. Substituting citric acid with 1.36 g of sulfuric acid per liter of urine led to a notable decrease in GWP across all scenarios, resulting in reductions of 94%, 190%, and 99% for S1, S2, and S3, respectively. This translates to a GWP reduction of 16.8–0.95 (S1), 8.4 to −7.45 (S2), and 16–0.18 kg CO_2-eq/capita y (S3), as shown in Figure 5. Among the three scenarios, S2 (basement-level treatment) emerged as the most environmentally effective configuration with a net negative GWP of

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−7.45 kg CO_2-eq/capita y, owing to the combined effects of sulfuric acid use and 70% heat energy recovery. To explore the robustness of this finding, an additional test examined the minimum energy recovery threshold required for S2 to remain carbon negative. The results showed that this configuration could sustain as little as 52% energy recovery and still maintain a net-negative carbon footprint.

Finally, replacing the Swedish marginal electricity mix with the EU marginal mix increased the net GWP to 19 kg of CO_2-eq/capita y for S1, 10 for S2, and 18 for S3. The absolute increase was the largest for the electricity-intensive S1 and smallest for S3. Importantly, the ranking remained unchanged (S2 < S3 ≈ S1), indicating that the comparative conclusions are robust across regions with a higher grid carbon intensity.

3.5. Interpretation for Decision Making. This LCA study indicates that the second scenario (S2—basement-level treatment) offers the most favorable environmental profile among the three configurations analyzed. Across all impact categories and modeling approaches, the basement scenario consistently demonstrates the lowest environmental burdens. However, it is essential to note that the material used for the construction of the urine recycling system, including treatment units, storage tanks, and ancillary infrastructure, was not accounted for in this study due to incomplete data for some scenarios. This omission means that the results cannot be interpreted as fully comprehensive, and further work is needed to incorporate these life cycle stages for a more definitive conclusion. In practice, the types and quantities of construction materials are likely to differ across the three scales. For example, the toilet-level system (S1) would require a compact but oversized heat pump to handle intermittent household flows, whereas the basement-level system (S2) would integrate a dedicated heat exchanger sized for multiapartment use. The centralized system (S3) replaces building-level evaporation with a large-scale vapor evaporator, using mechanical vapor recompression. Storage requirements also differ: S1 relies on small frequent-emptying containers; S2 uses intermediate-scale tanks to buffer multibuilding flows; and S3 includes large-scale centralized storage to manage peaks from a wider catchment. These differences could influence the environmental profile if construction and replacement impacts were included. Although adding construction materials would increase the total GWP for all scenarios, scenario 2 might require less total material than scenario 1 (fewer, larger units instead of many smaller ones) and scenario 3 (less extensive facility, storage, and sewer infrastructure). Therefore, while accounting for construction impacts would raise the overall impacts, it is unlikely to change the ranking order, and it could actually strengthen the favorable performance of scenario 2.

The most environmentally optimal configuration for S2 involves replacing citric acid with sulfuric acid as the stabilizing agent, which results in a net negative environmental profile. Despite the environmental advantages of sulfuric acid, several practical challenges may limit its application. Its use requires following stringent safety protocols during storage, transport, and handling, particularly if used near end-users, such as household or toilet-level treatment units. Furthermore, although sulfuric acid can be produced as an industrial byproduct, its supply chain is currently tied to fossil fuel-intensive processes. This dependence conflicts with broader sustainability objectives aimed at shifting to fossil-free systems and raises concerns about its long-term availability.[55] The baseline assumption for energy recovery in the basement scenario was set at 70%, but sensitivity analysis revealed that the system remains carbon negative, even at a reduced recovery rate of 52%, suggesting that this configuration can remain robust under varying operational efficiencies.

The GWP results obtained from the two modeling systems (consequential vs attributional cutoff) varied considerably, highlighting the importance of methodological transparency to decision-making. These discrepancies are particularly pronounced when substitution is incorporated within ALCA. For stakeholders seeking a static snapshot of a product's status or environmental profile, specifically the share of the global burden attributable to that product, the attributional (cutoff) model is generally recommended. The attributional cutoff model allocates impacts to the product's upstream consumption and enforces the "polluter pays" principle.[56] It considers only the system's direct physical inputs and outputs, where recyclable materials are "cut-off" from the system, treated as burden-free, while all waste-related impacts are wholly attributed to the producer. In this model, byproducts may either be allocated proportionally (e.g., by weight or cost) or removed without burden if recognized as recyclable. In contrast, consequential LCA (CLCA) analyzes the broader environmental implications of decisions, particularly those that influence supply chains and market dynamics. CLCA is appropriate when decision-makers aim to understand how introducing a product affects the global environmental burden. Instead of allocation, CLCA employs substitution: if a byproduct can substitute for another product in the market, environmental credits are assigned for the avoided production. In this study, for instance, a urine-derived fertilizer is assumed to substitute a synthetic fertilizer, and the producer gains credit for avoiding production. Importantly, CLCA emphasizes the role of "unconstrained/marginal" suppliers of synthetic fertilizer who are capable of adjusting production in response to shifts in the market demand.[29]

The system models also differ in the type of data drawn from the database Ecoinvent, in this case. For example, the urine recycling system involves the use of plastic for urine collection, and the associated environmental impacts vary, depending on the system model selected from the database. In both attributional and consequential models, virgin plastic carries the full burden of its production. However, when recycled plastic is used in the cutoff model, it is considered burden-free, with only recycling impacts accounted for, meaning no credits are granted to the producer. In contrast, the consequential model treats recycled plastic as a substitute for virgin plastic, awarding credits for avoiding virgin production. An increase in the demand for virgin plastic triggers marginal suppliers to boost production, which introduces additional environmental impacts. If recyclable plastic replaces other materials in this model, the producer receives credit through substitution.

The interpretation of cumulative energy demand outcomes is heavily influenced by the choice of the LCA modeling approach. The cutoff model reflects the average national energy mix and offers a snapshot of the system's current environmental impact, while the consequential system model focuses on marginal energy sources activated by the increased demand, providing a more dynamic perspective that is better suited for evaluating the effects of scaling or systemic changes.[57] In the consequential model, the primary energy supply from marginal producers is shaped by an incremental demand, which is typically met in the short term by fossil-fuel-based sources such as gas turbines or coal-fired units. As such,

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this modeling approach might provide a more accurate representation of the real implications associated with implementing new technologies, including urine recycling sanitation systems.[58] While the impact of a urine recycling system may be minimal at the individual level, its nationwide implementation can significantly alter electricity demand profiles. For example, if urine recycling were to replace conventional wastewater treatment across an entire city, introducing millions of new electric appliances, such as heaters, dryers, and pumps, the electricity grid would be forced to adjust. Under these conditions, the marginal energy mix becomes increasingly critical. Thus, the consequential model is advantageous for policy evaluation, strategic sustainability planning, and forecasting environmental impacts associated with the large-scale adoption of new systems.

The ongoing debate between ALCA and CLCA, particularly regarding the handling of multifunctionality and the appropriateness of applying substitution within the ALCA, remains a complex and unsettled issue. This LCA study does not seek to determine which approach is the most suitable. Rather, it emphasizes the importance of transparency in disclosing the type of LCA conducted and the system modeling choices made, as such clarity is essential to ensure that decision-makers correctly interpret results. Fundamentally, ALCA and CLCA are designed to answer different questions, and therefore, providing conflicting results without specifying the underlying methodology can lead to confusion and misinformed decisions, undermining the replicability of these LCAs and hindering their use by other practitioners. Just as it is crucial to clearly define the functional unit, it is equally important to specify the type of LCA being performed, the approach taken to resolve multifunctionality, and whether substitution (if applied) is based on average or marginal data. Drawing conclusions or comparing results across divergent LCA types without proper context adds to the ambiguity and contributes to the ongoing discord within the LCA community.

Beyond the environmental metrics, real-world implementation should also account for practical and contextual constraints.[59] Labor needs, for instance, are not captured in this LCA but can strongly influence the feasibility. The toilet-level scenario (S1) is expected to be the most labor-intensive due to the frequent handling of small storage units and decentralized maintenance. The basement-level scenario (S2) centralizes these tasks at the building scale, reducing labor requirements, while the centralized scenario (S3) is likely to require the least day-to-day labor, as most processes occur at a single facility. While S2 demonstrated the best environmental performance, local conditions for implementation may favor other options. Reusing existing sewer trenches, for example, could lower the footprint of S3, making it more competitive. Where sewer installation is impractical, basement- or toilet-level systems may be preferable, and in existing buildings with technical barriers to basement installation, S1 may be the better retrofit choice. For new constructions, however, S2 remains the most advantageous. Ultimately, by combining a robust environmental assessment with the consideration of labor, infrastructure, and site constraints and maintaining transparency in LCA modeling, urine recycling can be strategically implemented as a scalable low-impact alternative to conventional sanitation.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.5c09248.

> LCI data, including wastewater characteristics, mass and energy balances, system boundaries and assumptions, wastewater characteristics, layout of each scenario, data used for modeling urine collection; agriculture application of urine NPK pellets; urine drying; urine stabilization and concentration; and sewer network; NPK application, characterized life cycle assessment results, GWP, cumulative energy demand, and schematic diagram of the primary unit process (PDF)

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Notes

The authors declare no competing financial interest.

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This thesis investigates how urine recycling can support sustainable sanitation transitions and promote circular resource management. Using life cycle assessment, innovation system analysis, and system dynamics modeling, it connects environmental performance with social and institutional factors for change. Findings indicate that urine recycling can significantly lower emissions and close nutrient loops; however, widespread adoption depends on clear policy support, reliable services, and public legitimacy. These insights provide practical pathways for transforming sanitation into a circular system.

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