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

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ABSTRACT

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

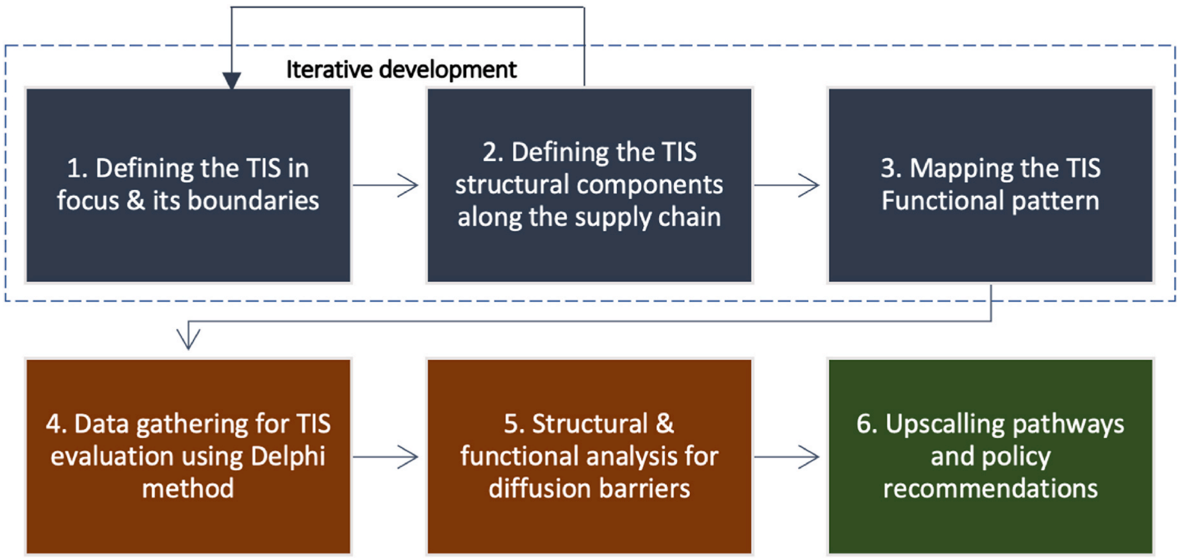

Fig. 1. This is the chain of steps utilized to conduct the TIS analysis. The first three steps blued colored depend on each other and are done iteratively. Outputs from these steps are used as a framework for steps 4 and 5. Browned colored steps are presented in the results and the green-colored step 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.)

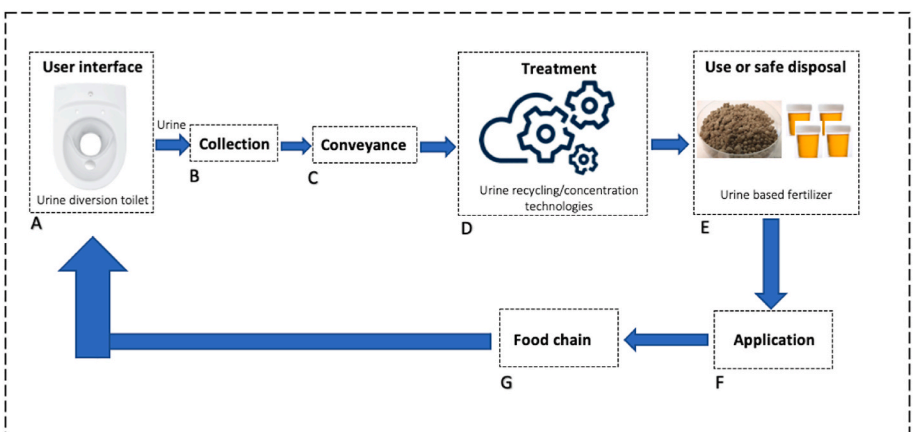

Fig. 2. Urine recycling supply chain segments. The supply chain differs between different systems depending on the type and scale of treatment but this is a general supply chain of off-grid urine recycling systems.

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

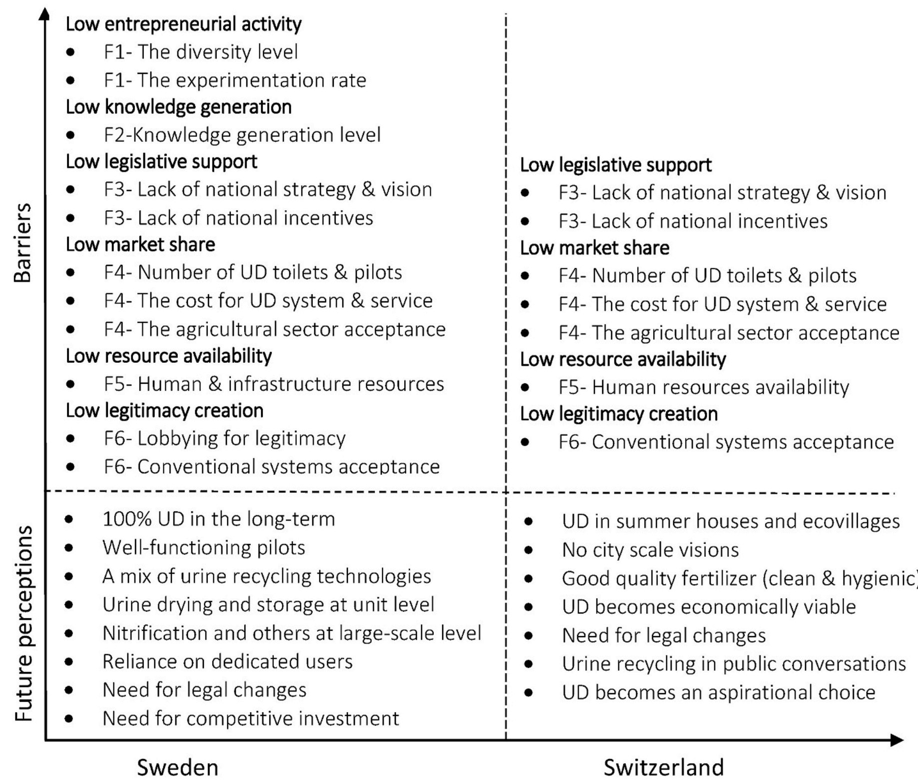

Fig. 3. An overview of the barriers and future perceptions regarding urine recycling systems in Sweden and Switzerland, according to experts in the field. The barriers are grouped under function/process headings that will be used later in this study.

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

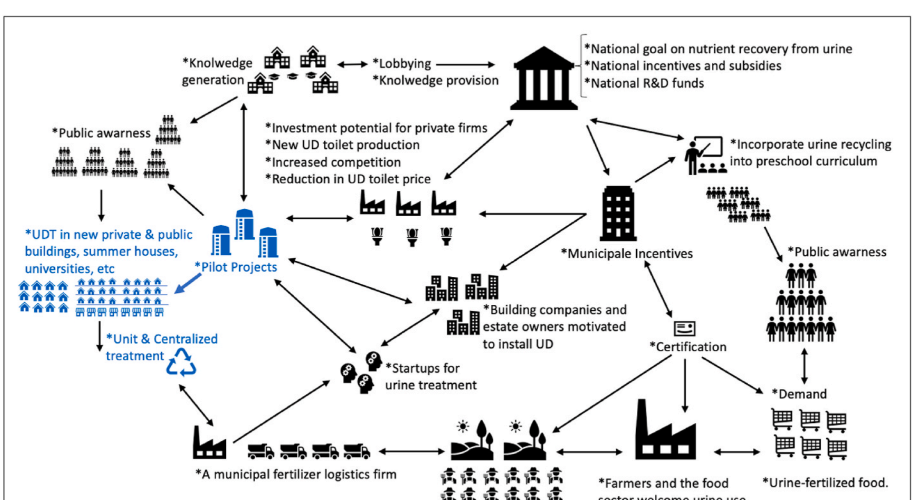

Fig. 4. Pathways on how urine recycling can be diffused. One direction arrow indicates a one-sided relationship, two directions arrow indicates a two-sided relationship. This illustration shows both bottom-up and up-bottom interventions and each icon can be a starting point. Pilot projects and scale 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

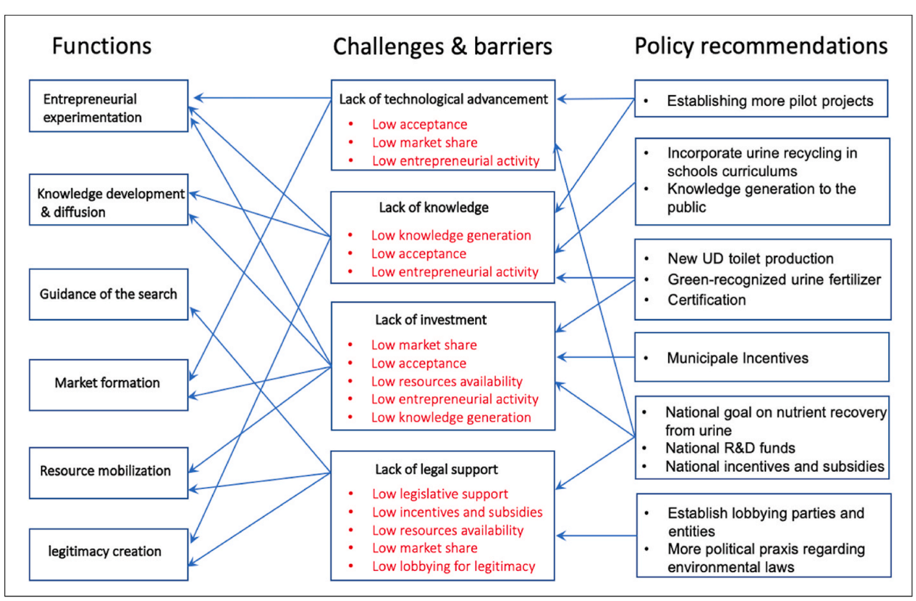

Fig. 5. Mapping challenges/barriers and potential policy recommendations for urine recycling TIS. The headings in the second column represent the challenges, whereas the red bullet points represent the barriers. These challenges/barriers are a result of the urine recycling TISs analysis conducted in 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

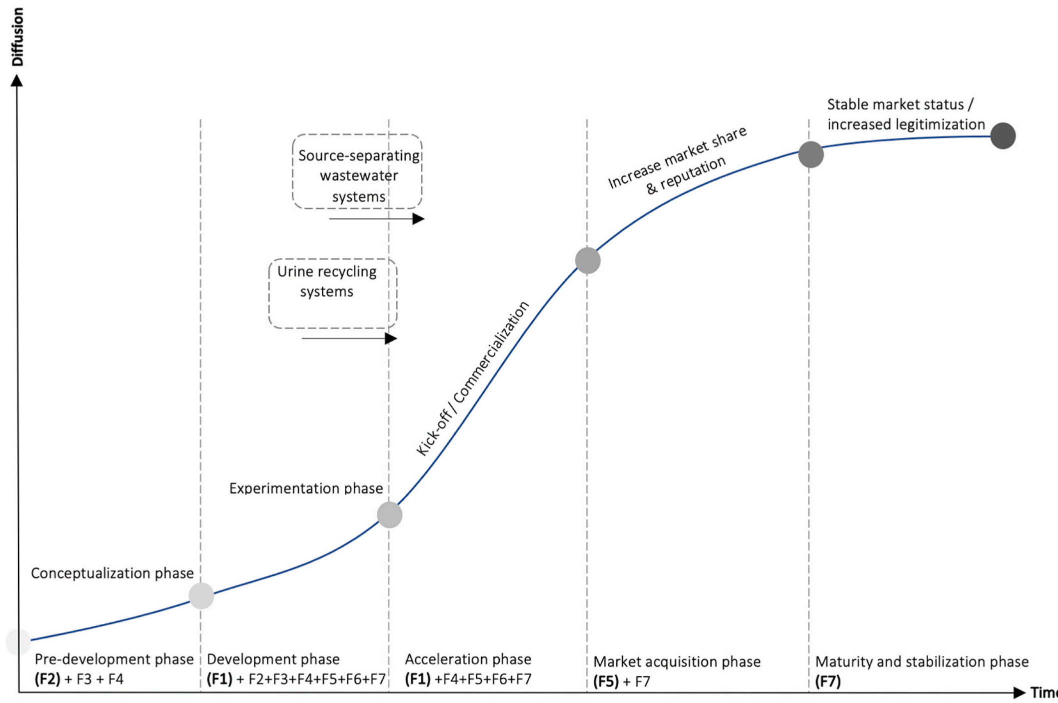

Fig. B. 1. TIS's development stages during its lifecycle with their corresponding functions. Primary functions in each development phase are highlighted with bold fonts.

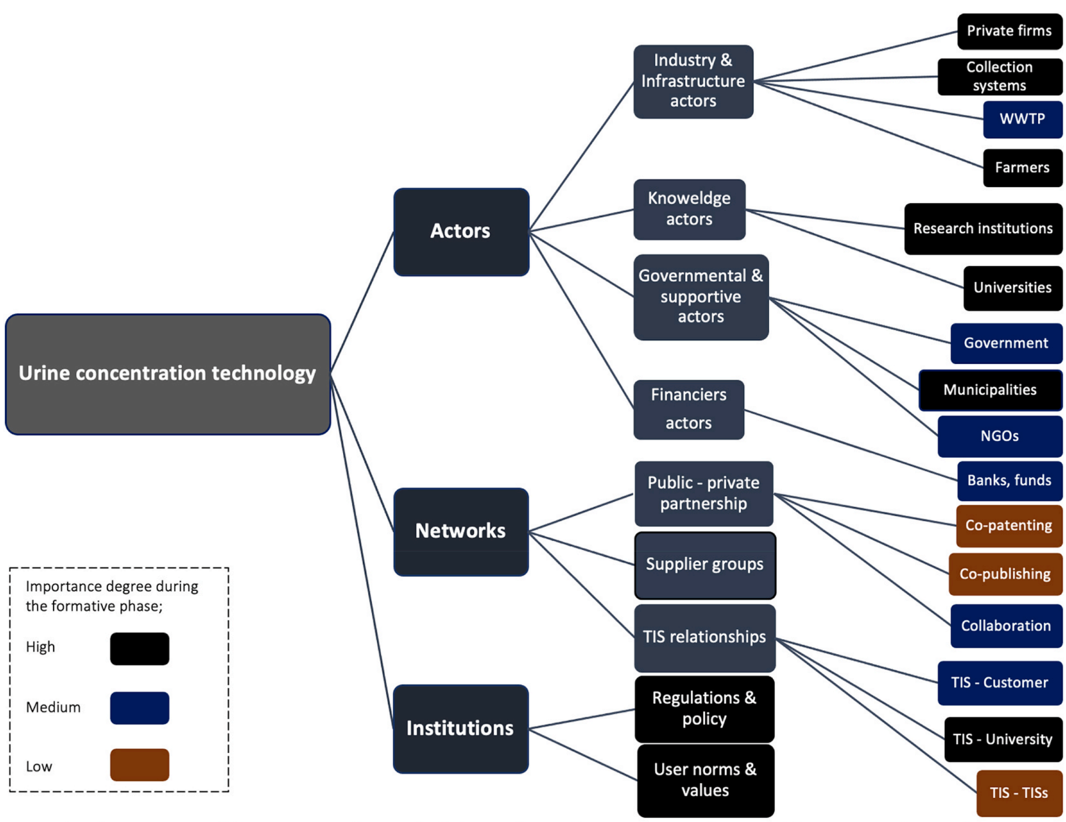

Fig. B. 2. The structure of the urine recycling TIS. Colors indicate the importance degree of these actors during the developed stage.

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