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

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A B S T R A C T

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

1. Introduction

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

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

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

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

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

2. Methodology

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

2.1. Defining relevant keywords

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

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

2.2. Bibliographic databases and search engines

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

2.3. Search strings

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

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

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

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

2.4. Article screening and map's eligibility criteria

2.4.1. Screening process

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

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

2.4.2. Eligibility criteria

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

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

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

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

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

2.5. Evaluation criteria for the knowledge development function

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

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

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

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

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

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

3. Results

3.1. String 1 results

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

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

3.2. String 2 & String 3 results

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

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

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

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

3.3. Comparing string 1,2 and 3

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

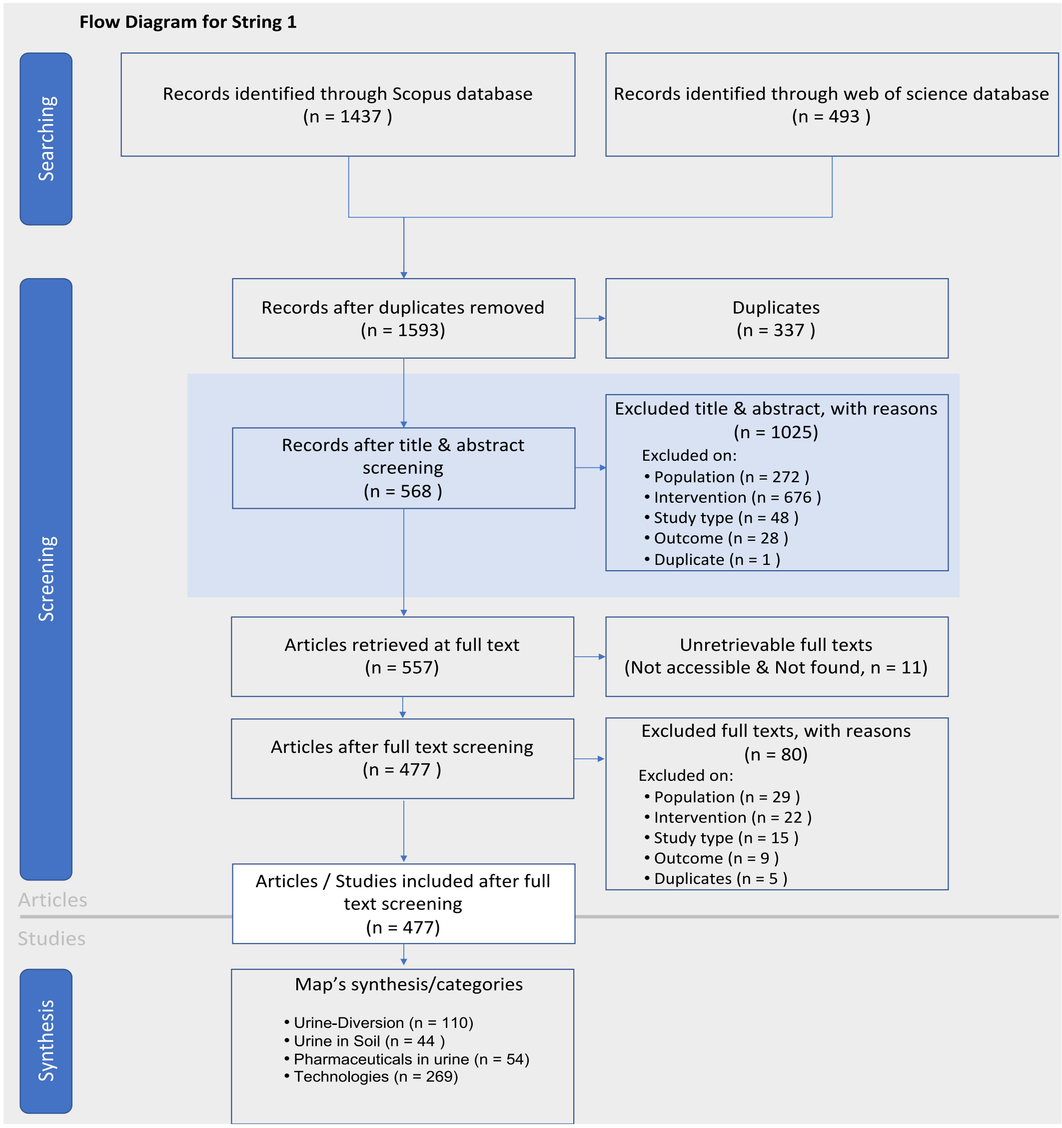

Fig. 1. Flow diagram illustrating the screening process and coding of string 1, i.e., the number of records excluded and retrieved on duplication, abstract, and full text.

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

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

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

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

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

4. Analysis and discussion

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

4.1. Interpretation of the results

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

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

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

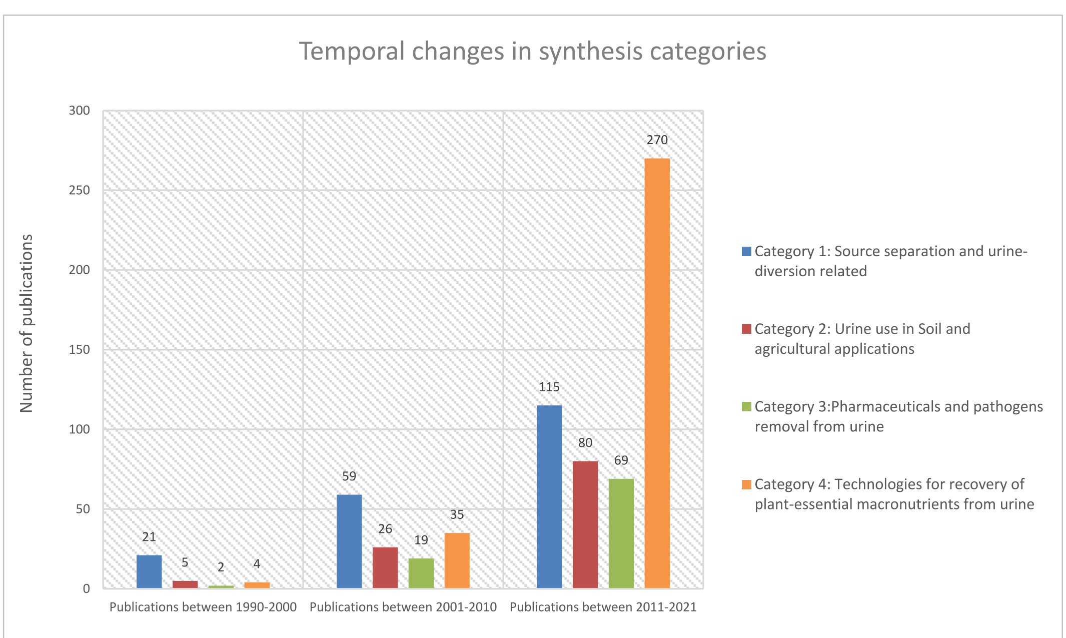

Fig. 2. Temporal changes in total number of urine recycling publications per decade within synthesis categories 1–4 during the period 1990–2021, based on searches in Scopus and WOS using a merged search string (1 and 3, see section 3.3) and a screening process (Fig. 1).

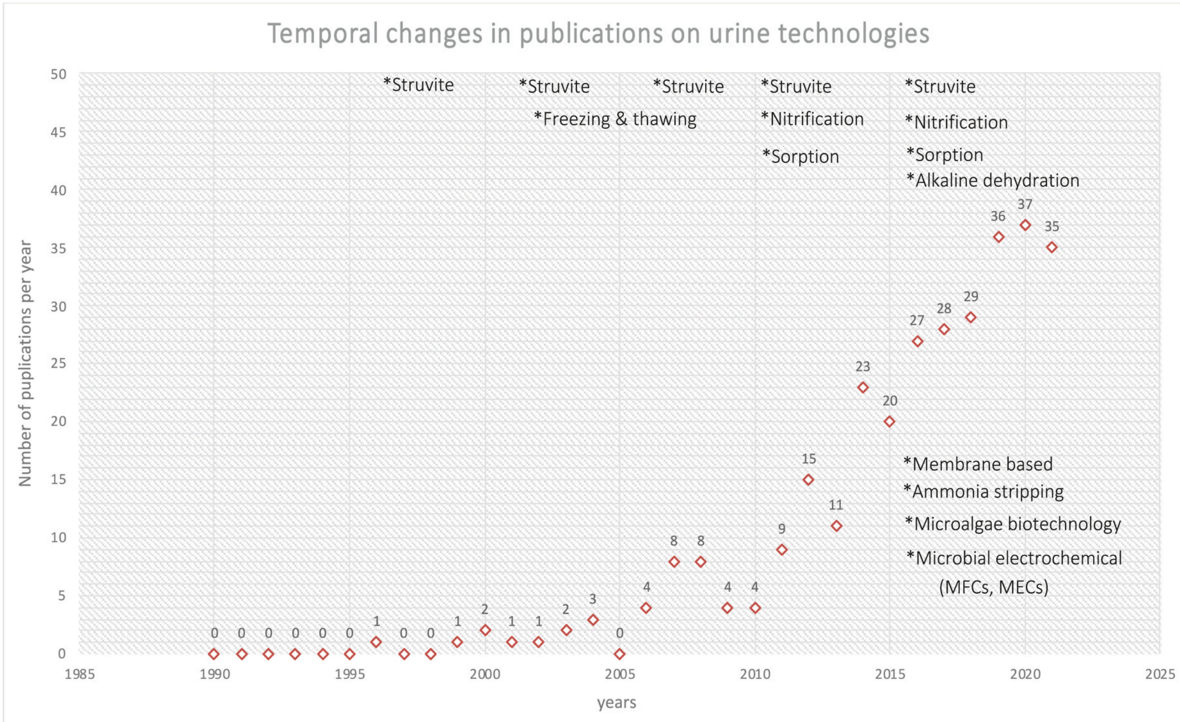

Fig. 3. Knowledge development in the periods 1990–2010 and 2011–2021 on technologies for nutrient recovery from urine (category 4). Technologies are shown based on publication year, with total number of publications for a particular technology shown above data points.

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

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

4.2. Evaluation of the knowledge development and diffusion function

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

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

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

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

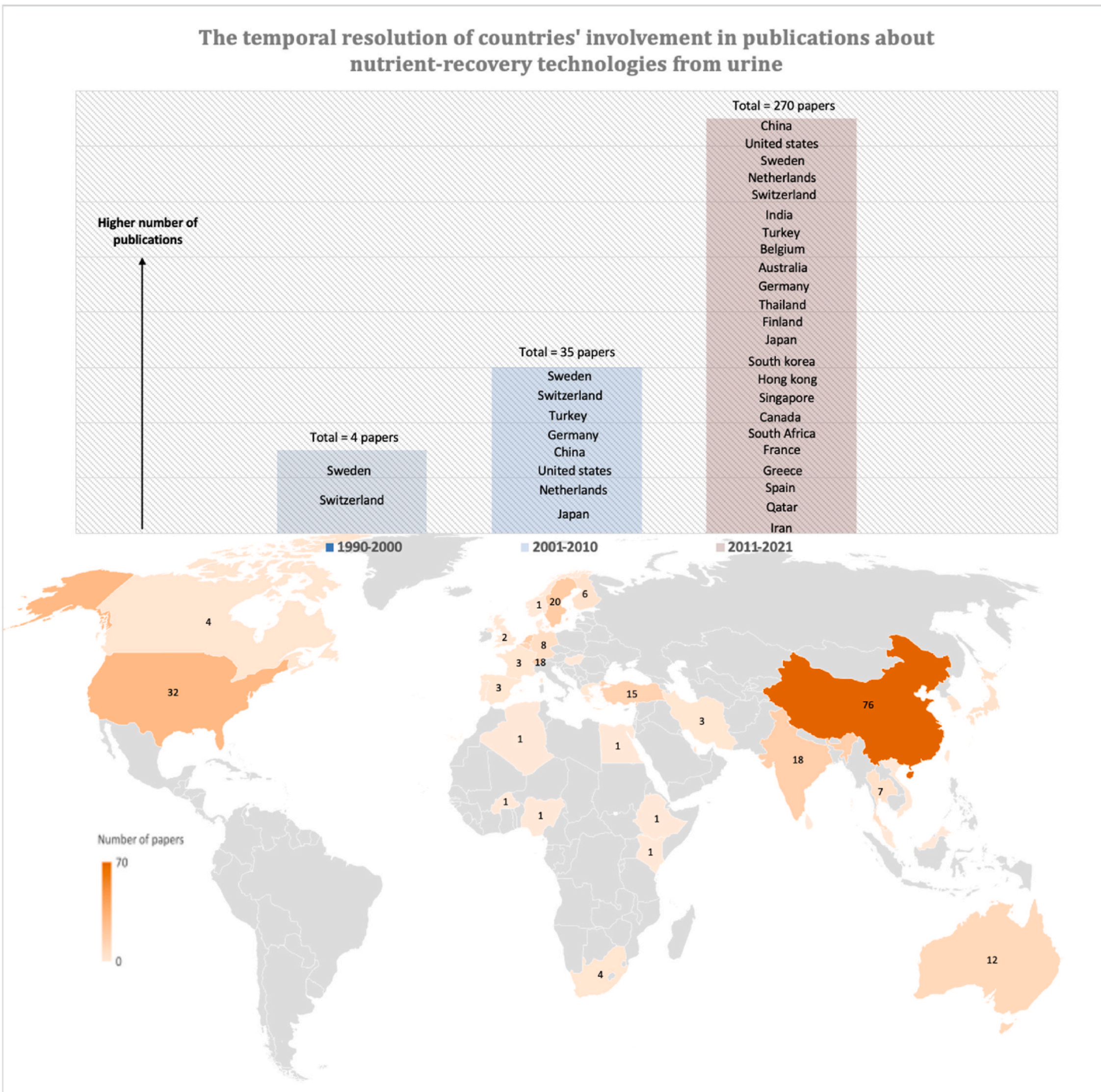

Fig. 4. Changes in the number of urine technology-related publications in different countries world-wide, 1990–2021. The top panel shows the total number of publications per decade, while the map shows total number of publications per country.

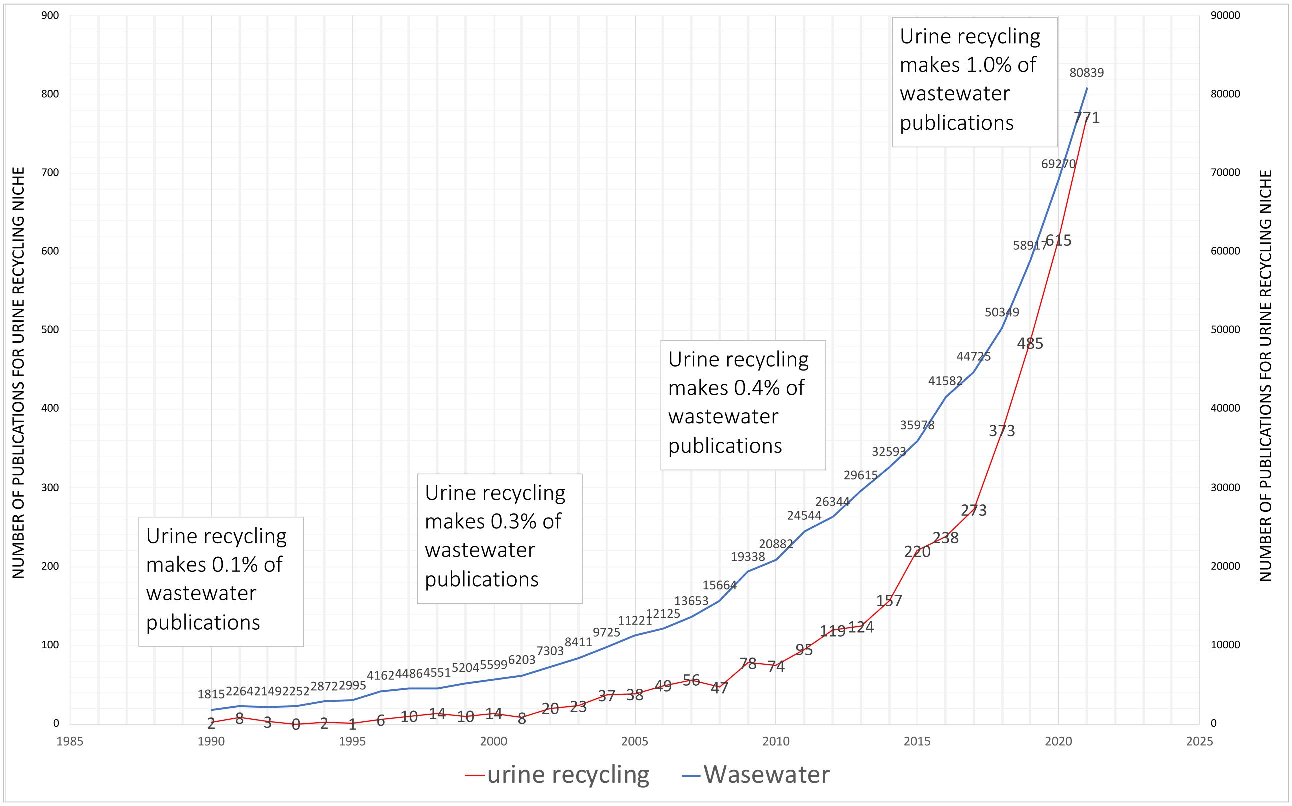

Fig. 5. Comparing the development of urine recycling research with the wastewater research over time. Each decade is highlighted and the proportion of urine recycling is presented in each decade. 0.1% in 1990, 0.3% in 2000, 0.4% in 2010 and 1% in 2021.

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

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

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

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

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

5. Conclusion

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

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

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

CRediT authorship contribution statement

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

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A

Table A1
Subject areas used for the three search strings

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

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

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

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

Appendix B

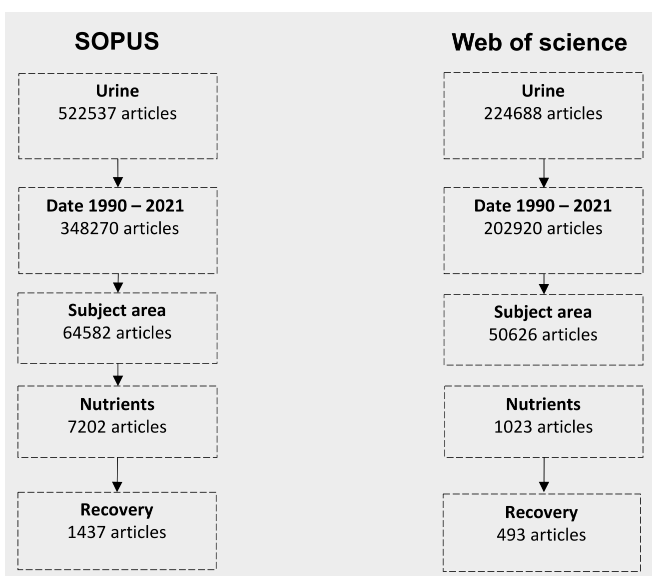

Fig. B1. Summary of the search and refinement process for string 1.

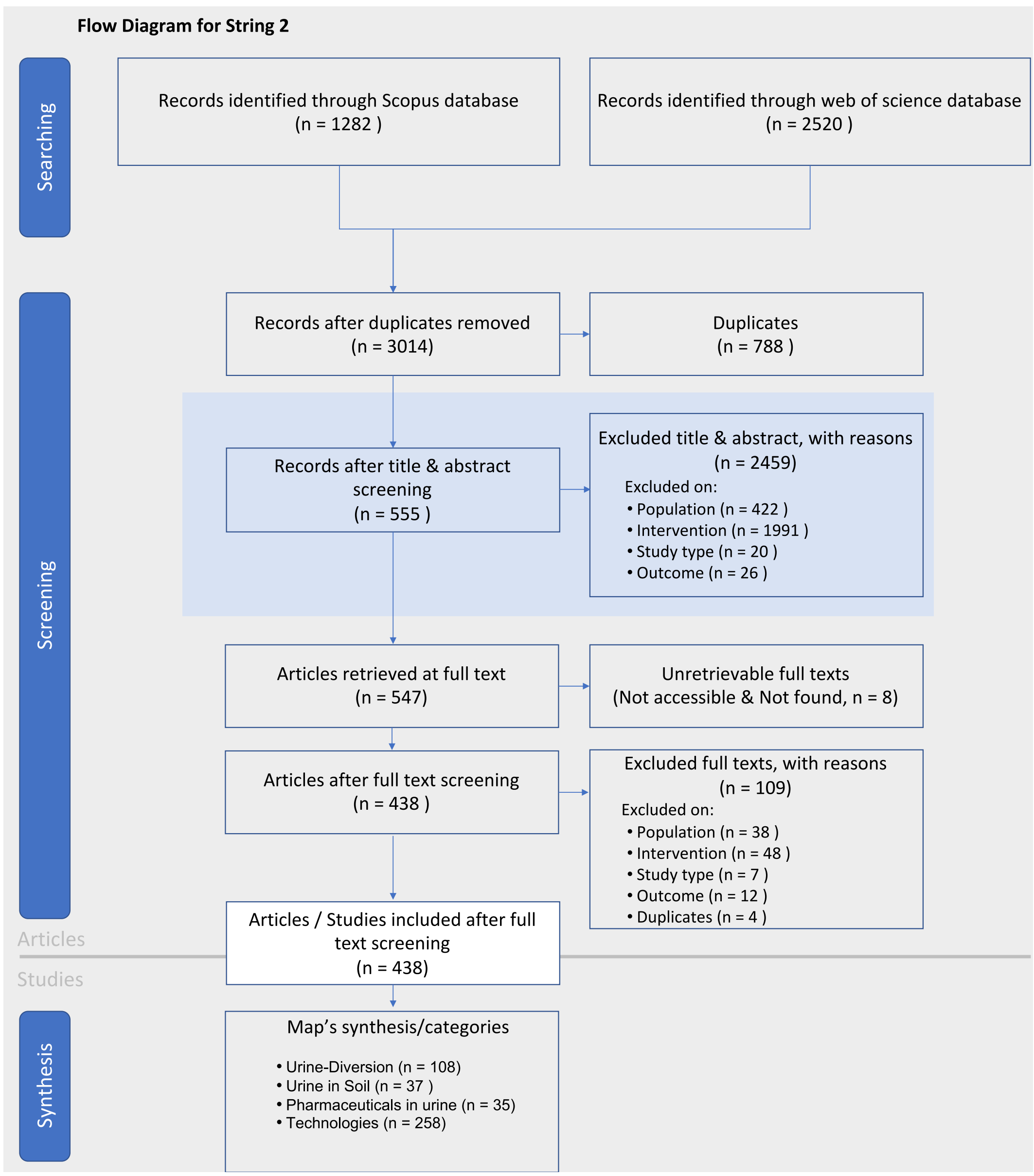

Fig. B2. Flow diagram illustrating the screening process and coding of string 2, i.e., the number of records excluded and retrieved on duplication, abstract, and full text.

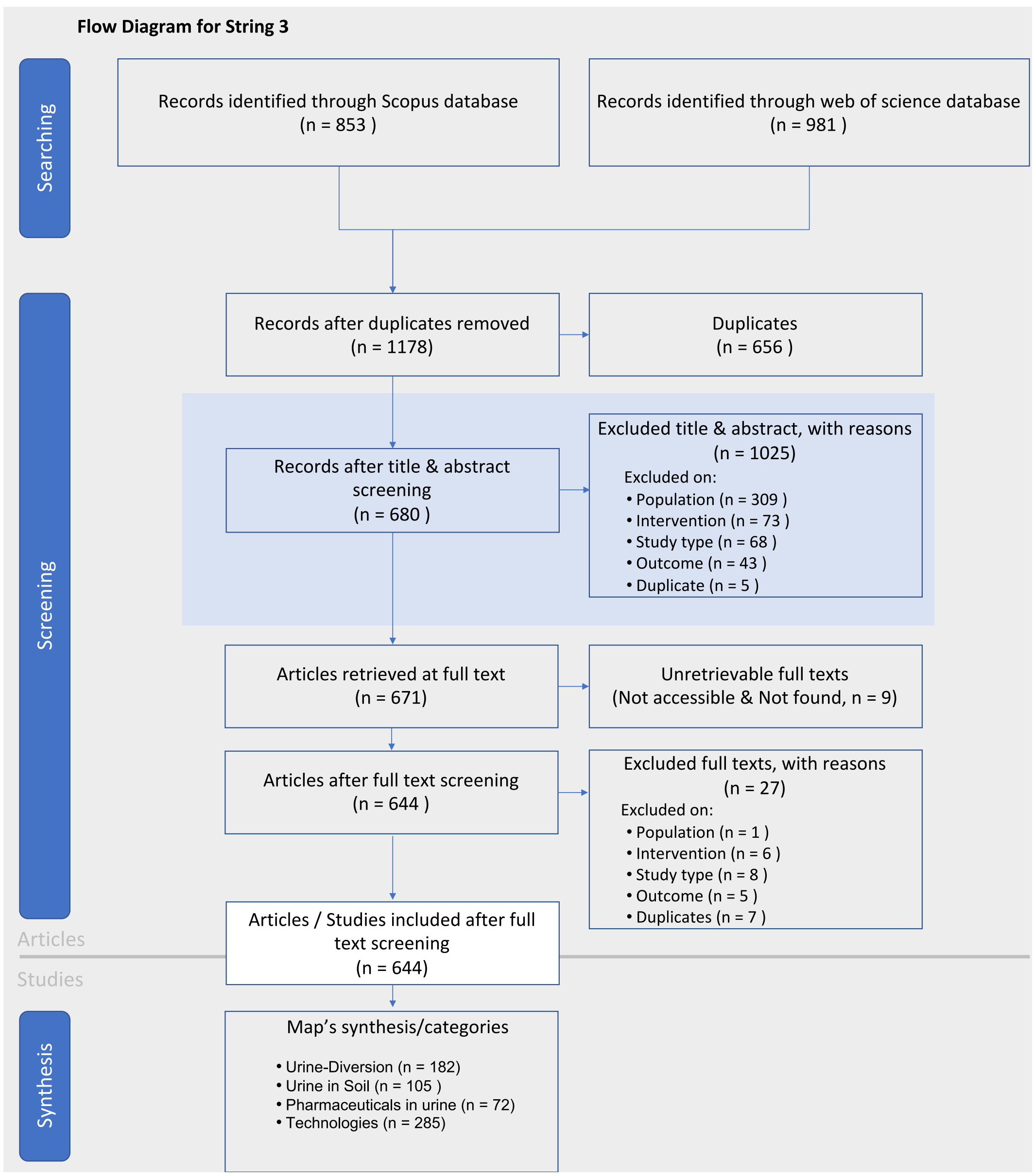

Fig. B3. Fig B2: Flow diagram illustrating the screening process and coding of string 3, i.e., the number of records excluded and retrieved on duplication, abstract, and full text.

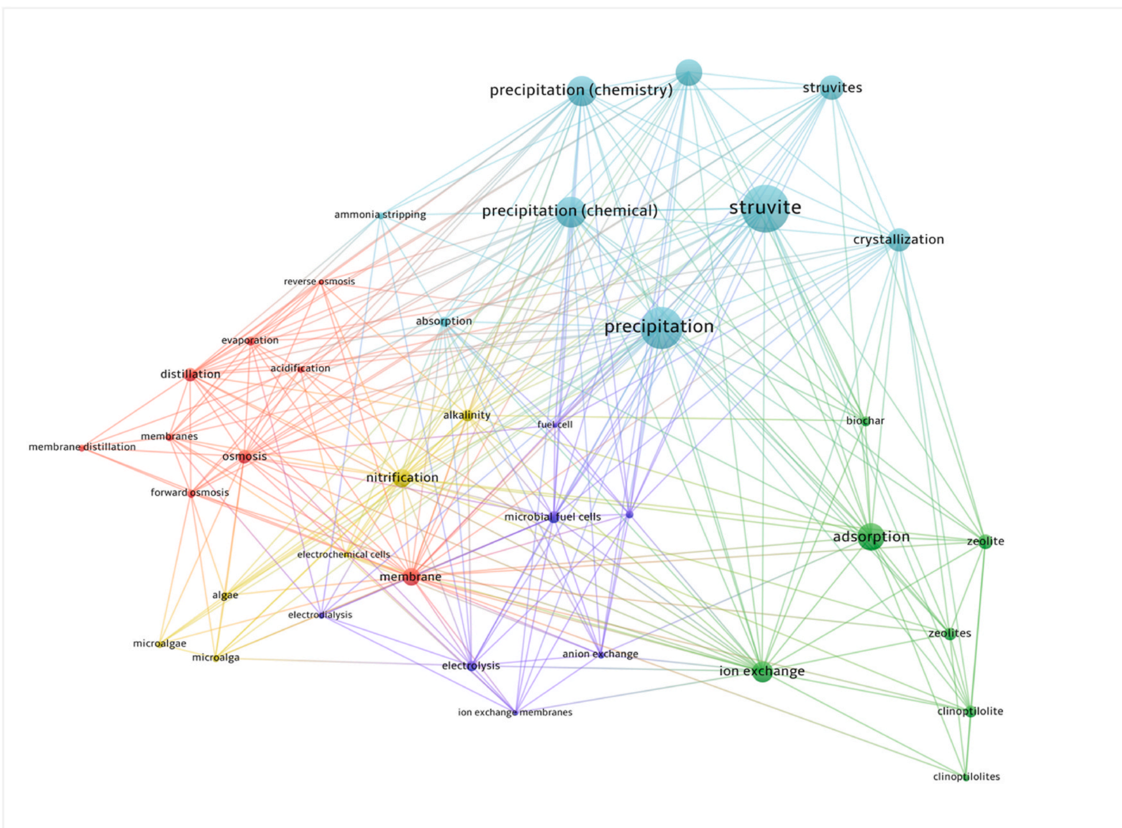

Fig. B4. Frequency of occurrence of technologies keywords within the urine technologies category, with larger circle size indicating higher frequency of occurrence. Diagram designed using VOSviewer tool. Colors represent technologies clusters, e.g., light blue

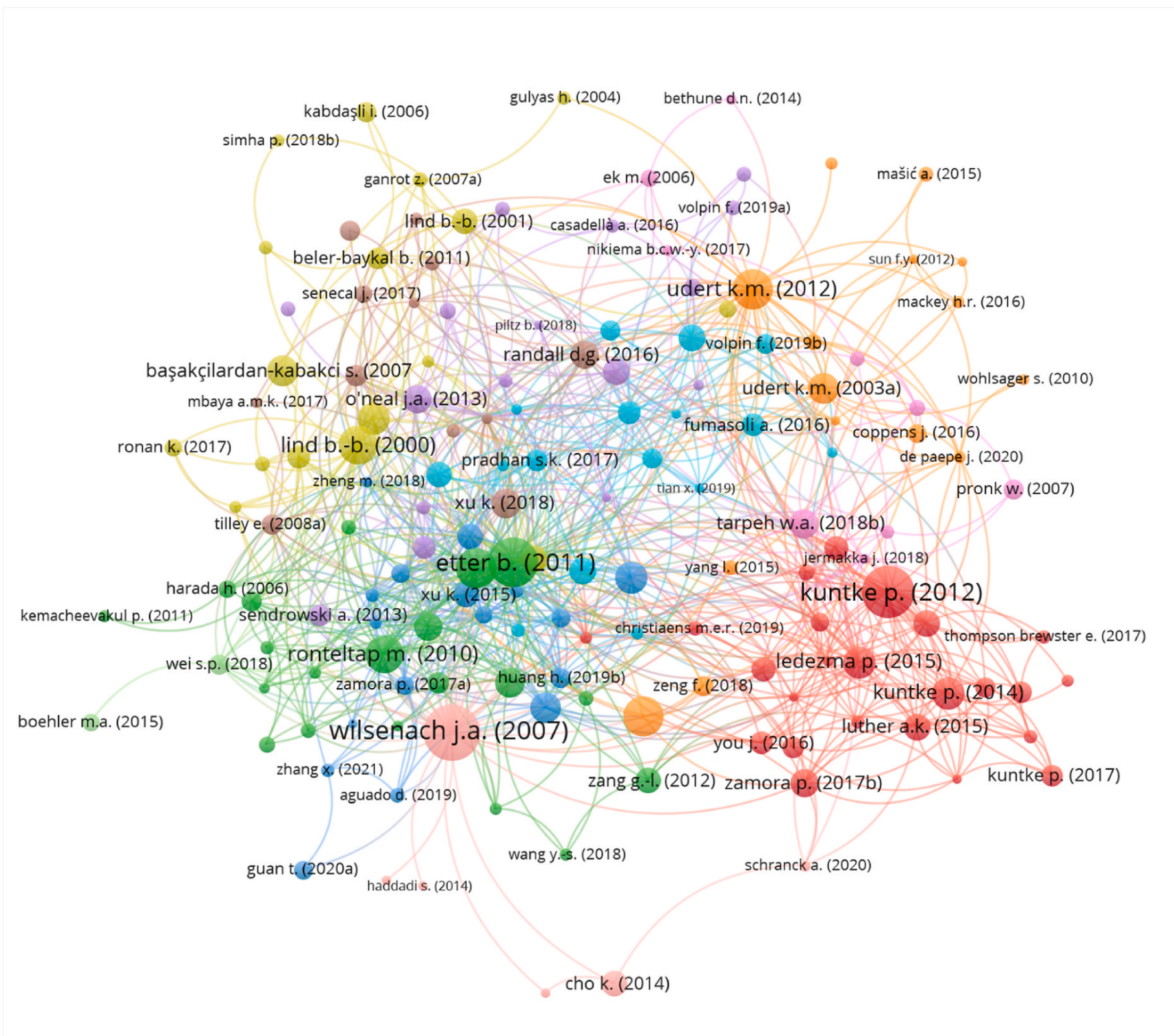

Fig. B5. Citation analysis results. Top cited papers within the urine technology subcategory are: (Etter et al., 2011; Ganrot et al., 2007; Hug and Udert, 2013; Kataki et al., 2016; Kuntke et al., 2012, 2014; Ledezma et al., 2015; Lind et al., 2000; Ronteltap et al., 2007, 2010; Udert and Wächter, 2012;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

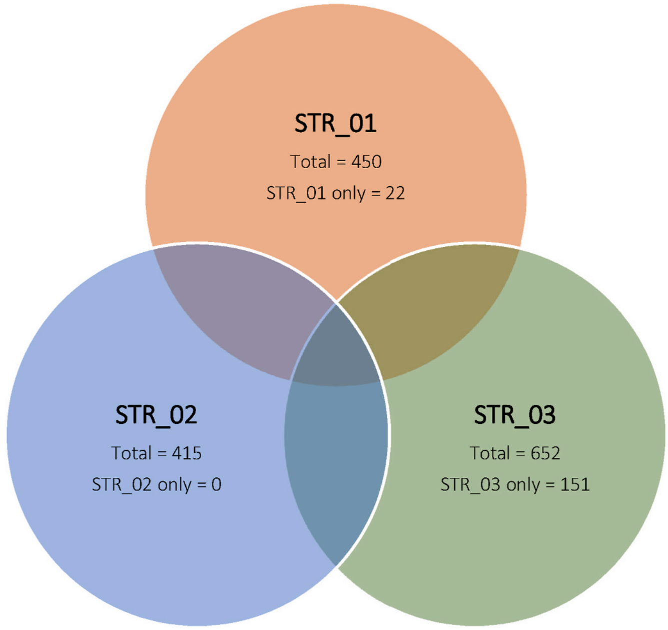

Fig. B6. Overlaps in hits between search strings (STR) 1, 2, and 3.

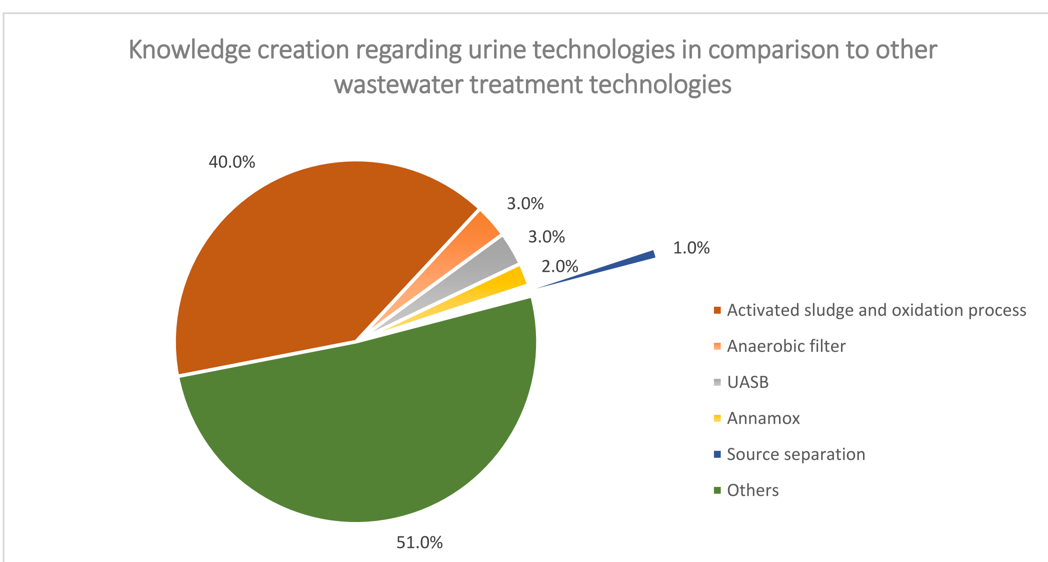

Fig. B7. Proportions of urine-related publications in the total number of wastewater publications 1990–2021.

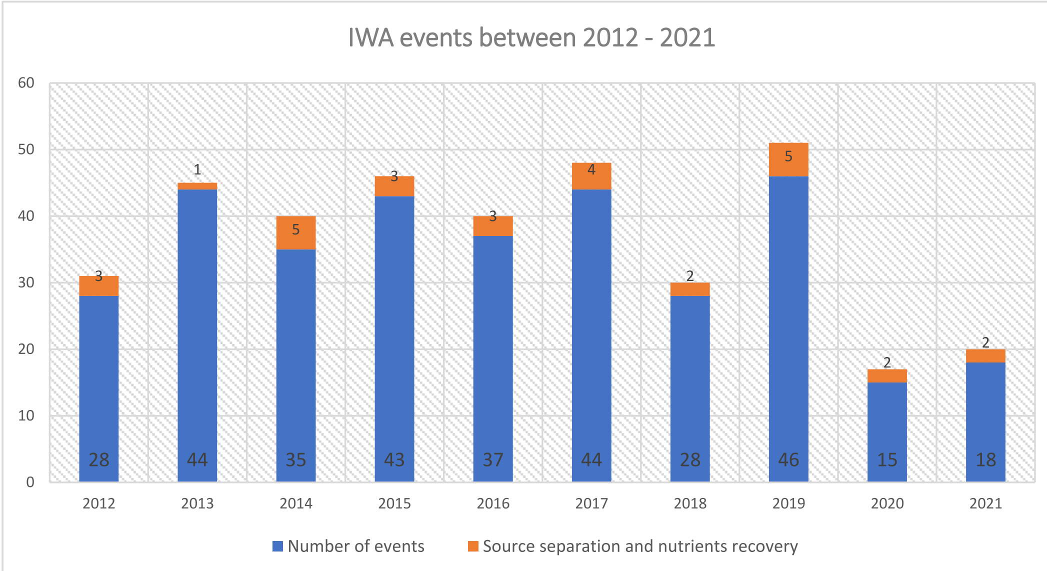

Fig. B8. Number of International Water Association (IWA) events per year, 2012–2021.

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