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REVIEW PAPER

Assessing the Potential of Water Reuse Uptake Through a Private–Public Partnership: a Practitioner's Perspective

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Abstract

Around 20% of the global water abstractions are originated by the industrial sector, while water demand overall will increase by 20–33% by 2050. Wastewater could provide an alternative source of water for industrial activities. There are not many studies exploring the potential of treated wastewater use under a private–public partnership (PPP), despite their potential of contributing to an effective integrated water management through the creation of inter-sectorial synergies. This paper aims therefore to provide a holistic overview of the main factors that affect the effectiveness of PPPs in using treated municipal wastewater in the industrial sector. Through a systematic literature review, the main barriers, drivers, industries and different applications of water use are analysed. Barriers and drivers are classified through the inductive Gioia method into seven categories. The results showed that economic and technical aspects related to the feasibility of the scheme were most prominent in the literature, while water availability seems to be central driving factor for such water reuse schemes. The conclusion of PPPs in water reuse, however, relies on the possibilities for such a partnership and on bridging the needs of the two parties, which entails effective communication through negotiation and information sharing. This paper is a first step to understanding how water circularity practices under an interconnected and sustainable urban environment can be facilitated and explored.

Keywords Systematic literature review · Industry · Implementation · Barriers · Drivers · Treated wastewater

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Introduction

The lack of adequate available water resources is currently affecting approximately 29% of the global population, with water stress being evident in 5 out of 11 regions worldwide [1]. Water stress imposes pressure to the ecosystem balance and negatively impacts economic activities or human health [2] and it is estimated to intensify in many areas of the world under a business-as-usual scenario [3]. Additionally, water demand is expected to rise by 20–33% by 2050 against the 2010 levels primarily due to anthropogenic activities as industrial development, power generation and domestic water use [4, 5].

Approximately 70% of total water use is accounted for agricultural activities while industries have experienced over time a growing dependency on water availability as water abstraction resulting from industrial intensification increased to 22% of the global freshwater use [6]. In the European Union (EU), 28.8% of the total water consumption is accounted mainly for power generation, manufacturing, mining and construction [7], while the rate for industrial water abstraction in Asia and South-Central America is 9% and 12% respectively [8, 9]. The numbers are expected to increase on a global level, specifically in electricity generation and manufacturing, stressing the need to seek efficient alternatives in water consumption in the secondary sector.

Large urban centres are particularly vulnerable to water stress [10], not only because of the increasing population density but also because it is the hub for economic activities and can become a source of water competing demands [11, 12]. Urban water resources need to be distributed primarily among domestic, industrial and peri-urban agricultural use, taking into consideration multiple factors, such as population size and structure, economic development patterns, urban infrastructure and technological adaptations while considering both real and virtual water flows [13]. Competing demands and interrelations with other resources and actors in urban environments showcase the complexity of the system and call for an integrated approach to water resource management. Coupled with the worldwide population growth projections, water resources demand immediate attention and the application of holistic resource management approaches that make use of circularity principles.

The latest report on the progress of SDG6 urges the incorporation of wastewater use in water stress strategies [1]. Wastewater is a promising alternative to freshwater use, which still lies largely untapped. While in certain areas the application of water reuse has been successfully applied in agriculture, industrial processes, urban purposes or aquifer recharge, around 80% of the wastewater produced globally is released to the environment without treatment, posing a threat to environmental and human health [14–17]. In the EU, only 2.4% of the treated wastewater is being reused, indicating an enormous potential for further utilization [18].

Treated wastewater is a valuable resource that has been the focus of circular economy practices through the prevention, preparing for reuse, recycling, recovery and disposal framework [19, 20]. In agricultural systems, wastewater is a multiple resource input by providing an alternative water resource and additional valuable nutrients for fertilization, such as phosphorus and nitrogen [21, 22]. Furthermore, through the wastewater treatment process, the generated sludge can be repurposed through the recovery of minerals and metals, as well as a resource itself for energy generation through biogas production during the anaerobic digestion and in industrial applications, such as the building sector [23–26].

Wastewater as a resource has been utilised in the industrial sector by many organizations in the form of water reuse schemes as a response to water scarcity. These schemes can either be applied internally within the company, or by using wastewater from an external

source. Most widely applied practice is the internal water reuse, which enables the company to repurpose its wastewater, decreasing the level of water consumption as well as the waste discharge rate [27]. Schemes for external water reuse have been less common. External water uses can take the form of an industrial symbiosis where wastewater of one company is used as an input for another [28], or as partnership between the municipal water provider and the industry [29, 30].

In the use of municipal wastewater within industries, industrial partners have a better capacity of covering costs for supplementary treatment [31] than the final users in agriculture where the costs for water treatment are mostly covered by the water provider [32]. Bringing the public water utilities and the industrial users under a private–public partnership (PPP) is a promising alternative water reuse scheme that could optimise urban water management and the industrial and business processes. In the case of the Netherlands, a series of discussions of a chemical company with the local water utilities resulted in replacing desalinated seawater with municipal wastewater in their processes [33]. Similarly, a PPP between a wastewater treatment plant (WWTP) and a refinery in California lead to the repurpose of the wastewater in boiler feed, creating benefits for both partners and the local community [34].

The inclusion of the private sector in natural resource management and strategies has been widely advocated [35, 36] and it becomes now one of the central stakeholders for the European Green Deal [37]. Additionally, the promotion of partnerships among stakeholders is pillar to the Sustainable Development Goals (SDGs) [38] because they recognise it as a fundamental component for a successful scheme outcome [39, 40].

Adopting the nexus thinking in urban management would result in an inter-sectorial and intra-sectorial cooperation that considers resource fluxes and interlinkages among resources, such as food, energy, water or waste [41]. This thinking comes into agreement with the circular approach of urban systems, where resource consumption and production need to be planned across all levels and actors [42]. Parallels between the nexus thinking with the circular economy paradigm clearly highlight pathways on how urban sustainability and resilience of urban systems could be fostered [43].

PPPs, as a form of such intersectoral cooperation, are known to facilitate the sustainable management of water resources through the participation of the private sector in water infrastructure projects, and for the transfer of technological know-how and financial capacity [44, 45]. Contracts of PPPs in water reuse have been increasing rapidly over the years, especially in upper-middle and high-income countries [46]. However, the number of PPPs in the water sector remains limited. The purpose of this paper is therefore to explore and assess the potential of municipal wastewater use in industries under a PPP and aims at defining knowledge gaps for a wider implementation of PPP in water reuse projects as follows:

1. In which sectors and processes can wastewater be reused?
2. What are the barriers for using treated municipal wastewater in industries?
3. What are the drivers for using treated municipal wastewater in industries?
4. What is the potential for a PPP between a municipal wastewater treatment plant (MWWTP) and the industry?

The paper is structured as follows: The "Methodological Approach" section explains the methodology that was undertaken for this study. The "Results" section presents the results of the systematic literature review, while the "Discussion" section expands on

the analysis of the results to give a comprehensive outlook on the applicability of urban water reuse under a PPP. The "Conclusions" section gives a short summary of the conclusions and suggestions for future research.

Methodological Approach

For the purposes of this study, the data was collected through a systematic literature review and was classified using the GIOIA methodology. The steps that were taken are presented in Fig. 1 and are explained in the following subsections.

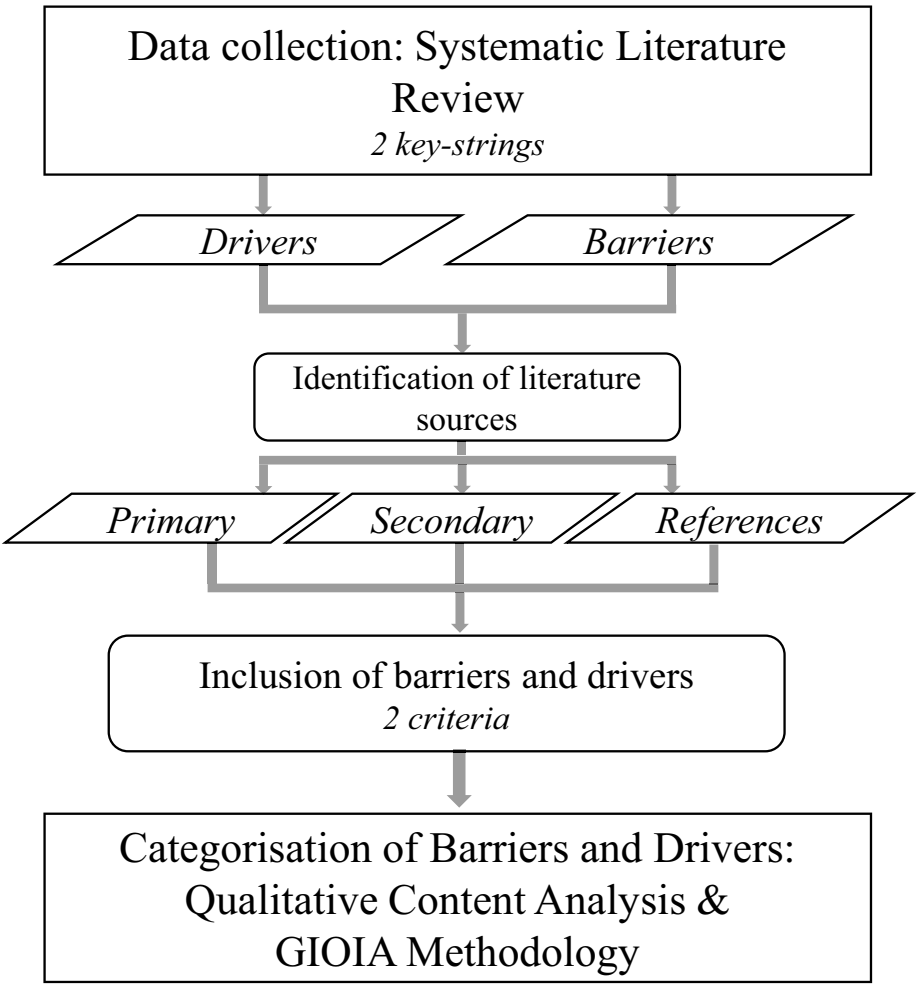

Fig. 1 Methodological process of the paper

Systematic Literature Review

A systematic literature review (SLR) was conducted with the purpose of identifying the possible barriers and drivers mentioned in the literature for reusing municipal wastewater in the industrial processes under a private–public partnership. Furthermore, through the SLR, potential or already applied cases were identified. SLRs have been widely applied in research for summarising and analysing previous knowledge in a systematic, replicable and reliable manner [47]. SLRs have been traditionally used in the medical sciences [48], but due to their suitability for objectivity maximisation in qualitative research, they have proven a key method in many scientific fields, including business, environmental science, technologies and political sciences [49–55].

Two different key strings were used, one for identifying the barriers and one for the drivers. Table 1 presents the keywords used for the two key strings, as well as the excluded criteria. Therefore, the following keywords and alternatives were included in the initial search: "barrier" or "driver", "water reuse", "industry" and "municipal". Only results in English language were considered. Due to the limited results generated by the initial search, the case* keyword was included in order to identify relevant cases of application, which would enable the identification of relevant literature and give further insight in the applicability of the scheme. Furthermore, the relevance of papers from different disciplines resulted in a very high number of hits from the key strings. Several excluded keywords from the title were, hence, introduced to increase the relevance of the identified papers, without risking the exclusion of important literature. Such keywords included uses of wastewater not relevant to the scope of the paper, such as those related to agricultural use or purification processes of wastewater, as presented in Table 1.

The databases used for the literature search were Scopus and Web of Science Core Collection, where 12,876 different articles were identified. It must be noted that the final results from Web of Science were included in Scopus and therefore the numbers shown in Table 1 correspond to results from Scopus.

The extracted literature was categorised into primary, secondary and reference. Primary literature includes peer-reviewed articles, whereas secondary literature refers to reports, book

Table 1 Systematic literature review process

	Barrier key string	Driver key string
Keywords	TITLE-ABS-KEY ((water OR wastewater OR "waste water" OR "waste-water") W/1 (reuse OR use OR re-use OR recla*) AND (industr* OR compan* OR business* OR municipal* OR plant*)) AND ALL (barrier* OR obstacle* OR limit* OR constraint OR restrict* OR challeng* OR case*)	TITLE-ABS-KEY ((water OR wastewater OR "waste water" OR "waste-water") W/1 (reuse OR use OR re-use OR recla*) AND (industr* OR compan* OR business* OR municipal* OR plant*)) AND ALL (opportunit* OR driv* OR enabl* OR facititat* OR case*)
Excluded keywords	TITLE (agricultur* OR irrigat* OR membran* OR *microb* OR remov* OR *aerob* OR river* OR osmo*)	
Hits	4803	1183[a]
Title scr	316	30
Abstract Scr	73	7
Final[b]	20	1

[a]Without duplicates with the barrier key string

[b]Including all literature (primary, secondary)

chapters, conference proceedings and case studies or examples. Reference literature refers to sources identified through the screening of the reference list of the identified literature. Twenty-one sources were identified through the SLR, whereas the reference screening resulted in the identification of further four sources, as shown in Fig. 2. Furthermore, three additional publications were identified that presented cases without mentioning barriers or drivers.

Categorisation of Barriers and Drivers

Qualitative content analysis and the inductive Gioia [56] methodology were used for the identification and categorisation of the barriers and drivers. Qualitative content analysis is a mixed methods approach that combines the advantages of quantitative and qualitative analysis for text coding and interpretation according to Mayring [57]. For the purpose of this study, qualitative content analysis is used to identify and categorise the passages to barriers and drivers, which will then be classified with the Gioia method, as well as analyse the findings. According to the methodology developed by Gioia et al. [56], the findings are classified based on the specific characteristics without pre assumptions or pre-assignment of the text to categories.

Identification of Barriers and Drivers

Per definition, a barrier can be a factor or physical object that prohibits or hampers access to a specific point [58–60] or an element that is obstructing the progress towards achieving a goal [32, 61, 62]. On the other hand, drivers are the elements that enable or facilitate access or progress. In this study, barriers are considered the sum of factors hampering the uptake of treated municipal wastewater for industrial uses, whereas drivers are the enabling factors for the same purpose.

Two criteria have been set for the inclusion of the barriers and drivers in the analysis:

1. The differentiation of water reuse practices,

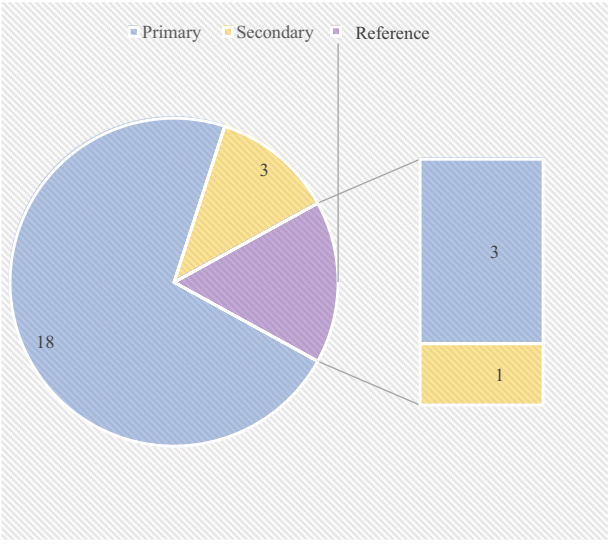

Fig. 2 Distribution of literature to categories

2. The exclusion of secondary knowledge in the papers that was derived from other peer-reviewed articles.

As the scope of the paper is to focus on the external (municipal) wastewater use, factors referring to industrial wastewater use were not taken into consideration. Subsequently, barriers and drivers related to internal water reuse or industrial symbiosis concepts were excluded. The second criterion addresses the issue of possible multiple counting of the same barriers or drivers. The included papers present original research and therefore, knowledge that is referred to another peer-review publication was not considered. In addition, context interpretation was essential for the conducted research and therefore, the second criterion further aimed to avoid misinterpretation of the identified passages, as validating the interpretation of the codes with the authors of the papers was not possible.

Classification Framework

Analytical frameworks for barrier classifications have been used in previous research, with most prominent the PESTEL analysis and its variations [63–65]. The PESTEL framework classifies factors to political, economic, social, technological, environmental and legal, and it has been primarily used as a decision-making support tool for business purposes [66–69]. Apart from the organisational perspective, due to its categorisation to key aspects, PESTEL has been used for assessing and analysing multi-faceted topics, such as trends, targets and policies [32, 69, 70].

Although the PESTEL framework is a widely applied and recognised tool, the results of the present research did not fit its classification adequately. Even though among its classifications only the social aspect was not found relevant in this research, aspects related to technical feasibility, such as the quality of the wastewater, and communication, such as information sharing between stakeholders, could not be appropriately fitted in the framework. Both aspects have special features that are not properly described in the traditional PESTEL framework. On the other hand, the Gioia method allowed the identification of categories while minimising the interpretive bias. This distinctive attribute was the comparative advantage of the methodology and was therefore selected for the purpose of the present study.

The Gioia methodology has been widely used for content analysis and interpretation of findings from interviewers in management studies [71–73] but to our knowledge, it has not been used so far for barrier or driver categorisation. The inductive process of the methodology ensures the minimisation of interpretive bias in content analysis and allows the researcher to cluster similar information based on the available content.

Identification of Categories

The classification of barriers and drivers was done in parallel, with the aim of comparability of the results while allowing for differentiation in the identified categories. As per the inductive reasoning approach, in the first categorisation, the observed barriers and drivers were classified narrowly, allowing for the immergence of a relatively large number of categories. In the second categorisation, patterns among the categories were clustered to form a smaller number of categories. During the third categorisation, the final classification of the barriers and drivers was done, where categories are distinct from one another but broad to serve simplicity and clarity. This procedure resulted in the identification of 7 different categories, as shown in Table 2. The process of the categorisation can be found in the Appendix.

Results

Scope of Publications

Most of the identified literature came from a technical and practical perspective, rather than a theoretical application, which can be reflected in the area of the journals and the focus of the studies. Feasibility studies on the industrial reuse of urban water started early on; however, the discussion has been segmented. The focus of wastewater reuse shifted towards agriculture, while industrial water reuse research explored in situ applications. Most of the identified publications are exploring the applicability and feasibility of municipal wastewater use in industrial applications, with the majority focusing on the technical and economic aspects (Table 3). The year of publications vary from 1988 to 2020 (Fig. 2), a number showing the relevance of the topic over the years. However, the small number of relevant publications in combination with the technical–economic focus of the papers suggests that the topic has great potential for further exploration.

Cases of Application

The practice of municipal water reuse in industries has been present in various arid regions of the world, such as in Arizona, USA or The New South Whales in Australia [74, 75] involving partnerships between entities that are public, private or both. This illustrates the technical feasibility of the scheme for certain industrial applications. Through the SLR and the reference screening, nine different cases of publicly owned municipal wastewater reuse by a private industrial partner were identified (Fig. 3). From those, five were presented in the form of a case study, three scientific and two empirical. Another three case studies of non-running projects were further identified in the form of preliminary findings or exploratory assessment.

It is noteworthy that more than half of the identified cases are located in the USA. The first application in the USA started already in 1942, between a steel industry and the local WWTP in Maryland [74]. The venture was concluded due to the economic feasibility of the scheme, the high water demand of the industry and the reliability of the wastewater supply [29]. Similar characteristics run most of the case studies. Except for the Netherlands, the application of water reuse takes place in regions where water availability is threatened or limited. In the case of India, an important enabling factor for water reuse implementation was the forbidden groundwater abstraction for industrial purposes, making reuse of water

Table 2 Explanation of categories

Economic	Costs and revenues that are associated with the life cycle and feasibility of the scheme
Technical	Aspects related with the technical requirements of the water
Governance	Regulations, policies or other measures taken by a governmental body or public authority on an international, national, regional or local level
Business	Decisions/factors that are related to the internal strategy and the characteristics of the industry
Communication	Information sharing, co-participatory approach between stakeholders
Environmental	Environmental (resource or spatial) characteristics of the area of application
Technological	Factors associated with the effectiveness and efficiency of water reclamation and reuse technologies

Table 3 Distribution of publications to primary subject area of journals

General subject area	No. of publications
Peer-reviewed journals[a]	
Environmental Science	12
Engineering	3
Social Sciences	2
Economics, Econometrics and Finance	2
Earth and Planetary Sciences	1
Mathematics	1
Secondary literature (source)[b]	
Milestones in Water Reuse: The Best Success Stories	1
Wastewater: Economic Asset in an Urbanizing World	1
Transactions—Geothermal Resources Council	1
WEFTEC 2018	1

[a]*Based on the classification from SCOPUS*

[b]*Subject area not available*

the only viable option [17]. The refinery receiving the wastewater uses around 2/3 of its water needs from the municipal WWTP and the rest recovers from internal reuse.

Figure 3b shows that the practice is being applied solely in water-intensive industries, such as power plants or refineries, highlighting the importance of reliance on water resources from the industrial user. Most of the cases apply wastewater for cooling purposes or as boiler feed, where water quality requirements are not demanding.

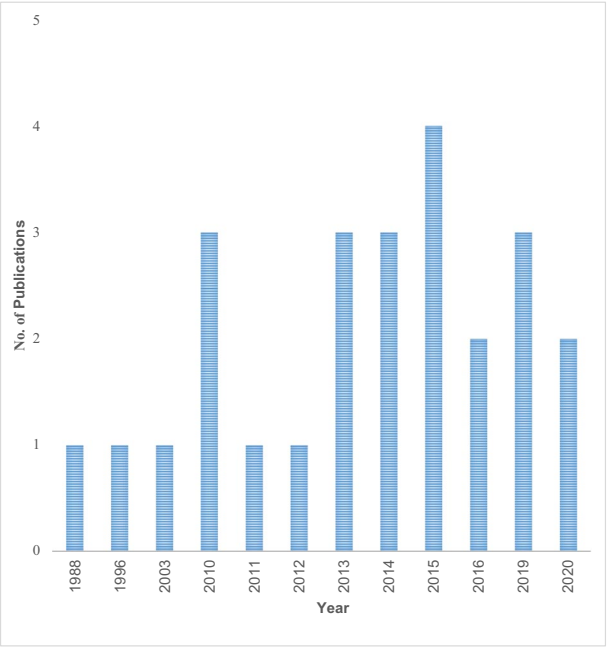

Fig. 3 Year distribution of publications

Barriers and Drivers

Multiple barriers and drivers were identified and grouped per category, as shown in Fig. 4. Most of the frequently mentioned barriers and drivers fall under the economic and technical categories (Table 4), which can be partially explained by the primary subject area of the papers on the same topics. Barriers relating to the costs and technical requirements of water are most present in the literature, highlighting the importance of infrastructure costs and water pricing and the high quality of water for the feasibility of such a water reuse scheme. In particular, the importance of water quality was mentioned twelve times in the literature, followed by the price difference between conventional water and wastewater being mentioned six times. On the other hand, drivers are more uniformly distributed among the categories, especially among business, economic, technical, governance and environmental. Here, environmental factors provide an important boost for water reuse uptake, as well as open communication between the stakeholders.

Barriers and drivers form a system of factors and cause-and-effect chains, which affects the outcome of the water reuse project. The difference in their distribution indicates the complexity of the system and stresses the need for a holistic approach to problem-solving [76]. While barriers provide the status of realizability from a project management perspective, drivers provide a more diverse representation of the factors that could potentially enhance the process. The most prominent interconnections between the categories of barriers were analysed based on content analysis of the identified literature and are presented in Fig. 5 to show how they can be addressed and to provide a pathway for action prioritisation. For example, low quality of wastewater causing corrosion, scaling or biofouling was reported to result in high costs for repairing or replacing the damaged area [77]. Similarly, the absence of a fit-for-purpose legislative scheme is connected to high wastewater treatment costs due to the costly technological demands for meeting the required quality [78]. Economic aspects are central to the system and mirror the relevance of such barrier in the state of the art. However, a number of factors have a direct or indirect relation to the economic feasibility of the project, which in turn can stir the outcome to one or the other direction (Fig. 6).

Discussion

The Use of Municipal Wastewater in Industries

It is evident from the existing case studies that water-intensive industries are the sole industrial users of municipal wastewater. Water availability seems to be central driving factor for

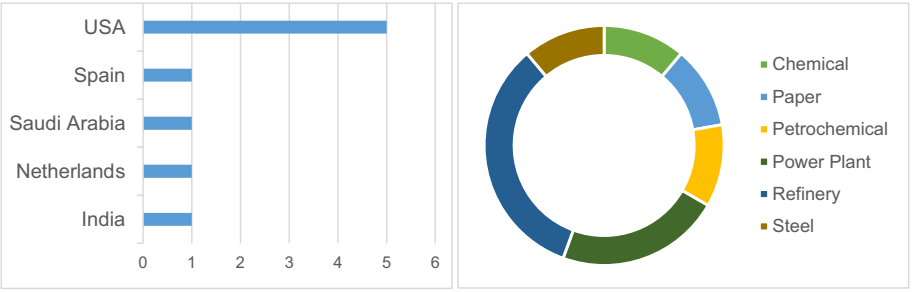

Fig. 4 Distribution of PPP cases on water reuse in industries. a Geographical location of application. b Industrial sectors of application

Table 4 Most frequently mentioned barriers and drivers in the literature

	# of mentions	Category
Barriers		
Low quality of wastewater: fear of corrosion, biofouling and/or scaling	9	Technical
Price difference between conventional and reclaimed water	6	Economic
High capital costs associated with changing from conventional to reclaimed water	4	Economic
Lack of effective/adequate wastewater policy	4	Governance
High cost of pipeline infrastructure	3	Economic
Possible fluctuations in wastewater effluent quantity	3	Technical
High O&M costs associated with water reuse	2	Economic
Drivers		
Higher cost of fresh water	4	Economic
Lack of water availability	4	Environmental
Appropriate quality of wastewater	2	Technical
Communication/information sharing with stakeholders/industrial partners/users	2	Communication
Presence of legislative mandates	2	Governance
Stricter regulations	2	Governance

such water reuse schemes, as industries seek to sustain their competitive advantage and find alternative solutions in case of resource availability limitations [79, 80]. Here, water reuse enables industries to be an integral part of sustainable cities by their connection to an optimised and smart water network that would allocate water resources to the end users based on water availability and quality. Apart from the water dependency of the industries, economies of scale are of essence. All the cases involved industries with large amounts of water use in their processes. The high costs associated with the implementation of the scheme make it very hard for small and medium-sized enterprises (SMEs) to cover [81]. Furthermore, large water users can have different water tariffs from SMEs, making them a more probable end user in some countries [82, 83]. Another factor that determines the potential industrial users is the required water quality. Water quality demands for cooling systems and boiler feed are low compared to other processing uses, such as washing or fabrication [84, 85].

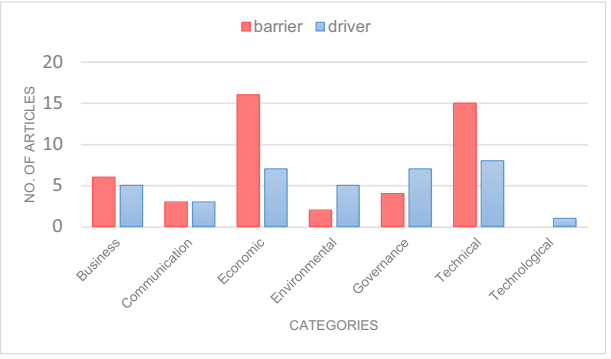

Fig. 5 Distribution of barriers and drivers to categories in respect to the number of mentions in the literature

Fig. 6 Interrelations between the different aspects in respect to the realisation of a PPP for urban water reuse in industries

Challenges of Implementation and Identified Solutions

The state of local infrastructure is considered key aspect for the uptake of urban water reuse. Wastewater needs to be transported effectively and frequently from the generating source to the WWTP and from the WWTP to the end user, which in this case is the industry. An extensive sewer network will allow the collection of wastewater from the urban area, as well as the transportation of the wastewater to the potential industry [86]. However, in many cases infrastructure is poor or non-existing and in heavily populated areas the replacement of the pipeline network is high cost demanding, making water reuse a non-viable option [78, 87]. Furthermore, industrial areas might not be directly connected to the wastewater provider. As such, one of the main factors affecting the feasibility of the project is the distance of the WWTP to the industry and the associated costs for infrastructure [88, 89]. The upgrade of infrastructure for the optimisation of wastewater collection and transportation and the minimisation of environmental impacts throughout its life cycle would enable circular applications in the urban and peri-urban areas and promote sustainability, as defined by SDG Target 9.4 [90]. However, supply of water for industrial use is less costly than that for residential use [91], which in combination with a lower water price could lead to the uptake of wastewater.

Technical requirements of the wastewater can influence costs associated with capital expenditure and operation and maintenance. Capital investment on retrofitting internal systems to enable the efficient use of wastewater can be cost demanding. Reclaimed water is primarily used in cooling systems or for boiler feed, as the technical requirements for these applications are relatively low. Open-loop cooling systems can potentially be used for wastewater; however, closed-loop systems are usually used [89] and therefore, a change in the system requires substantial capital expenditure. Potential limited reclaimed water availability from the WWTP also contributes to the choice of cooling system. Open-loop systems require a larger amount of water, which is unlikely to be covered by the provided wastewater [92]. In the case of a Nuclear Power Plant in Arizona, the conflicting high water demand from the industry with the local community compelled the industry to change its water consumption systems [74]. This adoption of circular approach to water consumption eased the pressure industrial activities put on local water resources and enhanced the sustainability of the area and the community.

Fluctuations in water availability also create the need for buffer tanks with make-up water in order to avoid water shortages in the industrial processes [93]. Furthermore, wastewater quality influences the operation and maintenance of these systems. Even though water quality requirements of cooling towers and boiler feed are not demanding in contrast to other water uses, characteristics such as the hardness of wastewater and the flow fluctuation can cause corrosion, fouling or scaling, which in turn requires a constant maintenance cost on applied chemicals and curing methods [30, 77, 88]. However, the relatively low water quality requirements in combination with the lack of human contact with the wastewater, thus minimising health risks and possible reservations from the population [94], make the reuse scheme a unique opportunity for maximising the benefits of the circular approach to water management. As defined by Kakwani and Kalbar [95], the type of water reuse that is discussed in this paper falls under the reclaim category of the "6R" strategies for circular economy. In the context of urban sustainability, industrial uptake of recycled water presents a unique solution that not only contributes to local water stress alleviation, but also optimises wastewater distribution to a socially sustainable and publicly acceptable application.

A much discussed debate lies around the pricing of water resources. Water-intensive industries rely heavily on water resources and their pricing. The main objective of the private sector is profit maximisation, which lies partially on cost minimisation. Treated wastewater is usually priced higher than conventional water due to the costs of collection and treatment, energy requirements or maintenance of the infrastructure [76]. Therefore, in areas with low freshwater prices, uptake of wastewater is not preferred [96]. Economies of scale are also interlinked in the determination of water pricing as a potential barrier, as they affect the costs per unit [97]. Additionally, Zapata [27] found that medium-sized firms consume on average more water than large firms, making thus the scheme more attractive to large water users. Apart from the limiting capability of SMEs to cover the increased per unit price of the wastewater, the viability of water treatment also depends on the amount of water received and treated by the WWTPs. Costs of water treatment are distributed more efficiently in large WWTPs, making the pricing of the reclaimed water more appealing [83].

Apart from the technical and economic aspects of feasibility, the lack of governmental action is a decisive factor for the uptake of the scheme [89]. Policies that do not target on optimal water resources pricing or that do not differentiate on the water requirements based on the type of use can influence the feasibility of water reuse [87]. Targeted policies and well-regulated water resources can result in efficient re-allocation of water consumption to the end users. Inclusion of fit-for-purpose water regulations that will allow the reuse of water based on the quality requirements of the targeted use combined with financial incentives, such as reduced tariffs for reclaimed water use or subsidies to companies, provides the pathway for

such circular practices. Furthermore, stricter regulations governing waste discharge and water consumption will enhance the financial sustainability of the reuse project [17, 88, 96]. Governmental action through the implementation of wastewater discharge fines would incentivise companies to find alternative solutions for its wastewater disposal [98].

Aspects for a Successful Private–Public Partnership

Aspects such as technical requirements, economic feasibility and regulatory mechanisms are essential to the application of the project and have been widely discussed and analysed in the literature. The conclusion of PPPs in water reuse, however, relies on the possibilities for such a partnership and on bridging the needs of the two parties. Here, the adoption of a sustainable business strategy will lead to the venture of innovative partnerships for sustainable resource consumption [34]. Furthermore, the two parties have different priorities. While the industrial sector highlights the importance of economic factors, public water utilities often focus on the social and legal criteria as most important for water reuse schemes [99]. This is a crucial component that needs to be addressed, as the difference in priorities of the different sectors is one of the main challenges when addressing nexus thinking in natural resource management [100]. Enhanced communication between the stakeholders is therefore essential, as it will lead to harmonisation of the different priorities and can lead to the identification of a common solution.

Timely and open sharing of information will allow to allocate from the beginning of the project the preferences and requirements of the parties involved, leading to win–win situations. Water requirements from the industrial users of wastewater not shared in time would result in higher costs to the WWTP, due to the time-sensitive adaption of the treatment process. A timely communication of the needs would allow for lower costs, leading to lower water prices, reducing thus negative externalities related not only to the project, but also to other possible water end users [101]. Key aspect is the long-term planning of activities, which allow the maximisation of the project efficiency and possible outcomes.

The appropriate negotiation in the terms of a PPP is not only crucial for the financial sustainability of the project, but also has the potential of expanding the applied circular economy strategies of the project. Through the optimisation of wastewater treatment processes and distribution network, recovery of resources from the wastewater could be a viable option for the WWTP and the industry. However, this cannot be done without open and timely communication between the two partners that would allow for an agreement to mitigate shortfalls from risk prediction and uncertainties of the project [102].

The duration of the PPP contracts is itself a topic of negotiation between the two actors. While public sector seeks the long-term sustainability and planning of the project, private actors prefer a shorter return of investment [103]. Here, open sharing of information and common planning between the partners will allow for a better estimation of the benefits of the project and create the opportunity for insightful discussion [88, 104]. The cover of capital costs can ease the conclusion of a PPP. In the example of Tarragona, Spain, the initial capital investment was covered by the public sector (EU, Country and State) [104].

A shared vision of the project can lead to a common finance model, which can in turn could ensure the success of the project [31]. Open communication and negotiation in relation to costs and benefits from the two parties enable the optimal cost allocation. Towey et al. [93] reported that negotiation processes resulted in economic benefits for the industrial partner through the establishment of a credit system for its use of recycled water. Case studies, such as the one in Maryland and California, showcase that the low water tariffs

from the water provider and the coverage of capital costs from the industries lead to successful implementation [29, 34].

Conclusions

It can be concluded that climatic conditions and water stress are the common denominator that leads to the water reuse uptake, with most identified cases being applied in the arid parts of the world. However, many of the characteristics are case specific, such as the urban infrastructure and the regulatory framework in place. In addressing the global challenges of water stress and urban transformation, synergies need to be identified in order to increase resilience of urban areas. Fostering the industrial use of wastewater through a PPP will not only enhance the resilience of urban systems, but will also bring tangible progress towards SDG6. Although PPPs for water reuse in industries are present for many decades, there has been little scientific discussion on the specifications of the schemes.

This is the first study that brings together the challenges and enabling factors of such a water reuse practice. While the use of municipal wastewater has been widely assessed in the agricultural context, the current study differentiates in the identified barriers and drivers, with the focus shifting from the social aspects of acceptance to the business characteristics and openness of the involved actors. The lack of health and environmental concerns in the possible industrial applications of wastewater use makes the scheme a viable opportunity for simultaneous freshwater stress alleviation. Furthermore, the systemic waste minimization concept of water reuse, adopting the circular economy paradigm, leads to water pollution minimisation. Comprehension and analysis of mechanisms to facilitate PPPs can promote circularity of water within a well-interconnected urban environment.

Overall, economic criteria such as infrastructure costs, water price and capital investments are undoubtedly the central factors influencing feasibility. However, regulatory actions, technical specifications of the water, information and knowledge transfer and the characteristics of the industry are pivotal elements that in turn influence these economic aspects. It is, therefore, important to understand the system dynamics of the area of application, not only to enhance the viability of the scheme, but also to create the circumstances that will provide the necessary incentives for the two sides to reach an agreement. The showcased complexity of the system makes synergies between sectors important and can lead to an increased understanding of the system, which in turn will allow for the adoption of nexus solutions in urban management.

The main limitation of the study was the focus of the identified literature on the technical and economic aspects of the scheme, where the emerging topic of sustainable business strategy and open communication across sectors were identified but could not be well assessed due to the limited available information. Although aspects of governmental support through fitting regulatory frameworks were frequently mentioned in the literature, details on the nature of these regulations were not adequately presented. In addition, the role of the public sector in the negotiation process was not well highlighted, as opposed to the general literature on PPPs. Future studies could deepen and expand our understanding of sustainable solutions in urban systems by analysing different business strategies, as well as co-participatory approaches that address the role of public sector actors for smart water reuse practices.

Appendix

Tables 5 and 6 show the process of categorisation of the barriers and drivers, respectively. The tables do not consider the number each barrier or driver was mentioned in the literature, but only the categorisation of all the different aspects that were identified.

Table 5 Categorisation of barriers

Barriers	1st categorisation	2nd categorisation	3rd categorisation
High capital costs associated with changing from conventional to reclaimed water	Capital costs	Costs	Economic
High cost of pipeline infrastructure	Infrastructure costs		
High costs associated with water reuse (not specified)	Costs		
High O&M costs associated with water reuse	Operational costs		
High tariffs for water services	Water costs		
Price difference between conventional and reclaimed water			
High variability of wastewater quality	Wastewater quality	Wastewater quality	Technical
Low quality of wastewater			
Low quality of wastewater: fear of corrosion, biofouling and/or scaling			
Low quality of wastewater: risk of reduction of performance effectiveness			
Low wastewater quality			
Low wastewater quality: effect on final product quality			
Possible fluctuations in wastewater effluent quantity	Wastewater volume	Wastewater volume	
Lack of effective/adequate wastewater policy	Policies	Policies	Governance
Lack of financial incentive due to high availability of water	Financial benefits	Industry incentives	Business
Long distance between MWWTP and industry	Industry location	Industry characteristics	
Low amount of water consumption	Industry consumption		
Potential health risk for employees	Health and workers	Health	
Wastewater stream quality does not meet the company's permit standards	Compliance and waste	Industry permits	
Disposal options of RO-reject	Waste disposal		
Different RoI expectations between industry and public utility	Expectations and stakeholders	Communication	Communication
Lack of trust in service provider for constant water supply	Trust between stakeholders		
Perception of the scarcity of alternative sources by stakeholders	Perceptions of stakeholders		
High population density	Population number	Demographic	Environmental
Fresh water availability	Water availability	Water availability	

Table 6 Categorisation of the drivers

Drivers	1st categorisation	2nd categorisation	3rd categorisation
Economies of scale cost-saving in water-intensive industries	Costs and water volume	Costs	Economic
Higher cost of fresh water	Costs and freshwater		
Only affordable method of water consumption	Total costs		
Appropriate quality of wastewater	Wastewater quality	Wastewater quality	Technical
Bio-monitoring and bio-film control			
Consistent water temperature to minimise power generation reliability	Wastewater quality Technicalities		
Mixing wastewater with conventional water			
Monitoring of effluent quality leading to authorization of the project/scheme	Wastewater quality monitoring and appraisal		
Only practical method of water consumption	Technicalities	Technicalities	
Possibility of freshwater use for safety and reliability of high-quality water supply	Water quality and safety	Water quality and safety	
Financial incentives for water reuse	Benefits and policies	Policies	Governance
Policy reform for enhancing financial sustainability in water sector			
Presence of legislative mandates	Regulations	Regulations	
Stricter regulations			
Subsidies for water costs to industries	Benefits and regulations		
Business sustainability strategy	Industry strategy	Industry strategy	Business
Constant high demand for water	Water volume	Industry characteristics	
Large size of company	Industry size		
Water reuse in cooling and processes	Water use process		
Protective equipment by workers for health risk minimization	Health and workers	Health	
Communication/information sharing with stakeholders/industrial partners/users	Stakeholders and communication	Communication	Communication
Negotiating favourable terms in partnership	Stakeholders and negotiation		
Lack of water availability	Water availability	Water availability	Environmental
Low quality of freshwater	Water quality and freshwater	Water quality	
New effective technology	Water quality and technology	Technologies	Technological
High quality/low infrastructure cost/low treatment-conditioning cost combination			

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Declarations

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