Facilitators and Barriers of Global Water Reuse: A Systematic Literature Review

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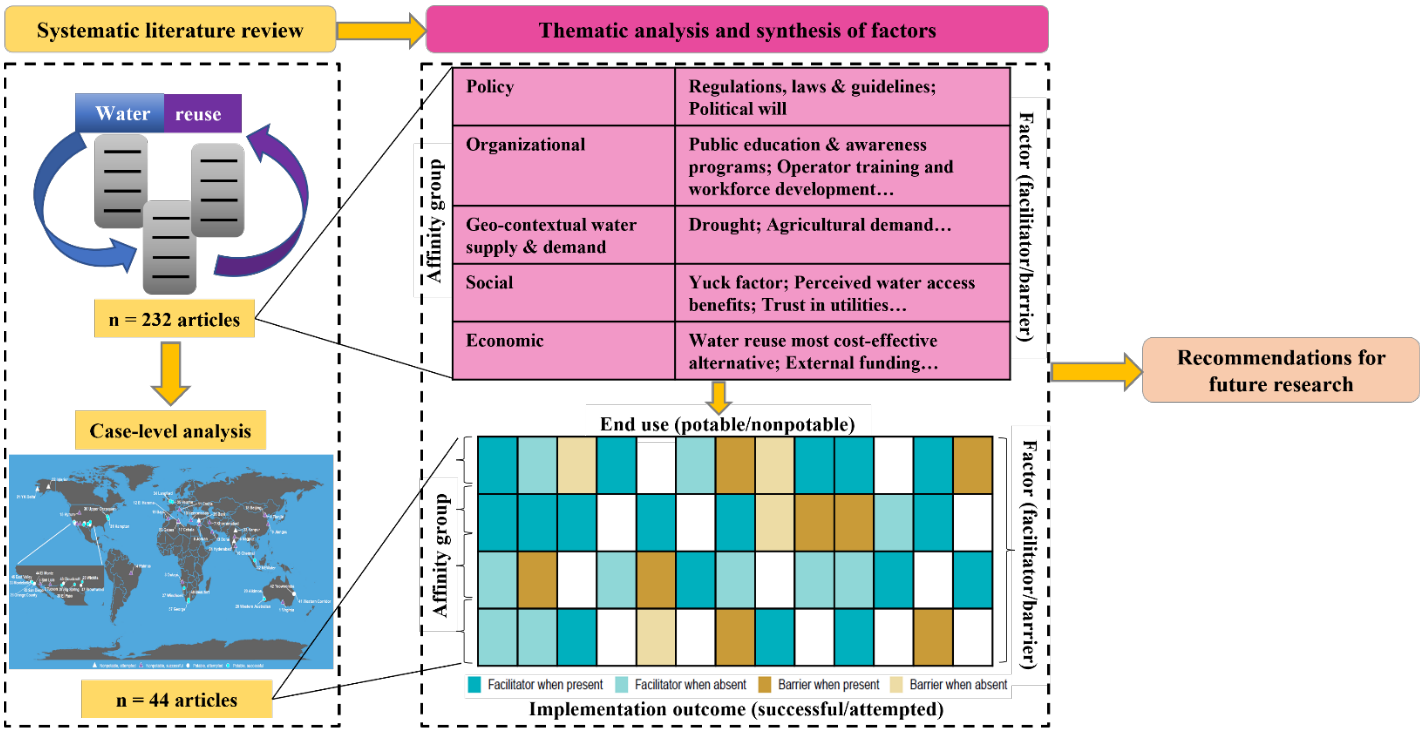
Abstract

Centralized municipal water reuse implementation, particularly potable reuse, remains slow despite the need in many global locations to supplement conventional water supplies. Analyzing factors associated with implementation can enhance our understanding of successful water reuse design and implementation. We conducted a systematic analysis of 232 peer-reviewed journal articles on water reuse implementation, identifying and classifying influential factors as facilitators or barriers to success. The most cited facilitators included clearly defined and feasible regulations, public education and awareness programs, and drought conditions. Next, we analyzed case-level data by examining the relationships between factors, implementation outcome, and end use (potable vs nonpotable). The literature enabled analysis of 47 cases with data from 44 articles. When analyzing factor co-occurrence within similar cases (e.g., successful nonpotable cases), several unique combinations of factors resulted in implementation success (e.g., fostering partnerships with the industrial/agricultural sectors, and increasing organizational capacity by improving existing infrastructure). Our analysis highlights preliminary recommendations for implementation success, as well as for future research to systematically collect data across cases. These recommendations will help to better understand the relative importance of each factor and causal relationships between factors, to ultimately identify comprehensive strategies for successful implementation.

Graphical abstract



1. Introduction

Water scarcity is a widespread global issue. Currently, 2.3 billion people reside in water-stressed regions where freshwater consumption is at or above the available supply.[1,2] The causes of water scarcity are multifaceted, encompassing natural phenomena like drought and anthropogenic factors such as uneven infrastructure development.[3–5] These causes have been – and are expected to continue to be – exacerbated by climate change and rapid urban densification.[1,3,6–11] Mitigating water scarcity requires improving the sustainability of water management.[1,3,12–17] Water reuse is being increasingly recognized as a promising solution to global water scarcity.[1,3] Water reuse refers to the process of treating wastewater to high chemical and biological standards to be used more than once before it is returned to the natural water cycle. The reuse water is potentially used in different geographical locations and end uses, effectively extending the life cycle of the water resource. It is distinct from water recycling, which typically refers to an internal process where water is treated and reused on-site for the same purpose, creating a closed-loop system.[2,18] Nonpotable water reuse treats wastewater to augment water supplies for uses such as industry processes and agriculture, while potable water reuse augments drinking water supplies for human consumption.[3]

Regions that adopt potable reuse often have already implemented nonpotable reuse and can work off existing infrastructure, public awareness, and policies.[8,9,14,19–21] There have been successful cases of nonpotable reuse implementation in diverse contexts around the world[22] – from water-rich urban Japan[23] to arid rural Tunisia.[24,25] These cases have been able to supplement their conventional water supplies, sometimes by up to 100%, particularly for agricultural and industrial reuse.[26] Potable reuse has been less widely implemented but has still been successful in a variety of contexts. For example, the arid city of George, South Africa supplements its drinking water supply with 10,800 cubic meters of recycled water per day, or one-third of its daily demand.[14]

The successful implementation of water reuse has been realized largely due to technological advancements in treatment processes. While technical barriers to reuse are limited, numerous non-technical challenges can slow or obstruct implementation. These non-technical challenges can include financing, constructing, operating, and maintaining infrastructure and public water consumer perception and acceptance of reuse water.[27–31] Previous literature reviews have examined these challenges to help identify opportunities for increasing implementation success; however, important knowledge gaps remain due to limitations in the scope of these reviews. First, most reviews have not comprehensively analyzed the non-technical factors that contribute to and limit water reuse implementation, also known as facilitators and barriers. For instance, some reviews only focus on one type of facilitator or barrier such as regulatory[32] or public acceptance[33] barriers; some of these reviews have also acknowledged the need for more holistic evaluations to better capture the complex nature of reuse.[29,34,35] Second, most reviews focus on compiling a list of factors without considering the interdependence of factors and/or their influence on implementation success.[29,36,37] A more holistic understanding of these complex factor combinations that facilitate or hinder implementation could significantly increase the likelihood of success. Third, previous reviews typically focus on one end use[29,36] and/or geographic context.[33,38] Despite the comprehensiveness of these reviews, researchers have noted the need for comparisons, especially across end use, to tailor implementation strategies. While previous reviews have contributed in multiple ways, addressing these limitations may advance the development of integrated strategies for successful implementation.

This literature review aimed to address these knowledge gaps by examining facilitators and barriers globally across end use contexts and implementation outcomes. First, we systematically analyzed 232 peer-reviewed journal articles discussing at least one non-technical barrier or facilitator to reuse implementation. We focused on centralized municipal reuse to address the needs of cities and towns looking to implement reuse in their communities.[3,39–41] Centralized municipal reuse is defined as a large-scale, municipality-managed system where collected wastewater is treated and redistributed for reuse across various sectors.[40–42] We used a hybrid thematic analysis to compile a comprehensive list of factors organized into five affinity-grouped categories. Second, we analyzed 47 individual reuse project case studies within the surveyed literature to examine the relationships between factors, end use, and implementation success. Based on our analyses, we offer preliminary suggestions for nonpotable and potable success strategies. Finally, we conclude with recommendations for future research.

2. Methods

To identify non-technical facilitators and barriers to centralized municipal water reuse implementation, we conducted a systematic analysis of the literature following the Preferred Reporting Items for Systematic Literature Reviews and Meta-Analyses (PRISMA) guidelines.[43,44] A systematic literature review is a rigorous and methodical approach to identifying, evaluating, and synthesizing available research relevant to a specific research question and follows a predefined protocol to minimize bias and ensure the review is comprehensive and reproducible so as to create evidence-based guidelines for practitioners.[45] We searched the Web of Science Core Collection database by Topic, which searches a record's title, abstract, author keywords, and KeyWords Plus®, using the following search terms that focused on identifying papers with water reuse facilitators and barriers: water NEAR/1 (reus* OR recycl* OR reclaim* OR reclam* OR "urban water management") AND (factor* OR facilitat* OR driver* OR enabl* OR promot* OR barrier*). We then refined the search by selecting filters for the publication years of 2010 to 2022; for document types of article and review article; and for the language of English. We chose the timeframe of 2010 to 2022 to enhance the relevance of our review to current water reuse practices that have shifted with the significant socio-technical and regulatory advancements in the last decade.[46,47] This search resulted in 3,038 articles. We reviewed the title and abstract of 10% of those articles to identify exclusion terms that could reduce the number of articles that focused on: technical factors (exclusion terms included: spectroscopy, concrete, materials science), industrial water reuse (exclusion terms included: metallurgy, petroleum, aquaculture), waste management (exclusion terms included: septic, solid waste, soil, incinerat*) and desalination (exclusion terms included: desalt*, desalinat*). A comprehensive list of exclusion terms is provided in Supplementary Information (SI) Table S1.

We then applied the updated topic search terms with the same three filters, which resulted in 612 articles. We reviewed the full text of those articles to refine our list to only include articles that discussed at least one non-technical factor of centralized municipal water reuse as a facilitator or a barrier. Our final selection included 232 articles. We defined factors as variables discussed as influencing water reuse implementation; and subsequently coded each factor as either a facilitator, when it contributed to implementation success; and a barrier, when it hindered implementation success. For example, the factor of public education and awareness programs was coded as a facilitator for the following article, based on:

> "*In the USA, over 230 reuse projects are operating and the reclaimed water being used for irrigation, parks, school grounds, landscaping and industrial uses. Researchers have attributed its success to public engagement and awareness campaigns, which were adopted*

by Orange County Water District from the start of the project in 2008."[37]

The factor of internal or private funding for capital costs was coded as a barrier in another article, where its absence was associated with a case's suspension, *"...the project was suspended in September 2011 due to revenue shortfall..."*[48]

Our intention was to develop a framework that would be relevant to water and wastewater utilities, in its inclusion of internal and external factors influencing implementation. We performed a hybrid deductive-inductive thematic analysis[49,50] on the 232 articles. Hybrid deductive-inductive thematic analysis is a qualitative research method that combines both deductive (theory-driven) and inductive (data-driven) approaches to identify, analyze, and report patterns (themes) within data.[51,52] This flexible method allowed us to leverage existing frameworks while incorporating emerging themes from the data to identify a comprehensive list of factors. This analysis was conducted using qualitative data analysis software NVivo version 12. We imported all 232 articles into NVivo, copying excerpts from the articles to code them into similar categories, or nodes as NVivo calls them, for each factor. We began the analysis with a set of deductively coded factors (e.g., funding sources, regulations, public perception) identified from our preliminary review of the articles. As our analysis proceeded, we added new nodes to NVivo as new factors emerged through inductive coding[53] and as our factor definitions were refined. After four iterations of analysis and coding on the 232 articles, we reached interpretative saturation[54] and finalized our coding dictionary (see Table 1 and SI Table S2). After reaching saturation in coding, we completed a fifth and final iteration, where we analyzed all 232 articles to ensure that coding was consistently applied according to our coding dictionary. Finally, we categorized these factors into five high-level affinity groups (policy, organizational, geo-contextual water supply and demand, social, and economic) that became the basis of our framework.

Table 1. Coding dictionary for factors. The table displays factor affinity groups, factor abbreviated names (as used in Figures 1 to 4) and factor definitions.

Affinity Group	*Factor Abbreviated Name*	*Factor Definition*
Policy	Regulations, laws & guidelines	National, state, or local regulations, legislation, and guidelines that directly or indirectly govern implementing water reuse.
	Political will	Willingness of political actors to promulgate policies relevant to implementing water reuse.
Organizational	Public education & awareness programs	Education and awareness programs for public water consumers, typically conducted by drinking water, wastewater, and water reuse utilities considering implementing water reuse.
	Existing infrastructure	The need for or importance of development and availability of infrastructural resources for implementing water reuse, including existing drinking water, wastewater and water reuse facilities; storage and distribution systems; ease of permitting; ease of land acquisition.
	Public participation in decision-making	Involvement and participation of public water consumers in any decision-making related to implementing water reuse.
	Operator training and workforce development	The need for or importance of education and training opportunities for utility management making decisions on water reuse and for staff responsible for water reuse operations and maintenance.
	Framing, branding, marketing & terminology	Use of effective communication strategies (including framing, branding, marketing, and terminology used) to provide information on water reuse to public water consumers.
Geo-contextual water supply & demand	Drought	Insufficiency of conventional water supply due to drought.
	Demand due to population growth	Increased demand for water due to insufficiency of conventional supply to meet water demand due to population growth.
	Agricultural demand	Increased demand for water due to insufficiency of conventional supply to meet agricultural demand.
	Industrial demand	Increased demand for water due to insufficiency of conventional supply to meet industrial demand.
Social	Perceived health risks	Perceived health risks associated with reuse water among public water consumers.
	Yuck factor	Psychological disgust ("yuck" factor) associated with water reuse among public water consumers.
	Perceived water access benefits	Belief among public water consumers that water reuse increases water access for human consumption; sometimes expressed as water consumers' moral obligation to the general public.
	Perceived environmental benefits	Belief among public water consumers that water reuse increases water availability for environmental protection and other benefits.
	Prior experience	Prior experiences among public water consumers with water reuse, including knowledge gathered and proximity to an existing water reuse project.
	Trust in utilities	Level of trust among public water consumers in authorities responsible for implementation, including drinking water, wastewater and water reuse utilities; water and sanitation districts.
	Trust in political actors	Level of trust among public water consumers in political actors such as policymakers involved in implementing water reuse .
	Trust in scientific professionals	Level of trust among public water consumer in the water reuse opinions of public-facing scientific professionals (other than utilities and political actors) such as, healthcare professionals, scientists, engineers.

	Trust in media	Level of trust among public water consumers in the media (e.g., radio, newspapers, television, social media) providing information on water reuse.
	Most cost-effective alternative	Water reuse is the most cost-effective solution to address local water needs when compared to other alternatives as determined by a cost-benefit or similar analysis.
	Internal/private capital costs funding	Availability of internal or private funding for capital costs associated with implementing water reuse.
Economic	External funding	Availability of public or philanthropic funding for (typically) capital costs and (sometimes) operations and maintenance (O&M) costs associated with implementing water reuse.
	Internal/private O&M funding	Availability of internal or private funding for operations and maintenance (O&M) costs associated with implementing water reuse.
	Public willingness to pay	Relationship between reuse water rates and public water consumers' willingness to pay for reuse water.
	Public pricing strategies	Pricing strategies (e.g., tax breaks for reuse consumers; using penetration or value-based pricing; setting water rates based on affordability metrics) to incentivize the public consumption of reuse water.

The influence of a factor further depended on whether it was present or absent. For example, the factor public participation in decision-making was discussed as a facilitator when present, based on:

"*...Developing a genuine partnership with the community such as to involve them in decision making process in order to build and maintain the trust among them is essential.*"[13]

It was coded as a barrier when absent, based on:

"*...The lack of public participation and supervision is another issue regarding reclaimed water management.*"[55]

As a result, we also coded each factor under the factor influence classifications of "facilitator when present," "facilitator when absent," "barrier when present," or "barrier when absent", reflecting its impact as discussed in each article (see Table 1 for abbreviated factor names and factor definitions; see SI Table S2 for complete coding dictionary along with supporting excerpts and citations for each factor).

We also found that some of the seeming contradictions – namely, when a factor was both a barrier and facilitator – could be explained by evaluating the implementation context. The implementation context is an individual reuse project, which we define as our unit of analysis of "project case study" or "case" for short. An example of a seeming contradiction can be seen with the factor drought-driven water scarcity. The following quotation illustrates drought as a facilitator for one case:

> "*In the West Bank, the reuse of wastewater is motivated by need and economics. Freshwater supplies in the West Bank are limited, and water is relatively expensive, so alternative sources of irrigation water are sought in order to have a sufficient quantity of water for a home garden.*")[24]

In contrast, the following quotation shows drought being discussed as a barrier: "*...However, since the drought officially ended in 2012 significant government funding is no longer available in the Australian water sector and is unlikely to return in the near future….*"[56(p127)]

Coding by case allowed us to analyze the data specific to implemented cases, ultimately to help identify strategies associated with successful centralized municipal reuse by: (i) examining the potential relationships between factors, implementation outcome, and water end use; and (ii) evaluating the co-occurrence of factors within a given case. We coded by case by creating separate case files in NVivo and assigned factors to each case. We imported these case-specific data into Excel for further organization and data visualization. All figures were created in RStudio[57] using ggplot2[58] with the assistance of the grid,[59] cowplot,[60] ggh4x,[61] ggpattern,[62] and gtable[63] packages.

A case was included in this analysis if it could be classified with an implementation outcome and water end use, and if at least one non-technical factor was discussed. Overall, non-technical factors were discussed for 47 cases over 44 articles, out of the 232 that we included in our comprehensive framework development. Some articles discussed multiple cases. Also, some cases were discussed over multiple articles. Therefore, for a given case, we compiled all data on factors to comprehensively evaluate each case across the 44 articles. For example, analyzing the case of NEWater (Singapore) involved compiling factors across five articles, including geo-contextual factors,[9,13,64–66] organizational and economic factors,[9,66] and policy and social factors.[13,64,65] Literature described some cases as having more than one factor influence classification (e.g., as a facilitator when present and as a barrier when present). In these instances, we coded the case's factor with each applicable influence classification. There were 10 occurrences when a case's factor was discussed across multiple influence classifications in the same article and 14 occurrences when a case's factor was discussed across multiple influence classifications across articles.

We then classified cases by outcome and water end use. For outcome, there were two classifications. A successful case was defined as one that was implemented and operational to reliably provide safe reuse water (e.g., Hyrum in Utah, USA[67] and Virginia Pipeline Scheme in Adelaide, Australia).[13] An attempted case was defined as one that was planned and may have had initial construction efforts but was ultimately not operational (e.g., Brownwood in Texas, USA[21,68] and Toowoomba in Queensland, Australia),[13,14,48,64,66,68–73] was temporarily operational but unable to provide a long-term source of reliable and safe reuse water (e.g., Bani Zeid in West Bank[24] and Hyderabad in Telangana, India),[74] or was decommissioned (e.g., East Valley Reclamation Project in California, USA[75] and Western Corridor Recycled Water Project in Queensland, Australia).[14,48,72] We evaluated each article's discussion of a case's outcome individually (Table S3). The outcomes for each were then compiled to conclude a single outcome; all articles explicitly or implicitly stated the same outcome for each case. Forty-two cases had an explicit statement of its outcome from at least one article. Five cases lacked an explicit statement on its outcome; therefore, we used each article's implicit statement to deduce an outcome. For example, Bani Zeid (West Bank) was classified as an attempted case since a 2017 article stated "*the treatment system is not currently part of any wastewater reuse scheme*"[24] even though it was constructed in 2004.

For water end use, there were two classifications: (i) potable, if the water could be used for human consumption; and (ii) nonpotable, if the water could only be used for nonpotable purposes, such as irrigation. We evaluated each article's discussion of a case's water end use individually (Table S3). We then compiled water end uses for each case to conclude a single end use; all articles stated the same end use for each case. There were 21 potable and 26 nonpotable cases. Three of the 26 nonpotable cases were noted as considering changing to potable reuse in the future; however, we analyzed these as nonpotable based on the end use for which factors were discussed in each of those articles. Overall, there were 20 successful nonpotable cases, 6 attempted nonpotable cases, 14 successful potable cases, and 7 attempted potable cases. These case classifications formed the basis of our subsequent analysis of the relationships between factors, water end uses, and implementation outcomes.

3. Results and Discussion

3.1. Factors that Influence Successful Water Reuse Implementation

The most discussed factor was regulations, laws, and/or guidelines (n = 158 articles) (Figure 1A; see SI Table S2 for definitions, example excerpts, and corresponding articles). The presence of regulations, laws, and/or guidelines was mostly discussed as a facilitator for successful water reuse implementation, with 93 articles discussing it as a facilitator when present and 52 articles discussing it as a barrier when absent. The focus on – and potentially the importance of –

this factor has increased with time, with 37% of the associated articles published in 2021 and 2022 (SI Figure S1). The heightened emphasis on regulations, legislation, and guidelines in recent years may reflect a significant political commitment to establishing unified standards for implementation.[32,76] This trend may have important public health implications as the integration of reused water into drinking water supplies becomes more common worldwide.[48]

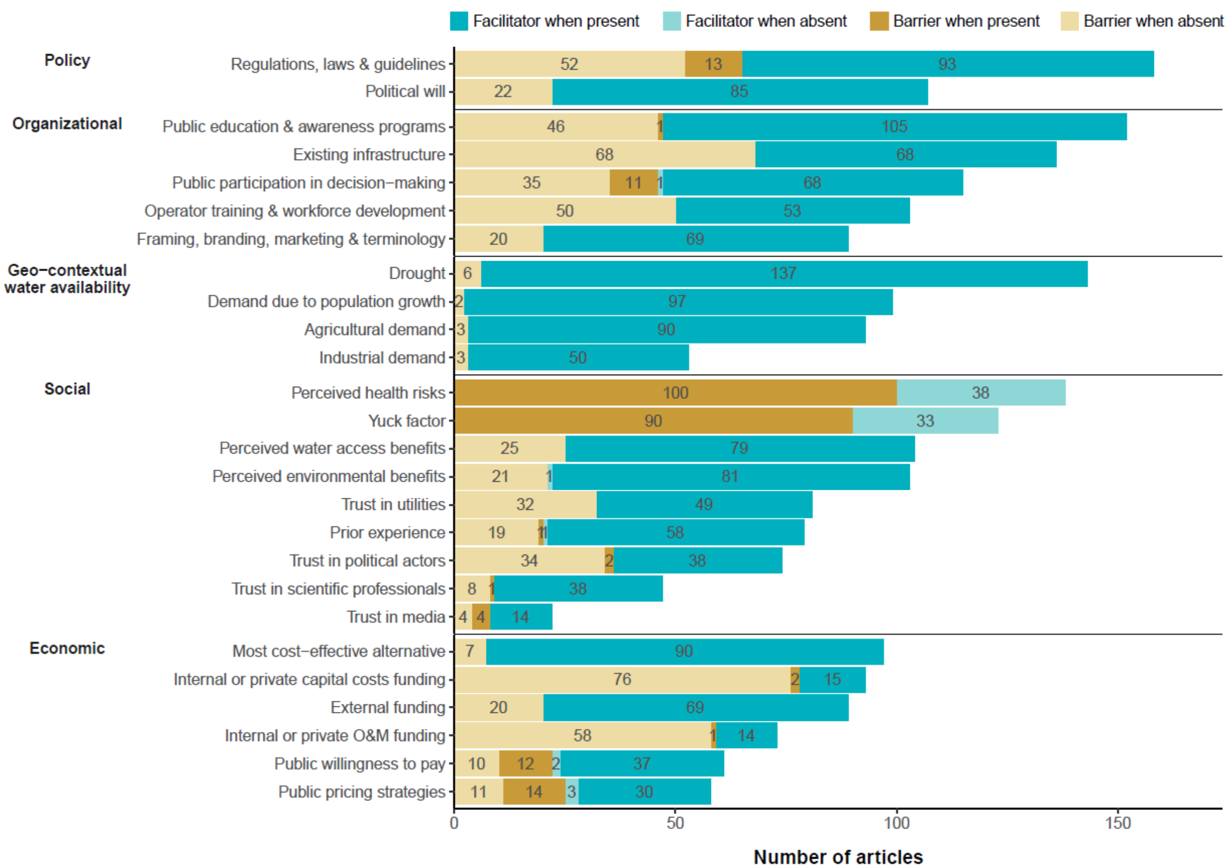


Figure 1. Distribution of factors across published articles. Number of articles in which factors were barriers when present, barriers when absent, facilitators when present, or facilitators when absent. The total number of articles discussing each factor is listed adjacent to each factor's distribution. Each row represents a factor as shown on the left y-axis and the bottom x-axis indicates the number of articles discussing that factor.

The presence of regulations, laws, and/or guidelines has helped to streamline processes,[14,77,78] ensure compliance,[15,79,80] and reduce uncertainties to promote investment in reuse infrastructure.[21,81,82] For example, as expressed by Power (2010), "*The benefits of a national*

[Australian] approach to treatment validation include greater financial and supply certainty for manufacturers and proponents in what is required by regulators."[83] Some articles also discussed the importance of regulatory frameworks in creating legitimacy.[84–86] Regulations, laws, and/or guidelines indirectly related to reuse such as wastewater discharge standards (e.g., in California and Florida, USA)[14,32] have also facilitated implementation. That this factor was also commonly a barrier when absent (n = 52 articles) further highlights its role as a facilitator when present. The absence of regulations, laws, and/or guidelines was discussed as a barrier in terms of the associated inconsistencies in water quality standards[35,87,88] and undermined the credibility of reuse.[89–91] For example, Cruz-Ayala (2020) discussed how the absence of a regulatory framework has hindered the implementation of managed aquifer recharge (MAR) in Mexico:

> "*We found that beyond the technical issues that MAR projects normally address, the regulatory framework is a barrier to increasing MAR facilities because there are no provisions for the recovery of stored water…the Law of the Nation's Waters does not include a definition for reclaimed water and lacks procedures to define how reclaimed water can be managed and allocated…Considering that reclaimed water can be used for agricultural activities and MAR projects, the lack of a regulatory framework is hampering the opportunities for reusing this water.*"[92]

On the other hand, while less common, the presence of regulations, laws, and/or guidelines has hindered implementation in some instances (n = 13 articles) because the standards were poorly defined, overly restrictive,[76,81] and/or inappropriate to the local context.[32,74] For example, nonpotable reuse implementation for industry was reported as being constrained in the state of Minnesota (USA) because its policies were based on those developed for nonpotable systems in another state. Minnesota developed its reuse policy based on the state of California's stringent requirement of advanced disinfection of closed-loop water systems that could not be feasibly achieved due to an absence of existing infrastructure capabilities in wastewater plants in Minnesota.[32] Therefore, this policy hindered the implementation of reuse in Minnesota.

The second most discussed factor was public education and awareness programs (n = 152 articles). As Zhu et al. (2018) discussed, "*It is important to improve public awareness and receptivity towards reclaimed water.*"[93] These programs were mostly discussed as being crucial to achieving positive perceptions of water reuse and therefore crucial to supporting successful implementation. Most articles (n = 105) discussed public education and awareness programs as facilitators when present, and the remaining (n = 47) discussed them as barriers when absent (n = 46) and present (n = 1), with the single article in this last category discussing the inadequacy and untimely administration of these programs when present as a major barrier to reuse implementation success. Water utilities typically administered public education and awareness programs, which included the sharing of information[94–96] and open dialoguing about water reuse.[25,97,98] The programs were designed to foster trust.[13,33,99] As expressed by Price et al. (2015):

> "*It has been suggested that provision of recycled water information may help to build trust between communities and water suppliers...For communication to be effective, however, the messengers need to be trusted, and the messages need to be accessible and to address key concerns that people have about drinking recycled water.*"[72]

The components of effective public education and awareness programs have been discussed extensively elsewhere.[100–105] In general, effective programs have prioritized communicating with the public in the early stages[19,70,106] about water access benefits (n = 79 articles discussed it as a facilitator when present,[67,75,107] n = 25 articles barrier when absent[108–110]), environmental benefits (n = 81 facilitator when present,[111–113] n = 21 barrier when absent[31,114,115]), and examples of successful cases elsewhere (i.e., framing, branding, marketing, and terminology factor; n = 69 facilitator when present,[116–118] n = 20 barrier when absent[68,106,119]). Positive framing has helped increase utilities' legitimacy by increasing public trust (n = 49 facilitator when present,[13,120,121] n = 32 barrier when absent[80,94,122]) and overcome common social barriers such as perceived health risk (n = 100 barrier when present,[115,123,124] n = 100 facilitator when absent[125–127]) and disgust surrounding reused "toilet-to-tap" water (i.e., yuck factor; n = 90 barrier when present,[71,128,129] n = 33 facilitator when absent[130–132]). Educating stakeholders and the public on the relative severity and immediacy of risks and benefits may promote more sustainable integration of reuse into long-term planning.

Programs have also considered providing the public with the opportunity to participate in implementation decision-making. Allowing the public to participate in decisions such as site selection and end use application[90,98,126] was shown to further facilitate implementation (n = 68 articles facilitator when present,[79,114,133] n = 35 articles barrier when absent[16,134,135]), contingent on other outreach efforts[136–138] and public's trust in its utilities[14,139,140] and government.[106,121,141] The one article that discussed public education and awareness programs as a barrier when present referenced a case that offered an outreach program in its later stages and did not allow the public to participate in decision-making.[70] Communication with the public in the early stages of a case about water access and environmental benefits has helped improve positive public perceptions of water reuse[20,142,143] and overcome common social barriers such as perceived health risks[25,144,145] and disgust surrounding reused "toilet-to-tap" water (i.e., yuck factor).[127,146,147] As Lucas et al. (2021) discussed, "*Persistent explanations during community* *visits of the water reuse concept countered some initial negative reactions, and more dialogue could continue to increase community support.*"[148]

The third most discussed factor was drought (n = 143 articles).[149–151] We found that local water scarcity due to drought was mostly discussed as a facilitator when present (n = 137 articles[56,152,153]) and barrier when absent (n = 6 articles[21,114,154]). The other factors in the geo-contextual water supply and demand affinity group focused on increasing water demands due to population growth,[11,155,156] agricultural demand,[20,157,158] and industrial demand;[42,74,159] each factor was mostly discussed as a facilitator when present since the increased demand could drive the need for water reuse to supplement existing water supplies. For example, Aldaco-Manner et al. (2019) discussed high water reuse potential for San Antonio (Texas, USA) based on projected demand due to population growth:

> "*With a rapidly growing population in the region, the TWDB's 2017 State Water Plan indicates that water needed in this Region is expected to increase from 573,634 acre-feet per year in 2020, to 995,247 acre-feet per year in 2070…water reuse is the third largest expected supply and is anticipated to relieve nearly 18% of the region's water needs. If water governing agencies in the region focus their efforts toward this state water goal, then TWDB's water reuse strategy has large potential to help satisfy the region's water needs.*"[91]

Water scarcity due to drought has been shown to prompt utilities to integrate water reuse into their circular economy[12,17,160] and long-term resource management plans to ensure resource conservation and optimal utilization.[86,161,162] These approaches may become more prevalent with increasing climate-related drought risk.[163–165] However, drought was not always a long-term or continuous concern. For example, the city of Brownwood (Texas, USA) abandoned its water reuse program after the drought which initiated it subsided. As Scruggs et al. (2020a) explained: "*...the City Council never voted to approve the sale of bonds because it began to rain.*"[68] While the city still acknowledged the need for a long-term plan (Scruggs et al. 2020, quoting the Brownwood public works director: "*...we should not wait until we reach the 'panic' phase of the cycle to act; there must be a plan beforehand.*"),[68] the absence of urgency seemed to moderate the facilitating effect of water scarcity, despite the presence of other facilitators (e.g., perceived water access benefits, trust in utilities; social affinity group, Figure 1A) and internal or private capital costs and operations and maintenance (O&M) funding (economic affinity group, Figure 1A).

The relatively sustained attention to economic barriers (SI Figure S1), such as the absence of internal or private capital costs and operations and maintenance funding (Figure 1A, n = 76 articles, n = 58 articles, respectively) may reflect the persistent need for economic solutions (i.e., more and diverse funding sources) to make reuse more accessible. Even when reuse was the most cost-effective alternative, it was insufficient for guaranteeing implementation success.[8,19,166] Water reuse requires substantial infrastructure investments, from the construction of conveyance and distribution networks to the O&M of advanced treatment processes.[167–169] As Giannoccaro et al. (2019) explained:

> "*The main factor hampering the development of [wastewater treatment plants] for reuse is related to the total costs of reclamation (plant construction, operation and maintenance).*"[170]

The evidence suggests that infrastructure costs have hindered implementation across both urban and rural high- and low-resourced settings in states such as Alaska, California, Florida, Georgia, Texas and New Mexico (USA)[48,80,91,148,154,171] as well as in Asian countries[11,74,172]and Middle Eastern and North African (MENA) regions.[24,88,173] Evidently, the absence of existing infrastructure resources has also acted as a barrier to implementation (n = 68 articles, existing infrastructure factor, organizational affinity group, Figure 1A). In the previously mentioned case of Brownwood, the city's lack of existing infrastructure also contributed to the case's termination.[21,68] Operator training and workforce development was also another noteworthy organizational factor. The increased focus on this factor in the literature post-2017 (over 30%, SI Figure S1) potentially highlights the need for increased organizational capacity to manage and operate reuse systems. Most articles reported the presence of operator training and workforce development as a facilitator (n = 53 articles, Figure 1A)[29,40,74,143,173,174] and absence as a barrier (n = 50 articles).[6,34,74,88,148,164,175] For example, Burgess et al. (2015) discussed:

> "*Effective operations are critical for any treatment plant, and will be especially crucial for the success of DPR [(direct potable reuse] due to its minimal response time…It is important to work together to standardize and disseminate the O&M plans and ensure that operators are well trained and certified.*"[14]

This analysis of facilitators and barriers to water reuse implementation across the globe underscores the complexity and multifaceted nature of these initiatives. While relevant regulatory frameworks, availability of existing infrastructure and need for additional development , operator training and workforce development, public acceptance, and geo-contextual water supply and demand factors emerged as key facilitators, understanding these factors and their relationships with each other is essential for developing effective strategies to enhance the success of water reuse cases.[27,28,176] Analyzing facilitators and barriers based on their co-occurrence within reuse cases can contribute to this understanding.

3.2. Case Study Analysis

3.2.1. Nonpotable cases

We found that factors in the policy, organizational, and geo-contextual water availability affinity groups were the most frequently discussed factors for nonpotable cases. All the factors in the policy and geo-contextual water availability affinity groups were always discussed as a facilitator when present and a barrier when absent (Figures 2A and 2B). For the policy factor of regulations, laws, and/or guidelines, all successful nonpotable cases discussed their presence as a facilitator (Figure 2A). Regulations, laws, and/or guidelines have a critical role in ensuring safety and consistency,[177–179] and their absence has hindered the implementation of nonpotable reuse (Figure 2B).[32,74,148] For example, in the cases of two rural communities, Yukon–Kuskokwim (YK) Delta and Interior (Alaska, USA; Figures 3 and 4B, cases 21 and 22, respectively), an absence of regulations at any level (i.e., national, state, local, or tribal) hindered reuse implementation.[32,148] Political will can drive project commitment,[7,13,93] resource allocation,[25,74,92] and public advocacy.[6,25,180] The combined presence of the regulations, laws, and/or guidelines and political will factors was facilitating for 60% of successful nonpotable cases. While the presence of regulations, laws, and guidelines alone may be enough of a facilitator to lead to success, the absence of both has hindered projects.[74] For example, the attempted cases of Hyderabad (Telangana, India; Figures 3 and 4B, case 24) and Kanpur (Uttar Pradesh, India; Figures 3 and 4B, case 23) were noted to have failed due to an absence of state-level regulations and political will promoting reuse, despite the presence of national-level guidelines in the Kanpur case that initially acted as a facilitator.[74]

The most common geo-contextual water supply and demand factors for nonpotable cases were drought and agricultural demand. The presence of these factors was discussed as a facilitator in 88% and 85% of successful cases, respectively (Figure 2A) and as a facilitator in 100% and 100% of attempted cases, respectively (Figure 2B). These findings indicate the importance of having enough supply to meet demand, especially in drier climates where most of the cases were located (Figure 3).

Figure 2. Distribution of factors across end use and implementation outcome. (A) Successful, nonpotable (n = 20), (B) attempted, nonpotable (n = 6), (C) successful, potable (n = 14), and (D) attempted, potable (n = 7) case studies for which factors were coded categorically as facilitators when present, facilitators when absent, barriers when present, and/or barriers when absent. Striped bars indicate where factors were coded as two categories within a single case; the stripe and bar colors indicate which categories.

Conversely, high demand initially facilitated reuse implementation. A change in the presence of these factors can impact a case's long-term success, as a decrease in drought severity or agricultural demand can reduce the need for reuse water. For example, a decrease in the agricultural demand for water led to a loss in political will for reuse, subsequent funding deficits, and then failure for the case in Hyderabad (Figures 3 and 4B, case 24).[74] A similar trend was observed in the case of Bani Zeid (West Bank),[24] where a decrease in the agricultural demand for water led to the reuse project's funding deficits and subsequent failure (Figures 3 and 4B, case 26).

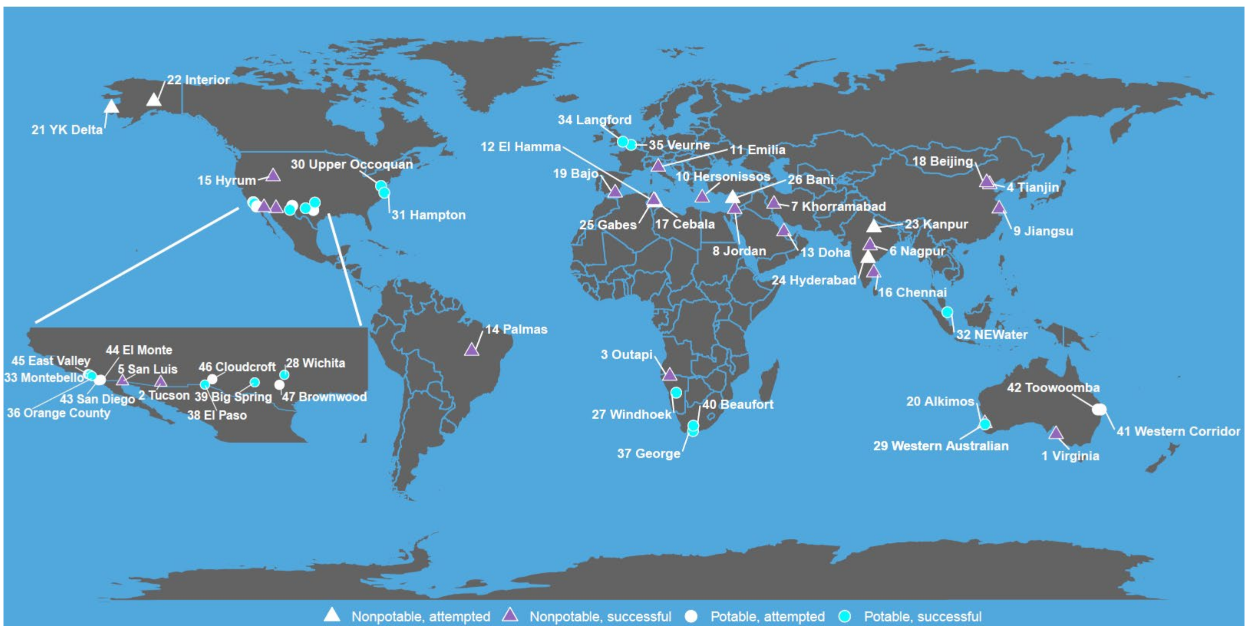


Figure 3. Locations of water reuse cases included in the analysis. All 47 cases are denoted by their case number and an abbreviated name in their location of implementation on the map. Different combinations of case marker colors and shapes represent the four case classifications of end use and implementation outcome, where a white triangle represents an attempted nonpotable case; a purple triangle represents a successful nonpotable case; a white circle represents an attempted potable case; and a turquoise circle represents a successful potable case. Additional information on cases is in SI Table S3.

Organizational, economic, and social factors were the most common barriers for attempted nonpotable cases (Figures 2B and 4B). Every attempted case cited an absence of operator training and workforce development and all but one mentioned the absence of existing infrastructure as organizational barriers (Figures 2B and 4B).[24,74,148] Limitations to organizational capacity have eroded the public's trust in utilities (33%, Figure 2B) and diminished public willingness to pay (50%, Figure 2B). For example, the cascading influence of these factors was observed in the aforementioned cases of two remote rural Alaskan communities (Figures 3 and 4B, cases 21 and 22).[148] Other common economic barriers for both successful and attempted cases included the absence of internal or private capital costs and O&M funding (15% each, respectively, for successful cases, Figure 2A, and 67% and 50%, respectively, for attempted cases, Figure 2B),[6,93,148] even in situations where water reuse was the most cost-effective alternative (100% of such cases, Figures 2A and 2B).[6,25,74,93,148,178]

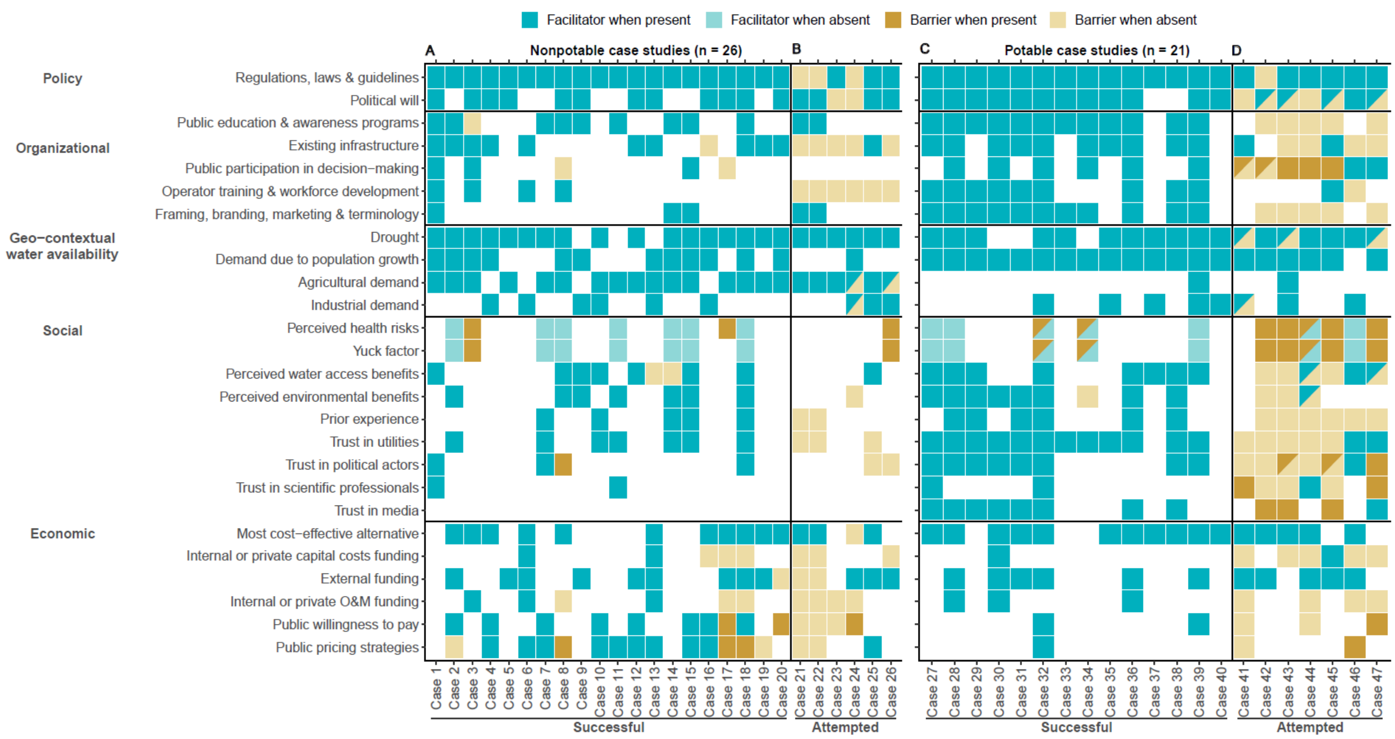


Figure 4. Distribution of factors across all case studies. The left panel displays factors for nonpotable cases organized by implementation outcome of (A) successful (n = 20) and (B) attempted (n = 6). The right panel displays factors for potable cases organized by implementation outcome of (C) successful (n = 14) and (D) attempted (n = 7) case studies. The left y-axis displays factors grouped by affinity groups. The bottom panel displays case IDs. Factors can be coded under more than one classification for a single case. Two-color cells indicate that the factor is coded under two classifications for a given case. Citations for articles discussing that case can be found in SI Table S3.

For example, in Beijing (China; Figures 3 and 4A, case 18), only the presence of external funding in the form of public funds has facilitated reuse implementation thus far; internal or private capital costs funding would be needed to expand reuse in the city.[6,93,178] Nonpotable reuse requires substantial investments in new infrastructure systems since the water cannot be added to existing potable distribution systems, and a case without the funding to build and maintain the additional nonpotable distribution systems will fail.

The economic factors of public pricing strategies and willingness to pay were either barriers or facilitators when present (Figures 4A and 4B) depending on their co-occurrence with other factors. For example, in the successful cases of Hyrum (Utah, USA)[67] and El Hamma (Tunisia),[24] setting water rates based on consumers' preferences benefited the projects by increasing public acceptance (Figures 3 and 4A, cases 15 and 12, respectively), while in Cebala (Tunisia; Figures 3 and 4A, case 17)[25] the same practice caused funding deficits even though the project was successful. Social factors were only mentioned in less than 40% of successful cases (e.g., in rural Emilia-Romagna, Italy; Figures 3 and 4A, case 11)[125] and were the only affinity group with factors discussed as facilitators when absent (Figure 4A).[6,7,40,67,124,152,181] The two social factors that were facilitators when absent were perceived health risks and disgust with water reuse (i.e., the yuck factor). These factors have been common misperceptions, which potentially caused researchers to note their absence more frequently than other factors. They may not have been potent enough to lead to a project's failure – especially since nonpotable water has fewer public health issues than potable water – but cases benefited from their absence.[7,67,93,125,152,178]

Attempted nonpotable cases that failed despite having mostly facilitators or succeeded despite having excess barriers can largely be explained by the temporal ordering of certain factors over others. The attempted case of Gabes City (Tunisia; Figures 3 and 4B, case 25) is a representative example.[24] The case was initially implemented with the help of geo-contextual, policy, and economic facilitators, but it could not be sustained due to social and organizational barriers such as a paucity of skilled staff, evidenced by the absence of operator training and workforce development; insufficient on-site water and electricity, evidenced by the absence of existing infrastructure; and institutional distrust brought about by political unrest, evidenced by the absence of trust in political actors. In this case, organizational factors created barriers later in the implementation process that critically project success.

Another interesting example of nonpotable reuse is the successful case of Cebala (Tunisia; Figures 3 and 4A, case 17).[25] While nonpotable reuse was successfully implemented in the region in the 1980s, post-implementation organizational barriers such as the absence of public participation in decision-making have hindered the expansion of reuse. While any factor could have been a barrier or facilitator at any time in a project, organizational factors were typically barriers after a project became operational, and geo-contextual factors had less direct influence post-implementation but could still indirectly influence other factors,[24,74] as discussed earlier.

Based on these findings, we offer the following preliminary suggestions for utilities implementing nonpotable reuse. Utilities may benefit from fostering strong partnerships with the industrial and agricultural sectors to ensure reliable demand for water reuse. Efforts may want to focus on securing political support to assist with acquiring adequate external (i.e., public and/or philanthropic) funding for capital and O&M costs. Nonpotable reuse may also benefit from high organizational capacity that comes from sufficient infrastructure and operator training and workforce development, which can help to establish public trust in utilities' management capabilities.[7,24] Higher public trust in utilities can also positively influence the factors of public pricing strategies and willingness to pay among public water consumers by increasing cost-recovery, thereby offsetting the frequently discussed barrier of funding deficits for these cases.

3.2.2. Potable cases

For potable cases, we found that factors in the geo-contextual water availability, organizational, social, and policy affinity groups were the most frequently discussed (Figures 2C and 2D). All factors in the policy and geo-contextual water availability affinity groups were discussed as facilitators when present and barriers when absent, while the presence of organizational and social factors was discussed as both a facilitator and a barrier depending on the case (Figures 2C, 2D, 4C, and 4D). Demand due to population growth[13,14,48] and water scarcity due to drought[30,32,183] were the most common geo-contextual water availability facilitators when present, cited in 100% and 79% of successful cases (Figure 2C) and 86% and 100% of attempted cases, respectively (Figure 2D). Demand due to population growth has been more closely linked to potable reuse than nonpotable as it more directly affects utilities' management of water supply and demand. For example, Western Corridor Recycled Water Project (Queensland, Australia; Figures 3 and 4D, case 41) initially designed their indirect potable reuse program in 2007 based on projected population growth in the region.[14,48,184] As Meehan et al. (2013) discussed:

> "*In an effort to "reduce dependence on imported water sources, or to correct the balance between available water sources and projected growth" (Marks, 2006: 139), potable reuse projects are typically planned in anticipation of population growth and subsequent water shortages.*"[48]

Water scarcity due to drought changed from a facilitator to a barrier for two cases in the United States and one in Australia when the drought was mitigated by rainfall (Figure 4D, cases 41, 43, and 47, respectively); rainfall lessened the sense of urgency and contributed to the cases' failure after weakening political will for two of the cases.[13,14,48,68]

Other cases where there was a decline in political will reported its absence in response to public backlash (Figure 4D, cases 42, 43, 45, and 47, respectively).[13,68–70,75] For example, high political will and a strong regulatory framework at the state level were both initially facilitators when present in the case of East Valley, Los Angeles (USA; Figures 3 and 4D, case 45).[75] The project ultimately failed when political will declined and became a barrier when absent due to public criticism of the project. These concerns reportedly stemmed from a combination of factors, including the absence of public education and awareness programs, the absence of supportive framing, branding, marketing, and terminology used, and the absence of timely public participation in decision-making.[13,14,48,75,101] Except for public participation, the other organizational factors (i.e., public education and awareness programs, and framing, branding, marketing, and terminology) were among the most frequently discussed facilitators when present across successful cases (86% and 79%, respectively, Figure 2C),[9,21,68,101,155,183] and their absence was discussed as a barrier across attempted cases[13,14,68,70,75] (71% and 71%, respectively, Figure 2D). Public participation in decision-making was discussed as a facilitator when present in 43% of successful cases[9,32,48] and 33% of attempted cases[21,68] (Figures 2C and 2D), as a barrier when present in 50% of attempted cases,[13,68,75] and as a barrier both when present and absent in 29% of attempted cases (Figure 4D).[69,70,116] Untimely or inadequate public participation was often a barrier when present because it delayed implementation and increased costs by prolonging approval processes and creating opportunities for public resistance (Figure 4D, cases 41-45).

Social factors were often discussed as barriers (e.g., presence of perceived health risks and the yuck factor, absence of prior experience; discussed in over 70% of cases),[48,65,75] as were economic factors (e.g., absence of internal or private capital costs and O&M funding, public willingness to pay, or public pricing strategies; discussed in 25% to 75% of cases).[21,48,68] The two social factors of perceived health risks and yuck factor were either barriers when present or facilitators when absent, or both in a single case study (Figures 4C and 4D, two-color cells for cases 32, 34, and 44). In cases where they were discussed as both, initial skepticism was overcome with effective public education and awareness programs, such as in the case of NEWater (Singapore; Figures 3 and 4C, case 32).[9,64,116] Perceived health risks and yuck factor were only barriers when present for potable attempted cases compared to nonpotable cases. This result is not surprising given the public is more personally invested in the water they consume. Similarly, other social factors and related organizational factors were more prevalent among potable than nonpotable cases. The absence of social factors such as prior experience of reuse water (86% of cases, Figure 2D), perceived water access benefits, trust in utilities, and trust in political actors was consistently discussed as a barrier across attempted potable cases (71% of cases for the last three factors, Figure 2D).[14,71,73] The absence of these factors co-occurred with the absence of public-opinion-related organizational factors such as public education and awareness programs and negatively affected case outcomes. Illustratively, in the case of Jordan Valley (Jordan; Figures 3 and 4A, case 8), distrust in the government's ability to implement potable reuse safely was due in part to its limited transparency and engagement with citizens,[7] although these social and organizational factors did not present as barriers to the region's successfully implemented nonpotable program. Trust in political actors was both a barrier when absent (i.e., lack of trust in government officials supporting a case)[13,71,134] and when present (i.e., trust in government officials opposing a case) (e.g., San Diego Water Repurification Project, USA; Figures 3 and 4D, case 43).[21,68,134]

The absence of internal or private capital costs and O&M funding consistently emerged as barriers among attempted cases (over 55% of cases, Figure 2D),[13,68,73] even in the presence of external public funding (Figure 4D).[21,48,68] Successful potable reuse has required substantial financial resources to support advanced treatment systems that comply with safety and reliability standards, and the absence of financial resources has negatively influenced the sustainability of these cases.

One notable potable case was that of Cloudcroft (New Mexico, USA; Figures 3 and 4D, case 46).[68] This project initially had multiple geo-contextual water availability, policy, and economic facilitators present (e.g., drought and industrial demand, political will, water reuse as the most cost-effective alternative, and external public funding); however, organizational barriers such as an absence of operator training and workforce development (i.e., a lack of skilled management) and subsequent detrimental decisions (e.g., faulty construction) on unifying the existing water supply infrastructure led to multiple delays in implementation. At the time of publication, Cloudcroft planned to implement potable reuse in the future although the timeline for project completion was unclear.

Based on these findings, potable reuse efforts may benefit from a focus on enhancing timely public engagement by appealing to public water consumers' sensibilities, building trust in water utilities, and securing robust policy and financial support to effect changes in existing infrastructure required to implement these projects. These strategies may help overcome the significant barriers related to public perception and organizational and regulatory compliance while also ensuring greater buy-in, reflected in high political will and public acceptance. Potable reuse is being increasingly acknowledged as the path forward for sustainable water management practices,[9,14,48,134,154,184] and while drought and demand due to population growth provide initial motivation to consider potable reuse, focusing on operationalizable facilitators that lead to success can help realize its full potential.

3.2.3. Future research needs

We now consider which factors were not discussed in the surveyed literature. Figure 4 is especially suited to help us identify patterns in the data. Missing data are important to consider as they can obfuscate the relationships between factors and implementation success, limiting progress in developing effective water reuse strategies. Missing data may indicate that factors were either entirely absent or not documented in cases. For nonpotable cases, social and organizational factors had the most missing data (Figures 4A and 4B). The social factors of trust in political actors, trust in scientific professionals, and trust in media were consistently sparse across successful and attempted cases. Health risks, yuck factor, water access benefits, and environmental benefits were also infrequently mentioned among attempted cases. The organizational factor of public participation was entirely missing from attempted cases and was uncommon among successful cases as well. Successful cases also rarely mentioned operator training and workforce development and project branding and marketing. Potable cases show that economic factors, especially internal or private funding for O&M, willingness to pay, and public pricing strategies, were more often undocumented among potable than nonpotable cases (Figures 4C and 4D). Geo-contextual factors of agricultural and industrial demand were noticeably absent from potable cases.

Missing data may indicate that a factor was unimportant and/or unmeasured. For example, the high percentage of missingness among social factors in nonpotable cases may be the result of the generally weak influence of social factors on case outcome combined with the fact that social science methods are uncommon in water reuse research.[29,38,84,185] The missingness among economic factors may be in part due to the challenge of collecting data on project finances. Other factors such as operator training and workforce development among successful nonpotable cases may often go unmeasured because, as a type of infrastructure, they are noticed only on breakdown.[186] We also recognize more generally that peer-reviewed literature and its findings are subject to reporting bias. Journal aims and scope, length restrictions, and authors' conflicts of interest can affect which cases and factors are published. That we identified nearly three times as many successful cases as attempted cases may indicate that academic journals are less willing to publish attempted cases (i.e., null results) than successful cases, or that it may be more difficult to study attempted cases.[187] We also found some evidence to suggest a case published in peer-reviewed journals was typically more selective in the factors it reported than the grey literature on the same case.[188–192] For this reason, we recommend future literature reviews on reuse implementation include grey literature to capture as much data on factors as possible to conduct comprehensive case analyses.

The missing data highlight opportunities for future research that can help to uncover the links between factors and implementation success across different end use contexts. We propose three aims for future research based on our findings. First, we recommend water reuse research strive for comprehensive factor identification and evaluation based on our identified list of factors. To enhance the reliability and applicability of the findings, future studies should aim to fill these data gaps by collecting primary data on factors and their influence in various end use contexts. While this review analyzed peer-reviewed journal articles in English from a single database, future reviews could synthesize data from multiple sources, including grey literature, books, and sources in other languages. Such an approach would allow for more thorough coverage of sector-specific factors, including technical factors and their interactions with non-technical factors, the latter being the focus of this review. Further, our qualitative approach consisted of identifying factors at the same level of granularity in the maximum number of articles and condensing them into the most data-dense meta-factors. Therefore, we also recommend future reviews aim to be systematic in their identification of factors. While a more quantitatively informed approach may have yielded different factors and frequencies, we doubt that our main takeaways would be substantively different, especially given our non-frequentist presentation of the case study findings. Second, using a comprehensive dataset of factors we recommend researchers identify the configurations of factors that lead to successful implementation in potable versus nonpotable cases. We found that the relationships between factors could change the influence of factors on a case's outcome, especially attempted cases' outcomes. This result may indicate that factor interactions may be more determinative of their influence on implementation than simply their presence or absence. Exploring pathways of success could also involve examining the relative importance of factors. Cross-case comparison techniques are well-suited for this task.[176,193] Visualizing the co-occurrence of factors collected using primary data methods would further enhance our understanding of these pathways of success across end use contexts. Third, we suggest future research focus on the dynamic nature of factors and examine their importance at different phases of implementation.[53,194,195]

We found that understanding the dynamic nature and timing of factors in real-world cases is crucial because these factors often interact in complex ways that change throughout different phases of a project, thereby influencing the implementation outcome. We recommend future studies consider using causal loop diagramming or other systems approaches to identify key causal mechanisms.[196,197] Overall, these research recommendations can assist water reuse researchers and practitioners in developing a more complete and nuanced understanding of the factors necessary for effective water reuse implementation globally.

4. Conclusion

Unpredictability in water supplies and growing water scarcity require long-term water management strategies, including water reuse. Implementing water reuse has been challenging, primarily due to a lack of comprehensive data on non-technical factors that utilities can use to develop success strategies. To address these knowledge gaps, we first conducted a systematic literature review and analysis of 232 peer-reviewed journal articles to examine the factors that facilitate or hinder the implementation of water reuse projects globally. We identified a comprehensive framework of facilitators and barriers. Key facilitators that emerged were clear and specific regulations, laws, and/or guidelines, robust public education and awareness programs, and drought. Major barriers that emerged were public reuse consumers' perceived health risks, a lack of internal or private funding for capital costs, and a lack of existing infrastructure.

Second, we analyzed 47 cases discussed in 44 of the surveyed articles to identify factors associated with implementation success in nonpotable versus potable cases. We found that, for nonpotable reuse, fostering strong relationships with the industrial/agricultural sectors, and investing in infrastructure development, were more often associated with implementation success. Barriers including a lack of organizational capacity and funding deficits were discussed in most attempted cases that failed. Facilitators for potable reuse included timely public engagement with appropriate branding and marketing and securing robust policy and financial support. Major barriers were negative public perception and regulatory uncertainty. This analysis based on case classifications specific to end use context allowed us to highlight the unique challenges and opportunities associated with each type of reuse.

Finally, we identified which factors were consistently not discussed in the surveyed literature to highlight knowledge gaps that require further study. For instance, we found that social and organizational factors had the most missing data for nonpotable cases, and the missingness may be attributed to certain types of data not being collected in research on reuse implementation. We recommend addressing these gaps by conducting rigorous, comprehensive case study analyses to systematically capture all factors, their influence classifications as facilitators and barriers when present or absent, and their combined influence on implementation outcomes based on end use context. These recommendations for future research will help to better understand the complete spectrum of factors, the relative importance of each factor, and the causal relationships between factors to ultimately identify comprehensive strategies for successful water reuse implementation.

Author Contributions

Conceptualization: SC, AJW, PS; Methodology: SC, AJW, PS; Formal analysis: PS, SC, AJW; Resources: SC, AJW; Writing - Original Draft: PS; Writing - Review & Editing: PS, SC, AJW; Visualization: PS, SC, AJW; Supervision: SC, AJW; Project administration: SC, AJW, PS; Funding acquisition: SC, AJW

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Supporting Information

The Supporting Information is available free of charge at http://pubs.acs.org.”.

- (Table S1) Overview of key search terms used in the literature retrieval process; (Table S2) detailed framework coding dictionary divided based on factor affinity groups and citations for all included articles; (Figure S1) distribution of factors by year of publication; and (Table S3) summaries of all included case studies identifying each case’s end use and implementation outcome analyzed

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