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REVIEW ARTICLE

Benefits and limitations of recycled water systems in the building sector: a review

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Abstract
Building construction requires important amounts of freshwater, thus depleting the already stressed natural water resources. This issue could be addressed by using recycled water in construction and in building systems. However, integrating greywater recycling systems is limited by complexity, costs, vulnerability to environmental fluctuations, and coordination of policymakers, developers, and construction practitioners. Here, we review recycled water systems in buildings with focus on case studies of successful implementations, policies, recycled water treatment in buildings, and health aspects. Compared to conventional tap water, the incorporation of recycled water enhances the consistency and workability of reclaimed water concrete by 12–14%, and it increases concrete viscosity by 11% and yield stress by 25%. We discuss the intricacies of building water recycling systems, with emphasizing on conserving water, mitigating environmental impact, and enhancing economic efficiency. Challenges include water quality assurance, dual piping infrastructure, and regulatory compliance. Government interventions, including incentives, mandates, and subsidy policies, emerge as drivers for widespread adoption. Technological advancements, such as membrane filtration and advanced oxidation processes, are examined for strengths and limitations.

Keywords Water scarcity · Recycled water system · Sustainable development · Building sector · Technological advancements · Policy frameworks

Introduction

In recent years, the global community has witnessed an escalating concern for sustainable practices in various industries, with particular attention on the building sector's environmental impact (Chen et al. 2022, 2023b; Yang et al. 2023b). One of the pressing challenges the construction industry faces is the ever-growing demand for freshwater, coupled with the scarcity of this vital resource (Orejuela-Escobar et al. 2021). In response to this critical issue, the concept of recycled water has emerged as a promising solution to mitigate water scarcity and reduce the environmental footprint of buildings (Orejuela-Escobar et al. 2021; Chen et al. 2023a). Imagine a world where buildings not only serve as

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shelter and space but also actively contribute to conserving our planet's precious water resources (Crini and Lichtfouse 2019). Therefore, promoting the use of recycled water and conservation of water resources is essential for the construction industry to achieve sustainable development goals (Gu et al. 2019). Such a vision is rapidly becoming a reality, with recycled water revolutionizing the building sector's approach to water management.

Recycled water, also known as reclaimed water or greywater, refers to treated wastewater undergoing rigorous purification to meet stringent quality standards, making it safe for non-potable applications (Crini et al. 2019; de Matos et al. 2020). This alternative water source presents a viable means to decrease the strain on traditional freshwater supplies and reduce the discharge of untreated wastewater into natural water bodies, thereby promoting a more sustainable and eco-friendly construction landscape (Zhang et al. 2022a). During construction, recycled water is employed for dust control and watering, lessening the burden on freshwater resources. It also proves valuable in concrete mixing and curing, maintaining quality while conserving water (Chen et al. 2013). In operational buildings, recycled water is used for toilet flushing, landscaping, cooling systems, and decorative features, contributing to sustainable water management (Takeuchi and Tanaka 2020). Green infrastructure elements and on-site greywater treatment systems further enhance water efficiency (Rahman et al. 2019). Additionally, recycled water aids in fire protection systems and supports research and testing for advancing water recycling technologies (Radcliffe 2022; Chen et al. 2023a). In summary, the wide-ranging application of recycled water in construction practices showcases its pivotal role in mitigating water scarcity, reducing environmental impact, and advancing sustainable building practices.

Therefore, this review aims to provide a comprehensive overview of recycled water in the building sector, exploring its various types, benefits, and challenges. It will present case studies showcasing successful implementations, examining the advantages of recycled water in different building types while also addressing the challenges faced during their adoption and the lessons learned. Additionally, the review will delve into the policy and regulatory landscape impacting recycled water systems in buildings, highlighting best practices and lessons learned from policy implementation. Moreover, it will explore recent chemical and technological advancements in recycled water systems, assessing their potential impact on adoption and discussing emerging trends in recycled water technology. Health and safety considerations will be addressed, including potential concerns, mitigation strategies, and an evaluation of the benefits and risks of using recycled water in buildings. By summarizing key findings and implications for policy, practice, and research, this review seeks to promote the potential for increased adoption of recycled water systems in buildings, identify challenges and opportunities for the future, and offer recommendations for further research and action in advancing sustainable water management practices and promoting sustainable development goals within the building sector.

Overview of recycled water in the building sector

Recycled water has emerged as a transformative solution in the building sector to address water scarcity and promote sustainable practices (Fu et al. 2020). This overview explores the various types of recycled water, including greywater, rainwater harvesting, and blackwater treatment, each offering unique benefits for non-potable applications. These systems contribute to water conservation, reduced environmental impact, and cost savings (Amaral et al. 2020). However, challenges like ensuring water quality, dual piping infrastructure, and regulatory compliance must be navigated. Specifically, Table 1 presents an overview of common types of recycled water applications in the building and construction industry and analyzes their advantages and challenges. Embracing recycled water practices empowers the building industry to actively participate in water resource management, fostering a greener and more resilient approach to construction practices. Based on Table 1, the findings show that recycled water benefits in the construction sector include water conservation, cost savings, reduced environmental impact, water reuse, and sustainability promotion. However, incorporating recycled water systems in building and construction offers promising prospects for sustainable water management and several challenges should be addressed to ensure successful implementation. One of the primary concerns is water quality assurance, as recycled water must meet stringent standards to guarantee safety and suitability for non-potable applications (Van der Bruggen 2021). To facilitate the distribution of recycled water, buildings often require dual piping infrastructure, which can be financially burdensome and necessitates meticulous planning during the construction phase. Compliance with regulatory frameworks governing recycled water usage is crucial, and this can be a complex process requiring ongoing monitoring and reporting to meet environmental and safety standards.

Another challenge arises from the seasonal variability of certain recycled water sources, such as rainwater harvesting, which may require additional measures or alternative water sources during dry periods to meet demand (Mishra et al. 2021). Proper storage and treatment facilities are essential for a reliable and consistent recycled water supply. Moreover, specific types of recycled water, like blackwater from toilets and kitchens, may contain pathogens and contaminants, necessitating advanced treatment

Table 1 Benefits and challenges of various recycled water in the building sector

Types of recycled water	Benefits	Challenges	Key findings	Reference
Greywater	Water conservation; Reduced water bills; Environmental impact reduction	Water quality assurance; Dual piping infrastructure; Regulatory compliance	Greywater refers to lightly used water from bathroom sinks, showers, bathtubs, and washing machines. It is relatively clean and can be collected and treated for reuse in non-potable applications such as flushing toilets, irrigation, and landscape maintenance	Yoonus and Al-Ghamdi (2020)
Rainwater harvesting	Water conservation; Cost savings; Reduced environmental impact	Seasonal variability; Water quality assurance; Storage and treatment requirements	Rainwater harvesting involves collecting and storing rainwater from rooftops and other surfaces. The harvested rainwater can be used for non-potable purposes such as irrigation, flushing toilets, and building cooling systems	Teston et al. (2022)
Blackwater treatment	Water reuse; Environmental impact reduction; Reduced water demand	Complex treatment processes; Health and safety concerns; Regulatory compliance	Blackwater consists of water from toilets and kitchen sinks containing higher levels of organic matter and pathogens. Advanced treatment systems can be used to treat blackwater and recycle it for non-potable applications, though this requires more complex and thorough treatment processes	Xu et al. (2023a)
Condensate water	Water resource management; Cost savings; Sustainability promotion	Collection and storage systems; Treatment and filtration requirements; Water quality assurance	In air conditioning systems, water is condensed from the air as a by-product of cooling. This condensate water can be collected and reused for non-potable purposes within the building	Li et al. (2019)
Stormwater harvesting	Water management; Reduced environmental impact; Reduced stormwater runoff	Water quality and contamination risks; Storage and treatment challenges; Regulatory compliance	Stormwater runoff from the building's surfaces and surroundings can be collected and stored for various non-potable applications, reducing the burden on municipal stormwater systems and promoting local water management	Martins Vaz et al. (2021)
On-site wastewater treatment	Water recycling; Reduced water demand; Sustainability promotion	Advanced treatment technologies; Health and safety concerns; Compliance with regulations	Some buildings incorporate on-site wastewater treatment systems that can treat and recycle wastewater generated within the building for non-potable purposes	Dewalkar and Shastri (2020)

The table presents six types of recycled water used in buildings: greywater, rainwater harvesting, blackwater treatment, condensate water, stormwater harvesting, and on-site wastewater treatment. Each type offers specific benefits such as water conservation, cost savings, and reduced environmental impact. However, challenges related to water quality assurance, regulatory compliance, and treatment complexity must be addressed for successful implementation. Embracing recycled water systems can significantly contribute to water resource management and sustainability in the building sector and handling to effectively mitigate health and safety risks. Public perception and acceptance also play a significant role in the widespread adoption of recycled water systems (Sapkota 2019). Building occupants and the public may have reservations about using recycled water due to concerns about its safety and cleanliness, highlighting the importance of education and awareness initiatives to foster understanding and acceptance of recycled water practices.

Therefore, a comprehensive and integrated approach is imperative to overcome the challenges associated with using recycled water in building and construction. Collaboration among building professionals, regulators, water authorities, and the public is essential to develop effective strategies. Advanced water treatment technologies, including filtration and purification processes, are crucial to ensuring water quality and safety and addressing concerns related to contamination and pathogens. Additionally, investing in robust storage facilities and infrastructure can provide a reliable supply of recycled water, overcoming seasonal variability and enhancing water availability during dry periods. Adherence to strict regulatory frameworks and continuous monitoring are vital to ensuring compliance and accountability for recycled water usage (Sokolow et al. 2019).

Additionally, raising awareness and education campaigns are indispensable to bolster public acceptance. Informing building occupants and the public about recycled water's safety, benefits, and environmental significance can help dispel misconceptions and encourage its responsible usage. Moreover, integrating recycled water systems into building designs from the outset can minimize costs and streamline implementation. By proactively addressing these challenges and leveraging sustainable practices, the building and construction industry can contribute significantly to water conservation efforts and bolster resilience in water scarcity (de Matos et al. 2020). Embracing recycled water as a valuable resource will advance the industry's commitment to eco-conscious and responsible water management, forging a more sustainable and water-secure future.

This section highlights recycled water as a transformative solution in the building sector, offering benefits such as water conservation, reduced environmental impact, and cost savings. However, challenges such as water quality assurance, dual piping infrastructure, and regulatory compliance must be addressed for successful implementation. To overcome these challenges, a comprehensive approach involving advanced water treatment technologies, collaboration among stakeholders, public awareness initiatives, and integrated water management strategies is essential to harness the potential of recycled water and foster a more sustainable future in building and construction.

Case studies of recycled water use in the building sector

Examples of successful implementation of recycled water systems

In recent years, using recycled water in the building sector has gained considerable attention as a sustainable solution to address water scarcity and promote efficient resource management. Case studies presented in Table 2 highlight the successful implementation of recycled water systems in various building projects, demonstrating the value and potential of this approach.

Greywater recovery systems can provide water for non-potable uses, ensuring efficient use of water resources at the building level (Wanjiru and Xia 2018). De Gisi et al. (2016) pointed out that the water-saving technology in operation in a residential apartment building in Norway is the on-site greywater treatment system, which has been in operation since 2000 and has been meeting the World Health Organization's requirements for sanitary purposes in apartment buildings. Similarly, the office building of Minnesota Mining and Manufacturing in Canada uses a greywater system to obtain recycled water for toilet flushing, reducing the site's annual water consumption by 25% (Van Rossum 2020). Due to the large amount of greywater impurities, its recovery system is relatively complex, with many treatment procedures and steps (Oh et al. 2018).

Rainwater recycling systems are also a good way to use recycled water in buildings. Rainwater is collected and used for garden irrigation, thus avoiding the additional pressure on the municipal sewage system, and the water is recycled through the on-site treatment system (De Gisi et al. 2016). The Vancouver Research Centre building collects rainwater from the roof and stores it in a reservoir, then filtered, disinfected, and distributed it throughout the building as tap water for flushing toilets and irrigation within the house (Van Rossum 2020). Bertrand-Krajewski (2021) believed that rainwater that is not collected and reused often flows directly into the river through building pipes and road drainage systems, but this is actually wasted. Therefore, collecting rainwater and using it as recycled water actually makes full use of water resources and avoids adding unnecessary pressure to urban drainage systems.

In addition, rainwater harvesting systems and greywater treatment systems can even help the building achieve water self-sufficiency. Radcliffe and Page (2020) stated that a Sydney law firm is completely disconnected from the drinking water and wastewater systems provided by Sydney water, and all wastewater goes through an equipped water treatment system, harvesting 100 m^3 of treated water per year for toilet flushing, laundry and garden irrigation.

Table 2 Case studies of recycled water use in the building sector

Utilization of recycled water	Nation	Construction phase	Utilization method	Environmental impact	Economic impact	Social impact	Reference
Water for vegetation conservation and sanitation	Norway	Operation phase	Toilet waste is pumped directly into the municipal sewage system, water is pumped into the courtyard water filtration system, and rainwater is collected in rain barrels for use in the garden	Save water resources; Maximize the use of water resources	Reduce the cost of sanitary water and vegetation maintenance of apartment buildings; Reduce accommodation costs for apartment dwellers	Relieving pressure on municipal sewage systems	De Gisi et al. (2016)
Flush the toilet, wash clothes and water the garden	Sydney	Operation phase	Collecting all rainfall is in the roof catchment area into the tank below the house's deck. All sewage is collected in a biomodified underground concrete tank containing three filter beds, sterilized by ultraviolet light and used to flush toilets, wash clothes and water the garden	To play the reuse value of rainwater, 100 m^3 of water resources are reused every year	Reduced water costs in the law firm's operations	Not applicable	Radcliffe and Page (2020)
Flush the toilet	Canada	Operation phase	Using cistern water from the basement sump weeping tile system is for flushing toilets	About 2400 m^3 of water used to flush toilets is saved each year	Reduced water costs in 3M company operations	Not applicable	Van Rossum (2020)
Drinking water, toilet flushing and irrigation	Canada	Operation phase	Rainwater is filtered and sterilized for drinking water; Wastewater is recycled for toilet flushing and irrigation in buildings	Realize the reuse value of wastewater and rainwater	Not applicable	Not applicable	Van Rossum (2020)
Production concrete	India	Construction phase	Recycled water is used in the preparation of concrete instead of tap water	Reduce the dependence of engineering construction on tap water resources	Reduce the resource cost of construction units and construction units to improve concrete performance and extend the building	Improve concrete performance and extend building life	Arunkumar et al. (2023)

This table presents the application of recycled water in building operation and construction phases. In Norway, the apartment building utilizes a filtration system to obtain recycled water for vegetation maintenance and sanitary purposes. Similarly, the law firm utilizes rainwater harvesting tanks and wastewater treatment pools to obtain recycled water for toilet flushing, laundry, and garden irrigation. Additionally, the office building of 3M company utilizes recycled water from an underground sewage tank for toilet flushing. The Vancouver Research Centre building utilizes a rainwater collection system to reuse water resources. Furthermore, recycled water can even be used to prepare concrete, contributing to the construction phase of buildings

Water is an essential component in concrete production as it plays a crucial role in the hydration of cement and the workability of fresh concrete (Dharmaraj et al. 2021; Chen et al. 2023c). Arunkumar et al. (2023) mentioned that the use of reclaimed water instead of fresh water can enhance the impact resistance of concrete, and the consistency and slump of reclaimed water concrete are 12% to 14% higher than that of concrete using tap water. Similarly, recycled water used to flush the mixer can be used instead of tap water. de Matos et al. (2020)'s experiments found that the use of recycled water increased the viscosity of concrete by 11% and the yield stress by 25%.

This section introduces some examples of successful use of recycled water in buildings, as well as the social, environmental and economic impacts. These cases are mainly related to the construction operation phase, through the equipped greywater treatment and rainwater collection systems to fully use water resources. During the construction phase of the building, recycled water can also be used as a raw material for the preparation of concrete and can even improve the performance of concrete, achieving two goals. The extreme dependence of buildings on water resources and the positive impact of using recycled water will certainly promote the deep use of recycled water in buildings.

Benefits of using recycled water in different building types

According to the study by Richter et al. (2020), recycled water can substantially reduce potable water consumption, thereby contributing to water conservation. The researchers discovered that using recycled water in residential structures can result in a notable reduction of up to 50% in the demand for potable water. Moreover, water recycling systems can substantially benefit commercial and industrial buildings, which frequently exhibit elevated water demands. According to a study conducted by (Miller et al. 2018), it was shown that there is a possible decrease in water use of up to 75% in the types mentioned above of buildings.

The utilization of recycled water might also yield economic benefits. Buildings have the potential to achieve substantial reductions in their water expenses by decreasing the demand for potable water. In the study conducted by Zadeh et al. (2013), it was observed that buildings utilizing recycled water had a noteworthy decrease in water expenses, with reductions of up to 30% being recorded. The utilization of recycled water can effectively mitigate the environmental burden by alleviating the pressure on freshwater resources and minimizing the discharge of wastewater into the natural environment (Pratap et al. 2023). The significance of this matter is particularly pronounced in areas with a limited availability of water resources, as it facilitates the adoption of a more environmentally responsible and enduring water management strategy.

The use of recycled water in buildings has obvious environmental and economic positive effects. This topic is worthy of further study for human beings and will contribute to the sustainable development of the earth's water resources.

Challenges faced during implementation and lessons learned

The implementation of reclaimed water in buildings has some obstacles. Previous empirical evidence has elucidated several significant challenges, encompassing technological impediments and societal reception, which necessitate adept navigation for good outcomes. The initial obstacles typically include technical complexities. The design and implementation of a water recycling system can be intricate, necessitating substantial knowledge and meticulous planning. Furthermore, these systems' continuous operation and maintenance might incur significant costs and necessitate expertise in the field (Lyu et al. 2016). According to Voulvoulis (2018), a notable obstacle to using recycled water, particularly in residential environments, is the limited public knowledge and endorsement of its application. Despite the potential advantages, many individuals maintain unfavourable attitudes towards using recycled water, primarily driven by apprehensions over potential health hazards (Fielding et al. 2019).

According to Ait-Mouheb et al. (2018), the effective implementation of recycled water systems frequently necessitates a multidisciplinary strategy that incorporates knowledge and skills from several fields, such as engineering, environmental science, and social science. One potential approach to addressing public resistance is implementing effective communication and public engagement methods. Spreading knowledge among residents about the safety and advantages of using recycled water has the potential to change public perception and promote greater acceptance (Hou et al. 2021b).

In summary, the use of recycled water in buildings faces obstacles such as technical complexity, limited public knowledge and acceptance. However, public engagement and multidisciplinary collaboration can help overcome these challenges and hopefully promote greater use and acceptance of recycled water in the future.

Policy and regulatory framework

Policy and regulatory landscape for recycled water systems in the building sector

Innovators face complex water cycle systemic innovation problems, including poor access to innovation knowledge, unclear markets and user groups, scarce investment and social capital, and lack of legitimacy of innovations. It is important to evaluate how participants create institutional matches or mismatches and how they interact with the appropriate institutional frameworks during the system development process in order to understand better the causal factors of technological legitimization (Binz et al. 2016). New organizational procedures for water quality monitoring or the support of drinking water reuse systems in communities can meet the needs of the local environment. A description of recycled water policies practiced in different countries is shown in Table 3.

By implementing environmental regulations, the building industry seeks to preserve a highly functional built environment while controlling the use of resources. Therefore, many governments are considering the use of green manufacturing

Table 3 Policies for water recycling in buildings in various countries

Country/region	Policy	Description	Reference
Australia	Water Smart Program	Encouraging the purchase and installation of 2,000–L to above 7,000–L tanks is with incentives of \$150–\$500; rainwater tanks connected to toilets or washing machines with incentives of \$150	Apostolidis et al. (2011)
Bangladesh	National Building Code	Each proposed residential building shall be constructed on a plot of more than 300 m^2 and shall have rainwater harvesting arrangements	Bashar et al. (2018)
Malaysia	Urban Stormwater Management—Part 6: Rainwater Harvesting, MS2526–6:2014	Encouraging the installation of rainwater harvesting and utilization systems is in government buildings; large buildings must be mandated to install rainwater cell phone systems	Lee et al. (2016)
United Kingdom	The Code for Sustainable Homes	Encourage installation of water-saving devices; install rainwater harvesting devices	Zhang et al. (2017b)
China	Evaluation Standard for Green Building 2014	Engineering design, system planning, and equipment selection stages must include mandatory criteria for rainwater gathering, water-saving devices, and green irrigation. standards that must be met by building drainage and water supply systems regarding water conservation	Zhang et al. (2017b)
United States of America	Leadership in Energy and Environmental Design for New Construction	Promote the use of drip irrigation for rainwater harvesting; encourage the use of rainwater harvesting and sewage treatment technologies; use sanitary ware	Zhang et al. (2017b)
Bermuda	Public Health Act	Mandatory roof rainwater harvesting for all buildings constitutes a major source of domestic water supply	Lo and Gould (2015)
Arizona, United States of America	2010 Residential Greywater Ordinance	In addition to one or more building drains for bathrooms, showers, and bathtubs, all new single-family and duplex housing units must have a separate multi-pipe outlet or diverter valve with an external “shorting” mechanism on the washer connection	Bell (2018)
Guelph, Canada	Greywater Rebate Program	1,000 incentive is for residential homeowners to install and utilize an approved greywater system	Municipal Government publication (2020)

Most policies encourage or mandate the use of rainwater harvesting systems in buildings to recycle water. Subsidized policies provide incentives to value recycled water systems and increase motivation to participate. Implementing water recycling policies helps reduce water waste and recycling costs in buildings and green technology as a crucial component of maintaining a green economy and low carbon emissions when formulating strategic plans for economic growth. By requiring the creation of integrated water management plans, the EU Water Framework Directive encourages the adoption of municipal wastewater reuse across Europe. Rainwater is a traditional form of conservation reused in areas without water supply systems. In Australia, the New South Wales Government has developed a water-smart programme that provides subsidies of \$150–\$500 to households for the purchase and installation of rainwater storage tanks for their homes and an additional \$150 for the implementation of linking the output of rainwater storage tanks to toilets and washing machines (Radcliffe and Page 2020). Depending on the size of the reservoir and the use to which the water is put, these incentives change from state to state.

The Government of Bangladesh has mandated that all proposed new buildings install rainwater harvesting systems to address the city's severe water scarcity, saving about 500–800 m^3 of water per year (Bashar et al. 2018). The rainwater harvesting system shall be fitted with a backflow prevention device or similar equipment to prevent backflow or back siphoning of untreated rainwater into the public water supply system, which also prevents possible contamination of the public water piping system by untreated rainwater that the household could ultimately consume (Lee et al. 2016). The National Code for Sustainable Homes guidelines for the design and construction of new homes encourage the installation of water-saving devices to reduce internal and external potable water consumption and enhance water-saving performance. It also requires the installation of rainwater harvesting devices to improve the efficiency of rainwater harvesting and reduce surface water loss (Zhang et al. 2017b).

In order to increase the effectiveness of landscape water use, decrease the consumption of potable water, and improve the quality of wastewater treatment through rainwater harvesting and wastewater treatment technologies, the implementation of Leadership in Energy and Environmental Design for New Construction in the United States encourages the use of drip irrigation for rainwater harvesting of reclaimed water. Improvements in sanitary fixtures and other measures are also needed to reduce total water consumption (Zhang et al. 2017b). Rainwater is collected for general cleaning and gardening, but toilet flushing-where rainwater tanks are linked to flush toilet fittings to reduce the consumption of treated water for non-potable purposes-frequently uses rainwater in buildings (Lee et al. 2016). The 2010 Residential Greywater Ordinance encourages the use of gravity-fed water systems by requiring the construction of new single-family and duplex dwellings with individual greywater lines to enable the recycling of residential greywater for irrigation purposes (Bell 2018). With the help of the ordinance, people may reuse greywater more easily and affordably while also conserving potable water, which can result in annual potable water savings of up to 13,000 gallons for the average family.

In addition, Tucson's water rebate programme provides reimbursements of up to \$1,000 and a greywater workshop in exchange for installing a permanent greywater irrigation system in residence (Bell 2018). Central Texas Utilities might provide financial assistance to the community to recover the additional cost of collecting 56,300 kg for an additional yearly cost of \$192,000 in 2016 to encourage communities to recycle their own water (Scott Vitter et al. 2018). The city of Guelph's greywater reuse programme established several relevant ordinances, regulations, bylaws, building permits, and specifications for installing authorized greywater reuse system technologies, which licensed plumbers and contractors must carry out. Systems for recycling greywater use the water from showers and baths to flush toilets. Additionally, the contractor is obligated to give the homeowner a user guide explaining how to operate the system and perform the necessary maintenance (Municipal Government publication 2020).

In conclusion, the current state intervention in implementing water recycling policies in buildings encourages or mandates the installation of water conservation and recycling systems, and the policy-based support for the recycling of rainwater and greywater in family homes and buildings promotes water efficiency. Subsidized policies give citizens a strong incentive to implement residential water recycling systems, thereby reducing the additional costs of water use.

Impact of policy and regulations on the adoption of recycled water systems

A key factor in guaranteeing the adoption of water reuse is the participation of regulators and policymakers. Decentralized wastewater reuse plans and unique dual-recycling systems can be developed in dense metropolitan areas with the right national policy criteria (Sgroi et al. 2018). Tax and financial subsidy incentives are more conducive to forming information systems than regulatory policies. In European Union countries, policies positively affect information systems development by improving environmental performance through indirect incentives rather than direct obligations (Yu et al. 2015). Promotion through rainwater and green building policies. Subsidizing water recycling at the community level may be a viable way for centralized utilities to progressively increase water supply to urban areas, as it is particularly important for supplying water to developing rural areas or newly annexed urban areas, which have long transmission distances from centralized facilities (Scott Vitter et al. 2018). Reducing supply requirements for centralized distribution systems may reduce or delay capital investments in pipes, pumps, or other supply-side water infrastructure. To enhance local communities' cost and energy efficiency, the Boston government permits the consideration of shared, integrated, decentralized residential rainwater collecting and greywater recycling systems (Stang et al. 2021). Greywater and rainfall collecting can enhance neighbourhoods, but lack of knowledge is one of the obstacles to modifying the 2010 Residential Greywater Ordinance to provide more precise design criteria.

In summary, implementing water recycling policies contributes to improving environmental benefits and information systems. Moreover, incentives for water recycling systems improve energy efficiency and reduce costs in residential complexes.

Best practices and lessons learned from policy implementation

Creating water that satisfies quality standards now involves significant expenditures for businesses. The government needs to provide adequate policy support to policies that direct the development of water reuse networks because the use of reclaimed water for urban landscaping is beneficial to the sustainable development of society, and the development of pertinent policies for such use is a public service (Gan and Zeng 2018). However, there is a pressing need to develop urgent legislation to improve water reuse in China's urban landscaping industry. According to Radcliffe and Page (2020), installing pressurized rainwater tanks with household pumps causes a sizable rise in energy use. For instance, homes with separate rainwater and greywater domestic systems rely on tiny electric pumps and ultraviolet disinfection systems to function properly, using an average of 4.3 kWh/d of energy. In Malaysia, only major structures like factories, schools, or bungalows are required to have rainwater collecting systems, and there are still no robust laws to encourage their installation (Lee et al. 2016). One of the major obstacles to residential greywater usage is the inconvenience of installation. The residential greywater ordinance does not mandate the installation of greywater irrigation systems in new residences, simply that the dwellings be built to allow the use of greywater in the future. Therefore, a homeowner must put effort into attaching even the most basic laundry room to a landscape gravity irrigation system (Bell 2018). It is crucial to choose the best set of criteria that reflect local needs and characteristics because overly strict requirements will prevent water reuse projects from being implemented and will hinder local industry growth, while lax regulations may encourage behaviour that has unintended negative effects (Wilcox et al. 2016).

Future research should focus on other designs for community-scale water reclamation, such as dual distribution systems for non-potable water and systems that combine rainwater collection, which would do away with the need for reverse osmosis (Scott Vitter et al. 2018). Understanding the difficulties and potential of integrating local water reuse networks into current water and wastewater infrastructure requires more investigation. By reducing sewage flows, adopting decentralized water reuse networks may also impact how well-established wastewater networks operate. The relationship between acceptance, risk, and trust has been experimentally examined in the context of new technology in the literature on risk communication. Authorities looking to adopt reclaimed water programmes, particularly drinking water schemes, now heavily weigh public support. The community-scale water recycling system suggested in this study faces various obstacles that must be overcome, including public acceptability, regulatory direction, and quality assurance. Many individuals rely on faith in the relevant authorities or governmental agencies to make judgments because they lack the resources, such as knowledge, time, and interest, to make decisions and perform actions linked to science and technology. Although the existing strategy for developing water resources looks unsustainable, creating a transformational strategy necessitates a shift in public views on water usage by acknowledging economic and environmental restrictions. A common social identity with the water industry and equitable procedures make recovered water schemes more likely to be accepted (Ross et al. 2014).

In conclusion, the current water recycling policy is not well-popularized in society; some policies do not apply to most buildings, and there is still a lack of policies with higher applicability and enforcement. Moreover, public confidence is still the main reason for limiting the development of water recycling policies, and it is important to make highly convincing decisions through appropriate policy instruments.

Recent chemical advancements in recycled water systems in buildings

Membrane filtration

Water resource management is facing increasing challenges due to climate change, population growth and urbanization, with two main advantages in locating reusable water sources as solutions compared to traditional long-distance water transport solutions. Firstly, it reduces the cost of long-distance water transport; secondly, it can increase the resilience and adaptability of local water systems (Van de Walle et al. 2023). The wastewater produced in the building usually comes from washing machines, dishwashers, showers, and sinks. In developed countries, the average daily production of domestic wastewater is equivalent to 98 L per person per day (Leigh and Lee 2019), making it an attractive water resource due to the low level of faecal pollution and the large amount available. Common recycled water methods include membrane separation, advanced oxidation process, electrochemical, and chemical-free treatment, as shown in Fig. 1. Membrane filtration is a popular method to remove impurities from water recovery. Membrane filtration technology has the advantages of high residue capacity, small footprint, and easy automatic operation and control (Yang et al. 2023a). Membranes are widely used as selective barriers and are usually made of polymers, biopolymers, and inorganic substrates (Barhoum et al. 2023). The membrane is divided into a filter cake layer and a gel layer, where the filter cake layer consists of a loose flocculate located on a nylon mesh with an average aperture of 75 µm as the support material for the coarse support net. The gel layer comprises colloids and dissolved substances clinging to the supporting material surface. The gel layer surface has polar functional groups to enhance the reactivity of the membrane, thus effectively removing contaminants (Jia et al. 2022). The main impediment to membrane use is the membrane in the scaling process, which affects the membrane flux. Table 4 shows how to increase the membrane's performance to reduce the appearance of scaling. Membrane filtration technology effectively promotes the cycle of water used in buildings compared to traditional sewage treatment plants or direct discharge of domestic wastewater is environmentally friendly and creates more significant economic benefits.

Membrane filtration systems can effectively assist plants in recycling water resources. Water consumption in the industrial sector has increased in recent years, particularly in the traditional petrochemical processing and emerging semiconductor industries. According to Tian et al. (2020) research, the petrochemical industry consumes large

Fig. 1 Four processes are commonly used in circulating water. This figure shows that the processes widely used in recycled water systems are membrane separation, advanced oxidation process, electrochemical, and chemical-free treatment. This figure shows how the four recycled water systems treat wastewater at the molecular level to remove related organic matter from wastewater. In addition, the physical and chemical methods used to treat recycled water are shown in this figure. This figure shows the scenarios used in the four ways to facilitate more rational choices

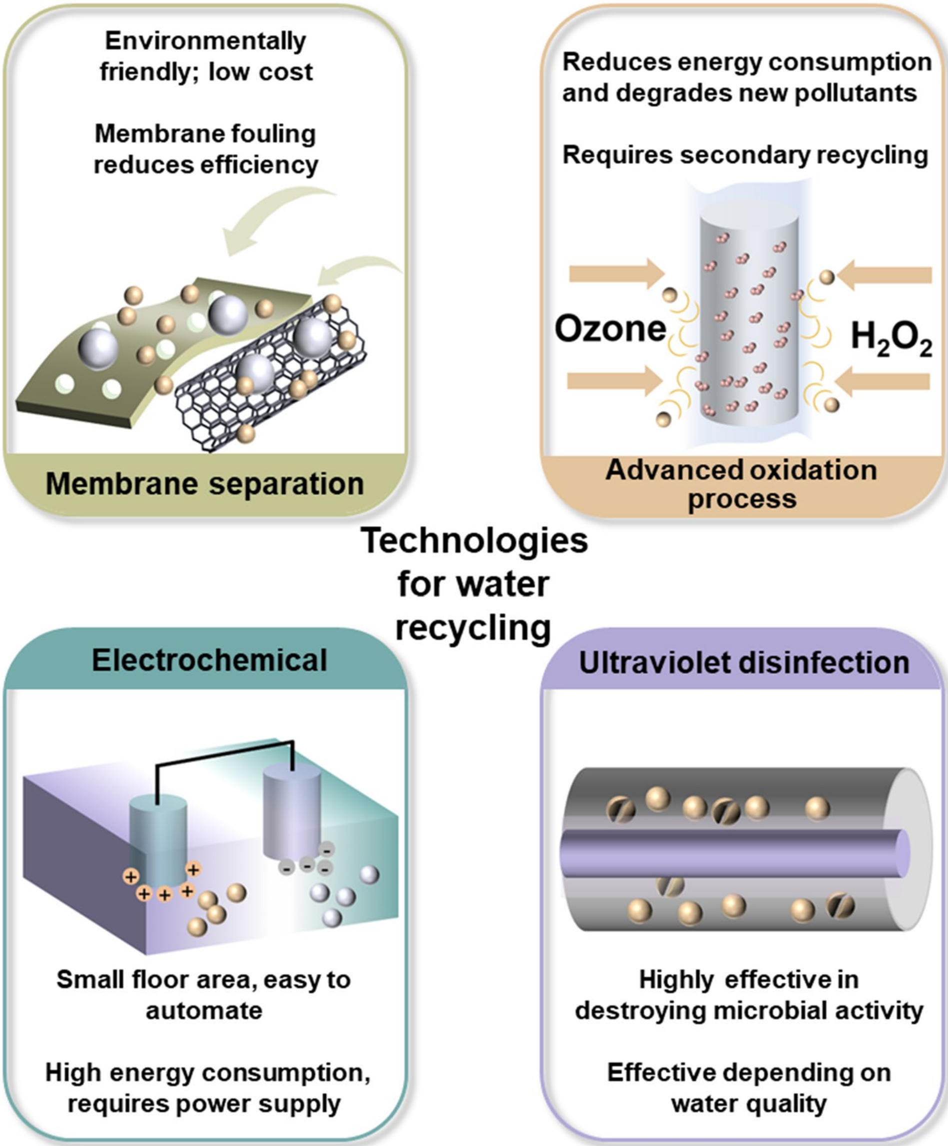

Table 4 Optimized way to enhance membrane performance

Optimization name	Adopting methods	Characteristic	Effect	Reference
Gravity-driven membrane reaction generator	In the direct treatment of domestic wastewater at a pressure of 45 millibars, the presence of ventilation shear on the membrane surface can lead to the collapse of the membrane structure	The gravity-driven membrane reaction generator can be continuously filtered without any physical or chemical cleaning, and its membrane flux can remain stable during long filtration periods	Gravity-driven membrane reaction generator enables chemical oxygen demand and ammonia to be effectively removed with an average removal efficiency of 60–80% and 70%, respectively. High bioactivity and diversity of microbial communities within the membrane can enhance their biodegradation and should contribute to effectively removing pollutants	Gong et al. (2023)
Fixed hydrolysis/fermentation of bacteria	A pretreatment tank filled with a porous polyurethane sponge as a biomass attachment carrier has been developed for organic hydrolysis or fermentation of inlet water	Most biomass (greater than 95%) is grown on porous carriers rather than physically preserved by filtration membranes	The porous polyurethane sponge fixation helps the membrane reach a fouling-free state for more than 100 days, while the control group has an average fouling period of 20 days	Xu et al. (2023b)
Membrane relaxation	Six hours a day, combining 25 min of membrane relaxation and the last 5 min of relaxation with air scour	Biomass exhibits elastic behaviour in relaxation cycles, expanding its volume without penetration (increasing thickness by 230%)	As the thickness of the membrane increases, higher biomass is removed from the membrane surface, and performance is significantly improved (250% flux increase)	Fortunato et al. (2020)
Regular ultrasound cleaning	High-frequency acoustic-induced cavitation bubbles can loosen the interaction of contaminants with the membrane and separate contaminants from the membrane	Ultrasound has a high energy footprint for wastewater treatment and can cause membrane damage during long-term operation	Regular ultrasound cleaning reduces filter cake resistance by 34%. The cost of purifying water is about 0.16 Euro/m^3)	Hube et al. (2023)
Fill the filtration membrane with porous impurities	Fill the filtration membrane with porous Icelandic lava	Scaling in Icelandic lava accounts for more than 80% of the generalized scale, proving that most impurities are adsorbed in the lava	Icelandic lava can form more holes in the filter cake layer, making filtration resistance less, achieving a larger than 75% organic material removal rate	Guðjónsdóttir et al. (2022)
Modified filtration membrane surface using different charged functional groups	The membrane sample is cleaned with 50% ethanol for 30 min to remove preservative material, then washed with deionized water, soaked in deionized water, and refrigerated for 12 h. Only the active layer side of each membrane is modified by graft copolymerization with different monomers at 29 ± 2 °C	Hydrophilic membranes are not susceptible to organic and biological contamination, as they form thick hydration layers that prevent the adsorption of contaminants	Membrane grafted with neutral or mixed charge poly (methacrylate) groups has the best anti-scale effect	Rathinam et al. (2022)

As shown in the table, membrane reactors are optimized to increase the service life of the membrane and ensure their efficiency. This table illustrates the physical or chemical ways people can avoid/address membrane fouling, thereby reducing the cost of filtration membranes. In addition, this table analyses the methods and characteristics of each optimization measure to help the membrane user understand how easy it is to use the following processes. This improves the membrane's purification efficiency and the associated cost of use amounts of pure water in the production process and produces wastewater containing high levels of chemical oxygen, challenging water resources in water-scarce areas. With increased awareness of environmental protection, the Chinese government requires a recovery rate of 94% for industrial water. Lin et al. (2023) find that industrial wastewater is treated using a combination of microfiltration, ultrafiltration, and reverse osmosis based on membrane technology. The treated industrial wastewater is used for cooling or flushing the related units. The net value of the treated water is analysed, and the cost of purifying the water after the membrane process combination is \$0.45 per cube, less than \$0.6 per cube for pure water. As a result, membrane filtration systems can generate higher benefits for traditional chemical companies. For the high-tech semiconductor industry, a large amount of pure water is used to clean and cool samples, and the wastewater, after use, contains a large amount of suspended silicon particles with high turbidity and a darker water colour than espresso. Tseng et al. (2019) pointed out the use of an ultrafiltration membrane system to filter wastewater; even for wastewater with a turbidity of 14,500 NTU, ultrafiltration membranes can reduce turbidity to 0.05 NTU. And the removal efficiency is more significant than 99.9%. Membrane filtration systems not only bring clean water to the plant at a lower cost. It can also be used in emerging industries to remove high turbidity pollutants.

For areas with more precipitation, membrane filtration systems can purify rainwater and provide residents with clean and inexpensive water. Rainwater has excellent potential for solving the world freshwater crisis, and its use by decentralized systems can replace water supply to individual households or communities (Alim et al. 2020). The use of rainwater can lead to higher energy efficiency than centralized water supply. However, chemical and microbial contaminants are present in rainwater, which are affected by location and air pollution levels (Du et al. 2019). The membrane separation process is attractive for treating rainwater, effectively removing colloids and suspended particles from rainwater. Baú et al. (2022) proposed to remove bacteria and viruses from rainwater using an ultrafiltration membrane with 0.001–0.1 micron aperture at 1–7 bar pressure. Ultrafiltration membranes can treat rainwater to drinking water standards regarding oxygen demand, sedimentary solids, coliform flora, and other parameters. Using an ultrafiltration membrane system to purify rainwater on a roof of 230 cubic meters, the cost of purifying water is \$0.14/m^3, nearly four times cheaper than the water provided by the water company. Therefore, using a membrane system to purify the roof of rainwater has a more significant economic attractiveness.

In short, membrane filtration technology is an economical wastewater treatment process, and easy-to-operate water purification technology can effectively treat domestic wastewater to facilitate people's reuse. However, the membrane filtration method has certain limitations; the membrane is easy to produce, but membrane scaling affects its performance and can produce more pollution. People can take higher quality membranes to deal with this, for existing membranes can also be treated in some ways to reduce the impact of membrane fouling, improve the life of the membrane, to reduce the cost of membrane filtration.

Advanced oxidation processes

Over the past few decades, new chemicals have been used in human activities, and large quantities of wastewater containing chemosynthetic substances and pathogens are incredibly harmful to ecosystems. These contaminants, consisting of cosmetics, pesticides, personal care drugs and steroid drugs, are known as emerging pollutants (Khan et al. 2021). Global production of these new pollutants is rising rapidly, from 10,000 tons in 2002 to five million tons in 2022 (Khan et al. 2022). However, traditional wastewater treatment plants are ineffective in removing these emerging pollutants. The current traditional wastewater treatment methods are inefficient, poor stability, high energy consumption and large numbers of bacteria that are difficult to clean up (Liu et al. 2023a). Advanced oxidation is considered one of the most effective wastewater treatment technologies. Advanced oxidation processes degrade emerging pollutants by inducing oxidants to produce reactive substances, decomposing refractory or toxic organic pollutants directly into harmless mineralization products (Li et al. 2023). Advanced oxidation processes are valued for their high treatment efficiency and less toxic products.

Advanced oxidation processes can help factories reuse industrial wastewater in situ. Industrial freshwater intake accounts for 55% of the total freshwater intake in industrialized countries, posing significant risks to national water security (Flörke et al. 2013). Much of this freshwater is used for cooling industrial processes in cooling towers, but cooling tower water needs to be less than 1mS/cm of electrical conductivity, which would otherwise lead to system scaling or corrosion of pipes (Wagner et al. 2018). When freshwater is used for cooling, its conductivity increases to 1.5–5 mS/cm under evaporation. By combining advanced oxidation processes with membrane filtration, 90% of the metal ions in the cooling water can be effectively removed, thus bringing the conductivity of the recovered cooling water into line with the standard of use (Wagner et al. 2018). Moreover, the advanced oxidation process effectively converts heavy metal ions from cooling water into harmless metal precipitation, which can be recovered further.

Advanced oxidation processes can efficiently recycle wastewater in plants. The highest water consumption is in the textile and dye industries. The biggest problem in the textile fuel industry is inefficient water efficiency and large amounts of sewage discharge (Liu et al. 2021a). Sewage contains a large amount of salt, high chemical oxygen demand levels and additives. Traditional sewage treatment plants require more space and associated infrastructure and consume much time. Advanced oxidation processes are proposed to treat this wastewater in less than 30 min to purify the wastewater produced in the weaving process into reusable freshwater, with a decolourization capacity of 100% and a 25-fold reduction in footprint compared to conventional water purification devices (Tanveer et al. 2023). The advanced oxidation process provides the plant with a cheaper and more effective treatment solution.

Under extreme conditions, advanced oxidation processes can cycle water resources in more remote areas or buildings. Greywater reuse has become increasingly accepted, especially for uses where water is not directly exposed to humans, such as toilet flushing and garden irrigation (Van de Walle et al. 2023). Compared to greywater, Englehardt et al. (2013) proposed the concept of net-zero greywater, which recovers the greywater produced in life in a near-closed-loop fashion, returning it to the quality of its original use. There are no imported water resources in the net-zero greywater system, nor is the system water discharged outward. This concept requires a higher level of treatment of organic compounds and pathogens. Gassie and Englehardt (2017) proposed using titanium dioxide combined with ultraviolet light to oxidize organic matter in greywater at 320–380 nm to achieve clean disinfection. Although the method is costly and requires secondary disinfection, it still provides new ideas for building the water cycle under special extreme conditions.

In summary, advanced oxidation processes can handle emerging organic substances that are difficult to remove in traditional sewage plants in daily life. Advanced oxidation processes typically use hydrogen peroxide or sulphides to treat domestic wastewater, breaking down difficult or toxic organic pollutants into harmless mineralization (Ma et al. 2023). Optimization for advanced oxidation processes is usually the selection of the right catalyst or low-cost process. Advanced oxidation processes can be combined with electrocatalysis to accelerate the electron binding of oxidants to organic pollutants.

Electrochemical processes

Electrochemical technology is applied to circulating water systems in buildings in common ways, such as capacitive deionization, electrooxidation, electrical reduction, and condensation. At the heart of electrochemistry is the design of a suitable electrochemical reactor using the right electrode material, which needs to contain a reaction chamber, cathode, anode, and agitator (Liu et al. 2021b). Electrochemical technologies are low-cost, have a small footprint, are easy to automate, and are therefore suitable for use in buildings. As a decentralized circulating water device, wastewater flows through electrolytes between the anode and the cathode; when contaminants come into contact with the anode, oxidation occurs, and contaminants are oxidized to harmless products or precipitation (El Kateb et al. 2019). During the application of the current reaction, the anode gradually dissolves to produce many high-charge metal cations that will act as coagulants and flocculating pollutants to remove contaminants by precipitation and flotation (Guo et al. 2022).

Electrochemical technology can be used to disinfect cisterns. The current common disinfection methods are chlorine disinfection or ozone disinfection. However, these technologies are affected by toxic by-products and excessive ozone costs during chlorine disinfection (Chu et al. 2016). For the treatment of microorganisms, the primary disinfection mechanism of electrochemical oxidation is direct oxidation and indirect oxidation on the electrode surface (Feng et al. 2023). Microorganisms react directly with the anode during direct oxidation to lose electrons, resulting in inactivation (Hu et al. 2023). The indirect oxidation process is the direct adsorption of microorganisms on the electrode and then the transfer of electrons to inactivate the microorganism. Ni et al. (2021) proposed that at alternating current pulse current, the hydroxide root is used to bring the bacteria together in the cathode negatively charged, and then under the influence of alternating current pulse current, the cathode becomes anode to inactivate the bacteria immediately. With 6 V and 3 mL/min flow rates, 95% of *Escherichia coli* can be effectively killed in the reservoir, and the number of bacteria will not grow in ten hours. Electrochemical techniques ensure water safety in cisterns by killing bacteria.

Electrochemical technology can help plants selectively recycle heavy metals from wastewater to ensure water recycling. Heavy metals are extracted from industrial wastewater using electrochemical technology to avoid environmental contamination and recycle heavy metal resources (Du et al. 2023). Electrochemical techniques recover metal ions from wastewater into single-ion solutions or precipitated ionic compounds by electrochemical reduction or electrodeposition. Tang et al. (2023) used composite electrodes for uranium recovery in wastewater from nuclear power plants. At the low operating voltage of 831.5 V and pH equal to 3, the next hour has a 5.5 mg/g uranium absorption efficiency. Li et al. (2020) indicated that smelting wastewater containing lead at 5–120 ppm or zinc at 30–150 ppm would be produced during the smelting of gallium and zinc. They developed an electrodeposition system using different cathode materials to selectively recover lead and zinc from smelting wastewater in higher impurities. The electrodeposition system can recover 98.5% lead for ten hours at 0.7 V and 98.7% zinc for six hours at 1.2 V. Through sixteen hours of electrochemical treatment, the treated industrial wastewater meets the cooling water utilization standards and can be reused. This demonstrates the critical potential of electrochemical technology in-plant applications.

Although electrochemical oxidation and coagulation are effective methods for treating domestic wastewater, they still have some limitations. The biggest limitations of electrochemical oxidation are high energy consumption and operating costs, the relatively slow rate of electrochemical oxidation treatment of domestic wastewater, and the need to always link the power supply for discharge, which makes the operational cost of electrochemical oxidation treatment a hidden risk (Liu et al. 2023b). For electrocoagulation, the biggest challenge comes from electrodes. The main mechanism of electrocoagulation is a continuous dissolution of the anode to produce metal ions. Let the metal ion act as a flocculant, so the anode must be constantly changed during electrocoagulation. The resulting sludge needs to be treated accordingly, impacting operating costs (Shokri and Fard 2022). Therefore, the ideal state is to pretreat the domestic wastewater before applying electrochemical treatment to further purify it.

In short, the primary electrochemical treatment of domestic wastewater in the main way is electrochemical oxidation and electrochemical condensation, both in the living wastewater electrodes, through current discharge to promote the exchange of electrons to achieve the purpose of purification of water sources. However, there are some limitations in the electrochemical purification of domestic wastewater, such as excessive energy consumption and the need to remove the sludge layer and replace the anode (Bajpai et al. 2022). Therefore, people need to optimize their electrochemical processes in a more environmentally friendly way by reducing energy consumption and optimizing their sludge cleaning processes so that more people accept electrochemical processes to treat their living wastewater.

Chemical-free treatment processes

The disinfection by-products formed in the drinking water disinfection process cause construction adverse effects and are increasingly concerning. Common disinfection by-products are dichloroacetaldehyde and trichloroacetaldehyde, which are cytotoxic, genotoxic, teratogenic, or carcinogenic (Pan et al. 2022). In a Chinese study, dichloroacetaldehyde and trichloroacetaldehyde were treated in water at 3 and 7.8 mg/L, and to reduce the harm caused to the human body, the Chinese government issued a maximum pollutant limit of 10 and 30 mg/L (Huang et al. 2021). Residents remain concerned about the largest contaminants in the water, so people seek to reduce physical or biological processes to remove impurities and organic substances in the water and to reduce the production of disinfectant by-products by reducing the use of chemical agents so that people get cleaner water (Moussavi and Shekoohiyan 2016). Physical and biological processes are common for purifying domestic water: filtration, precipitation, adsorption, ion exchange, ultraviolet disinfection, electrochemical water purification and ecological restoration.

Ultraviolet disinfection is the most commonly used way of recycling greywater in buildings. Vacuum ultraviolet light is the latest treatment for ultraviolet disinfection and is often used to degrade micro-pollutants without adding chemicals. The most common source of vacuum ultraviolet radiation makes low-pressure mercury vapour lamps, which can simultaneously emit 185 nm of vacuum ultraviolet light (about 10% of power) and 254 nm of ultraviolet light (about 90% of power) (Wu et al. 2020). Nitrates in domestic wastewater are difficult to treat, and traditional treatment processes use bio-denitrification to remove nitrates and reduce them to nitrogen. However, for the reuse of water resources, bio-denitrification has the defect of secondary contamination of water by bacteria and organic matter (Amanollahi et al. 2021). Therefore, removing nitrates using chemical methods is more acceptable, but its process is complex; nitrate removal requires a reduction process, and drug removal requires an oxidation process. In cases where nitrates and drugs coexist in water, separate oxidation and reduction processes are used to remove them. The 185 nm vacuum ultraviolet technology removes both drugs and nitrates in a single process (Han et al. 2021). The vacuum ultraviolet light of 185 nm can produce a series of free radicals through water haemolysis and ionization without the need for catalysts. Vacuum ultraviolet light not only generates hydroxyl radicals (shown in Eq. 1) and hydrogen radicals (shown in Eq. 2). Also, dissolved oxygen in water can form superoxide anion radicals (shown in Eq. 3), further removal of domestic wastewater.

$$\mathrm{H_2O} + h\nu_{185\ \mathrm{nm}} \rightarrow \cdot\mathrm{H} + \mathrm{OH}^- \tag{1}$$

$$\mathrm{H_2O} + h\nu_{185\ \mathrm{nm}} \rightarrow \cdot\mathrm{H} + \mathrm{OH}^- + \mathrm{e}^-_{aq} \tag{2}$$

$$\mathrm{O_2} + h\nu_{185\ \mathrm{nm}} \rightarrow 2\mathrm{O}^{2-} \tag{3}$$

Ultraviolet light at 254 nm wavelengths is suitable for removing microorganisms in domestic wastewater, characterized by shorter wavelengths and higher energy (Mohammadi et al. 2022). When ultraviolet light at 254 nm wavelengths acts on domestic wastewater, it can penetrate the cell walls of microorganisms and the molecular structure of organic matter and thus resonate with the nucleic acid bases in the DNA and RNA molecules of microorganisms to make them photolyze and destroy their biological activity. These reactions cause microorganisms to lose the ability to replicate and spread, thus achieving disinfection (Dixit et al. 2021). Ultraviolet treatment of domestic wastewater has some limitations. The factors that most affect the treatment of domestic wastewater by ultraviolet light are the water quality of domestic wastewater, such as turbidity, colour and dissolved substances; poor water quality affects ultraviolet penetration and sterilization (Kim et al. 2023).

In short, recycling wastewater used in buildings is very economical and environmentally friendly. This part introduces various methods for treating building water. Most treatment methods have the characteristics of simple operation, and fewer processes make it possible to recycle building water. By analysing a variety of processes for domestic water use, one can discover their advantages and the limitations they face but combine different methods of the process so that the cost of wastewater treatment to reduce the weight of metal elements further to be preserved and reused, promoting the concept of the material cycle in nature.

Technological advancements in recycled water systems in the building sector

Potential impact of technological advancements on the adoption of recycled water systems

Technological advancements can optimize regenerative water systems, and technology advances can properly handle increasing sewage production while also generating greater profits for recycled water. Despite significant advances in wastewater treatment technology in recent decades, many cities still face significant challenges in wastewater management (Rivera-Montero et al. 2023). In 2020, the proportion of safe sewage treatment worldwide varies widely, ranging from 25 to 80%. The lack of timely treatment of sewage does not only occur in developing countries but in the United States, where sewage productivity in many cities has exceeded the capacity of existing wastewater treatment plants, and much wastewater is being discharged directly into freshwater systems (Ramírez-Morales et al. 2020). According to the survey, of the 2,400 wastewater treatment stations in the United States surveyed, 360 wastewater treatment stations have exceeded their capacity, with the remaining average operating capacity of 81% of the maximum capacity (Shanmugam et al. 2022). Some underdeveloped and developing countries cannot secure reliable and clean water sources for urban dwellers due to infrastructure failures, unavailability of resources, weak regulatory frameworks and urban expansion. This uneven distribution of water resources, poor quality and water scarcity persist in water systems in these countries (Agarwal et al. 2019). Therefore, for building-based regenerative water systems, technological advances can reduce the pressure on sewage treatment plants and avoid pollution of the environment by overtaking their capacity.

Technological advances can help people reuse water multiple times according to their quality by making their awareness of recycled water clearer. When membrane filtration and ultraviolet disinfection are used in wastewater treatment plants following advanced tertiary treatment standards, wastewater can be used for drinking water applications, and new pollutants in wastewater can be removed by ozone or electrochemistry, as well as harmful substances such as pharmaceutical compounds (Shewa and Dagnew 2020). Some wastewater that only meets the secondary standard can be used in non-potable water industrial applications, such as recharging with cooling towers or irrigating gardens or crops. Urban dwellers recycle recycled water in such a way as to reduce water costs and groundwater consumption in cities. Resch et al. (2021) believed building a building-based wastewater treatment plant can help make water more secure for residents while also better achieving sustainable development goals and reducing the environmental impact of wastewater. However, it is noteworthy that Leonel and Tonetti (2021) believed that recycled domestic wastewater is not suitable for reuse, that it may alter soil properties and hinder crop growth, and that it is easy to scale when used in mechanical equipment such as condensation towers, thus affecting mechanical life.

Technological advances can reduce the demand for groundwater in cities and reduce the vulnerability of urban water supplies. In urban water supply, electricity demand for water transport and treatment accounts for almost 3–4% of electricity consumption in urban areas, a transport process that is also susceptible to extreme weather and thus reduces the reliability of urban water supply (Osman et al. 2022). Analyzed from the perspective of life cycle analysis, Tarpani et al. (2021) suggested that indirect drinking water reuse treated with oxidation ditches has relatively low environmental impacts and is considered a viable option for increasing water supply in urban areas. In the operation stage of the wastewater treatment plant, because its electricity can affect the environment much more than the dispersion treatment of recycled wastewater, the dispersion treatment of recycled wastewater helps to expand the existing water source. Take Kinmen County, the county seat of China, which is 153.1 square kilometres and has 140,000 inhabitants (Lin et al. 2020). With the development of tourism and urbanization, the limited water resources in Kinmen County have become an urgent problem. Of the existing water supply schemes in Kinmen County, the main water sources before 2018 were groundwater (77%), followed by surface water (18%) and recycled water (4%) in catchment areas. Soil surveys show groundwater use exceeded groundwater safe production in 2010–2018, putting Kinmen County at risk of groundwater salinity. At the same time, the large use of external water also makes golden gate water supply security not guaranteed. Shiu et al. (2023) Analyzed from the perspective of life cycle analysis and system dynamics. Thus, when Kinmen County uses low-cost filters to recycle water per building, dependence on groundwater can be reduced from 77 to 43%. Compared to desalination, regenerative water technologies consume 19% less energy. This greatly reduces the vulnerability of urban water services while conserving more energy than other water purification processes.

With technological advances, recycled water technology can be used for power generation. The greatest concern for humans and ecosystems is the increased demand for energy and the lack of clean water (Farghali et al. 2023). Anaerobic biofuel cells, as a sustainable technology, can provide both clean water and electricity. They convert some of the energy contained in the biodegradable matrix directly into electrical energy (Saket et al. 2022), through electroactive biofilms on the anode surface. As technology advances, people design the best-balanced anaerobic biofuel cells for energy efficiency, simplicity, affordability and durability. For the design of anaerobic biofuel cells, low-cost anaerobic biofuel cells are made using laterite and nano-ground clays. Compared with the original clamber, the nano-ground clam stone provides a larger surface area and more active sites, which enhances its performance as an earth film nanocomposite (Suransh et al. 2023). Batteries made of clay and classite are stacked in parallel, as parallel-stacked anaerobic cells perform bioelectrochemical processes faster than series-stacked anaerobic biofuel cells. The voltage generated by an anaerobic biofuel cell is processed by external boost transformers and coupled capacitors and can be boosted from the original 700 millivolts to 4.1 V for use. The system directly oxidizes the nitrate and nitrite present in wastewater to nitrogen gas via electrons in the consumption system (Gupta et al. 2021). Anaerobic biofuel cells remove up to 93.5% of organic matter in sewage, and higher organic removal means better anodic oxidation and higher electrical recovery. Recycled water treated by anaerobic biofuel cells can also be reused to guarantee the stability of people's water sources.

In short, technological advances can gradually reduce the cost of purifying water from recycled water systems, thus giving people more profit margins. Research also shows that decentralized water regeneration systems are more economical than traditional sewage treatment plants because they avoid the energy consumed by sewage transport. By classifying the wastewater treatment system, it can reduce the cost of wastewater treatment, reduce the pressure of wastewater treatment plants, also reduce the vulnerability of the water supply system. At the same time, anaerobic biofuel cells can further reduce their costs as technology advances, while purifying domestic wastewater can also provide people with electricity.

New trends in regenerative water technology

As science and technology continue to advance and environmental awareness increases, recycled water technology, an important tool for sustainable water resources management, has great potential to address global water scarcity and pollution. Future trends in regenerative water technology should be integrated with intelligent digital technologies to avoid resource waste and further reduce costs (de Simone Souza et al. 2023). If handled properly, the ideal decentralized health system is reliable and affordable, especially for developing countries. With the further development of technology, the trend of recycled water should strictly adhere to the principle of "reduction, reuse and recycling" of the circular economy so that recycled water technology can make a sustainable contribution to society (Nishat et al. 2023). Recycled water systems should be subject to the following requirements under the influence of the circular economy: First, treatment of wastewater to comply with regulatory standards and, ideally, complete elimination of its contamination load, including removal of emerging pollutants; second, according to the quality of treated sewage, treated sewage is reused in various ways to avoid discharge into the environment; third, reuse of biogas as a source of energy, fuel or chemicals; finally, recovery of sludge as soil modifier (if permitted) or extraction of residual resource value through thermochemical or biochemical recovery materials (Roshan and Kumar 2020). The current future trend of the building water cycle is decentralized processing, next-generation sequencing technology and modularization, as shown in Fig. 2.

Recycled water technology can be combined with digitalization for cleaner recycled water. In the traditional process of regenerative water, the factors that influence the growth of autotrophic and heterotrophic microorganisms in domestic wastewater include, but are not limited to, the characteristics of the intake wastewater, the type and operation of the treatment system and the geographical location of the wastewater treatment plant (Song et al. 2021). These factors have a significant impact on the structure and distribution of bacterial communities. In conventional sewage treatment, people do not understand the characteristics of bacterial colonies, which results in a waste of chemicals or redundancy of processes. The combination of regenerative water technology and next-generation sequencing technology helps people understand the organic components of living wastewater in advance, thus helping people choose the right treatment process (Zahedi et al. 2019). Next-generation sequencing technology is also called high-throughput

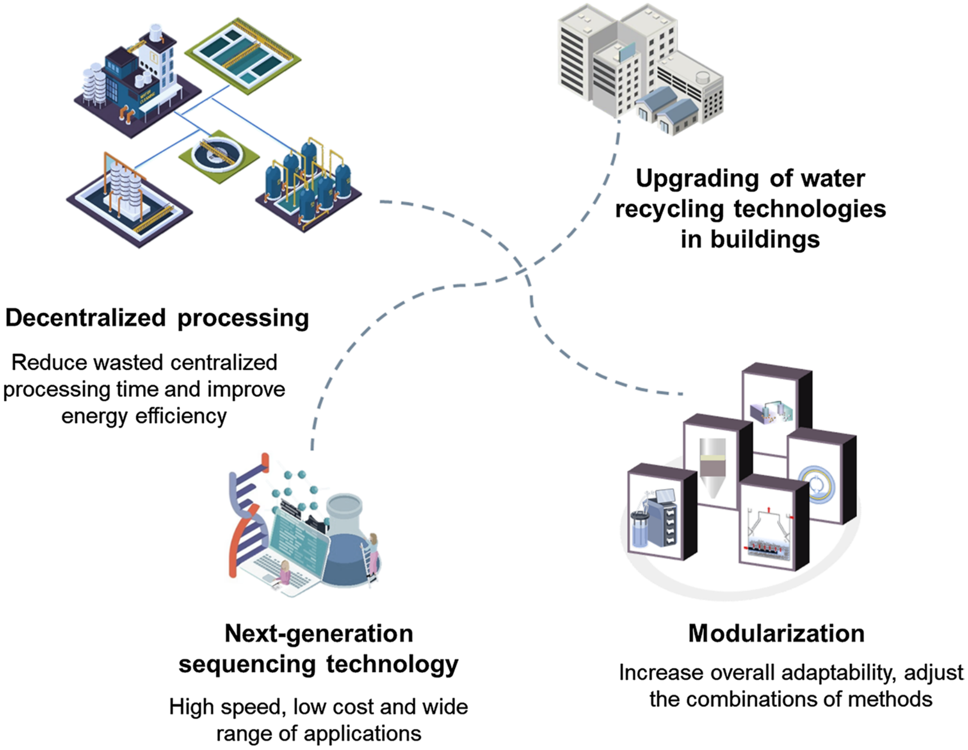

Fig. 2 Upgrading the water recycling technology in buildings. This figure shows the enhanced water recycling technologies in buildings: decentralized processing, next-generation sequencing technology and modularization. Most technologies promote water recycling by increasing the efficiency of water recycling technologies, faster processing times, and cheaper costs. Decentralized processing can reduce wasted centralized processing time and improve energy efficiency. Next-generation sequencing technologies can provide a comprehensive understanding of biological composition and function, improve contaminant elimination at a reduced cost, and enable fast processing and a wide range of applications. Modularization can be applied to multiple scenarios based on combinations of different methods, thus increasing overall adaptability

sequencing technology, which is a rapidly evolving method of DNA and RNA sequencing in recent years. Compared to traditional sequencing technology, the next-generation sequencing technology has high throughput, high speed, low cost and a wide range of applications (Garner et al. 2021). Next-generation sequencing technology provides a comprehensive understanding of the genome and transcriptome composition of biological systems and the diversity and function of microbial communities, which can meet the need to eliminate each target organism. The information provided by the next-generation sequencing technology provides more comprehensive data and a scientific basis for optimizing water treatment processes and improving water quality. Water regeneration can also help to observe deficiencies in water treatment methods.

In household wastewater purification, Cabreros et al. (2023) used an encapsulated living membrane and an electro-encapsulated living membrane bioreactor to treat domestic wastewater simultaneously. However, these two films are detected by next-generation sequencing technology. An electro-encapsulated living membrane bioreactor was found to handle organic matter better than the encapsulated living membrane, but the microbial community of the former is more diverse than the microbial community of the latter. This is because electrochemical treatment removes most bacteria and organic matter. However, current stimulation promotes the growth of electrically active microorganisms; this proves that electro-encapsulated living membrane bioreactor is a hidden hazard in everyday use (Xue et al. 2019). Next-generation sequencing provides more reliable data for recycled water technologies.

The trend of regenerative water technology can shift from traditional sewage treatment plants to decentralized water purification plants. For rural areas or areas with backward development, water resources in this area have characteristics such as high water quantity, wide geographical range, wide dispersion and large changes in water quality (Wang et al. 2022). The current sewage treatment rate in rural areas is less than 35%, and most wastewater is discharged directly into freshwater resources, thus polluting water sources (Xia et al. 2023). Rural sewage treatment technology must consider the local economy and ecological environment; the sewage treatment process should be simple and robust. Therefore, the development trend of recycled water should meet the needs of backward areas and complete the purification of water sources at the lowest possible cost (Marques et al. 2021). At present, in less developed areas, the performance of decentralized water purification devices is not ideal; in Beijing Miyun District, 13 towns of 231 village sewage treatment stations, 24% of sewage treatment stations are due to technical and management problems idle. Of the 146 decentralized water purification units in Dali, China, only 94 units can be used normally after one year of use (Chen and Yang 2021). Most decentralized water purification devices fail because they receive too much domestic sewage in a short period of time, which exceeds the treatment capacity of the dispersed water purification devices and causes damage to them. Therefore, future trends in regenerative water can focus on how to build lower-cost, more robust water purification units to meet the development needs of backward areas.

Recycled water technology is combined with modularization to adapt to different water conditions. The recycled water technology meets the reuse standard by properly treating and purifying wastewater. Modular water purification technologies emphasize modularization of the water treatment process and more practical needs for combination and adjustment, thereby improving treatment efficiency and adapting to different water quality conditions. Combining different modules simultaneously increases their overall adaptability and facilitates the recovery of more resources (Yadav et al. 2023a). The modules used in regenerative water technology can be broadly classified according to the techniques used in four categories: first, active sludge processes, such as rotary biological contactors and membrane bioreactors; second, anaerobic technology, such as upper flow anaerobic sludge blanket digester and anaerobic filter; third, ecological principle techniques, such as artificial wetlands and wastewater hydroponics; ultimately, electrochemical technologies such as electrooxidation and coagulation (Saidulu et al. 2021; Tarpani et al. 2021).

The active sludge process combines anaerobic technology to treat organic matter and suspended particles in domestic wastewater. Biofilm reactors are used in filters to filter relatively large particle sizes of suspended particles and direct the filtered liquid into an anaerobic filter to remove organic matter (Ramírez-Vargas et al. 2018). This modular combination facilitates the clean-up of sludge during water purification and increases the efficiency of biogas generated through anaerobic reactions (Lin et al. 2020). By combining ecological principles with electrochemical techniques, wastewater can be treated efficiently, and pollutant removal and generation can be further achieved. Artificial wetlands—Electrochemical fuel cells adsorb colloids in water with suspended particles through an electrocoagulation device placed at the bottom to create sludge precipitation. Sludge is then biodegraded using aquatic plant placement on porous bed substrates (Ni'am et al. 2022). The scalability of modular water purification technology enables regenerative water treatment systems to operate efficiently at different scales and scenarios. In the face of complex water quality such as industrial wastewater, high-salinity water bodies and special pollutants, customizable and upgradable modular water purification technology provides a solution for recycled water technology. Thus, water resource utilization efficiency and water supply stability are further improved.

In short, the future development trend of regenerative water technology should follow the circular economy principle combined with digital intelligence. Combining digital technology and recycled water technology can help people choose a more suitable process and determine the appropriate amount of chemical agent. At the same time, the recycled water technology is optimized to transform the traditional centralized recycled water technology into decentralized recycled water technology. Water purification technologies should also be further optimized to produce simple and robust water purification units for use in rural and remote areas. The combination of recycled water technology and modular technology is also a future development trend of recycled water resources, combining different modules to provide solutions for complex sewage water quality.

Health and safety considerations

Benefits and risks of using recycled water in buildings

In developing countries, the proportion of urban populations vulnerable to water scarcity can be much higher, and in the context of sustained population growth and climate change, water scarcity is putting further pressure on water supply systems. Regenerative water technology provides water companies in many places with a way that goes beyond traditional water supply. The key advantage of recycled water is that it has nothing to do with rainfall or groundwater and can effectively reduce the impact of extreme weather due to climate change (Iftekhar et al. 2021). There are many benefits to the use of recycled water in buildings, reducing the cost of treating domestic wastewater by dispersing it and facilitating direct reuse (Thebo et al. 2017). In California, where the price of drinking water is 1.08 times that of recycled water, the cost of using recycled water can be reduced (Palazzo et al. 2019). Recycled water systems are sometimes seen as alternatives and supplements to drinking water, significantly increasing the total amount of locally available water. Maier et al. (2022) believed that every unit of recycled water can be used to avoid using 0.8 units of drinking water, which increases local water security and contributes to the sustainable development of local resources.

Treatment of domestic wastewater using recycled water technology can reduce the pressure on sewage treatment plants and avoid direct contamination of freshwater resources. Wastewater contains organic substances, nutrients, chemicals, metals and pathogens that can cause harm to humans (Manasfi et al. 2017). For developing countries, due to urban sprawl and increased water use, traditional centralized sewage treatment plants do not treat all domestic wastewater, and some domestic wastewater is discharged directly, thus polluting people's water sources (Rasheed et al. 2022). Surface and groundwater water resources provide a variety of goods and services, and any adverse changes in these water resources can result in economic losses. Bouyakhsass et al. (2023) explored the economic value of recycled water technology by analyzing the water purification system in Mohammedia, a coastal city in Morocco. The cost of recycling a cubic meter of domestic wastewater varies from 0.15 to 0.35 euros when people recycle domestic wastewater in buildings. However, when domestic wastewater is discharged directly beyond the purification capacity of a sewage treatment plant, a cubic meter of domestic wastewater can pollute 50 cubic meters of freshwater resources. Despite higher concentrations of pollutants in domestic wastewater, it takes 1.1 euros to purify freshwater resources contaminated by one cubic meter of domestic wastewater (Alzamora and Barros 2020). This shows that regenerative water technology can not only protect the environment but also reduce the cost of treating contaminated freshwater resources.

Using recycled water technology in buildings also presents certain risks, threatening people's lives and health. With the development of urbanization and technology, wastewater treatment technology has not been updated promptly, and various emerging pollutants are endangering people's health (Yadav et al. 2023b). With the implementation of recycled water technology, people can access clean water sources, but the by-product of recycled water can impact people's daily lives. Take microplastics as an example; plastic is an important part of modern life, often used in every aspect of daily life, but its widespread use causes serious environmental pollution. Microplastics are defined as plastics less than 5 mm, including plastic particles, fragments, fibres and other similar materials (Hassan et al. 2023). Microplastics have infiltrated the oceans, the land and the atmosphere, posing a huge threat to wildlife and humans (Ni'am et al. 2022). Exposure to microplastics for prolonged periods of time can cause various toxicity injuries that affect reproductive performance and disrupt human energy metabolism by affecting human viscera (Anbumani and Kakkar 2018). Although existing wastewater treatment methods reduce the content of microplastics in wastewater by 58.8–99.9%, approximately 79% of treated microplastics enter the sludge (Xu et al. 2021). The sludge is sent to landfill and returned to the water by rain, infiltration and underground runoff during the stacking process, causing some physical harm. When sludge is applied to land, microplastics infiltrate the soil and contaminate crops, and microplastics have the potential to absorb heavy metals. Their hydrophobic surface attracts various types of organic matter, biomolecules and bacteria, thus contaminating the soil (Shi et al. 2022a). Recycled water technologies should, therefore, provide clean water while also paying attention to its by-products and avoiding their environmental impact.

The content of emerging compounds in recycled water is low, but its use still needs to be monitored to avoid its environmental impact. The application of recycled water avoids direct contact with or references to the human body, so the application of recycled water technology in construction is usually used in garden planting. A small number of emerging pollutants in recycled water are difficult to remove and are constantly introduced into soil-plant systems at

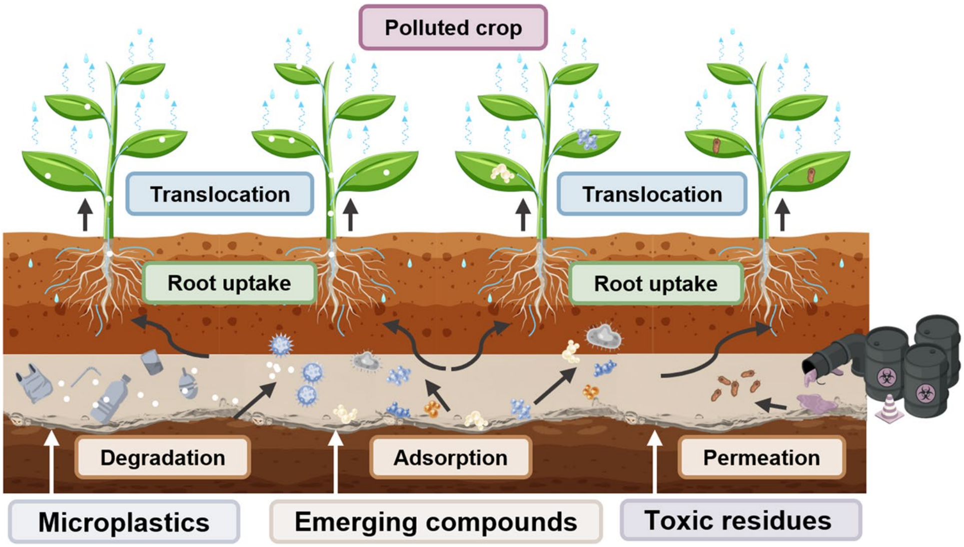

Fig. 3 Emerging pollutants pollute crops. This figure shows how emerging pollutants enter the soil from recycled water through watering and affect human health through plant absorption. This diagram shows the main components and related sources of emerging pollutants. In addition, it shows that some of the emerging pollutants are digested in the soil through the degradation of the soil, while the other part enters the human market through crops. These contaminated crops have a certain impact on human health

low levels, as illustrated in Fig. 3. Since soil is difficult to decompose for such emerging pollutants, the potential bioaccumulation of emerging pollutants in the soil may have unintended adverse consequences (Wagstaff et al. 2022). Assuming that most of the recycled water is received by the soil, plant roots are the main way for plants to absorb emerging pollutants, which are transported to the entire plant by transporting nutrients (Zhang et al. 2019a). The use of recycled water in the soil also exposes new pollutants to soil organisms such as microbes and earthworms. Some antibiotics in emerging pollutants can disrupt nitrogen recycling in soil, and there are some adverse effects of emerging pollutants on earthworms. Shi et al. (2022b) showed that after 28 days of exposure to apramycin at 100 mg per gram in agricultural soil, the number of earthworms in the soil decreased by 45.6%. Although no effect on adult mortality has been observed, it is proved that some of the new pollutants can affect the soil's ecological environment. Through Sun et al. (2019) research, they believed that most emerging pollutants undergo metabolism in plants and can be converted into less toxic compounds to reduce their effects on humans. And because the new pollutants in recycled water are extremely low, therefore, soils watered by emerging pollutants require regular detection of pollutant accumulation. If the contaminant content is low, the recycled water is still suitable for garden planting.

In short, regenerative water systems can greatly help people's lives, effectively reducing the pressure on local water supply systems, while regenerative water systems can provide people with less expensive clean water. But regenerative water systems should also be aware of the hidden hazards in their use, such as the potential pollution of the environment from by-products of regenerative water systems and the potential for large concentrations of pollutants to cause harm to the human body when recycled water containing small amounts of emerging pollutants is used in the watering process.

Strategies for mitigating health and safety risks

As analyzed in the previous section, by-product sludge in the water purification process is part of the environmental impact of regenerative water technology. Annually, the global production of municipal wastewater amounts to 380 billion cubic metres, and it is foreseen to experience a 24% augmentation by the year 2030, followed by a substantial 51% escalation by the year 2050 (Sheikh et al. 2023). Besides, wastewater sludge production in China exceeds 700,000 tons in 2021 and maintains a 3% growth rate, which poses serious environmental challenges as sludge contains a variety of heavy metals, persistent organic pollutants, bacteria and pathogens (Zhang et al. 2021b). If poorly treated, these toxic and harmful substances can spread to the soil, water sources and the atmosphere, causing pollution (Zhang et al. 2022b). Therefore, reducing the risk of recycled water technology should start with the treatment of recycled sludge by reducing the adverse impact of sludge on the environment to reduce the risk of recycled water technology to people's health.

The sludge produced by regenerative water technology contains a variety of volatile organic substances that pollute the air. At the same time, the smells in the sludge have a particular irritation, even at deficient concentrations, and still have a specific impact on people's everyday lives. Therefore, in recycled water technology, preventing odour formation takes precedence over implementing costly mitigation or treatment measures (Toledo and Muñoz 2023). Stench discharge is inherent in wastewater storage, transportation, and treatment activities; odorants are mainly released by the anaerobic decomposition of organisms containing sulphur and nitrogen or sulphate reduction in wastewater. Hydrogen sulphide, organic acids, and nitrogen compounds are the primary air pollutants emitted from sludge (Piccardo et al. 2022). The formation of volatile organic matter is prevented mainly through activated sludge and nitrogen oxide recovery techniques (Toledo and Muñoz 2022). Active sludge treatment is divided into two main steps: the degradation of organic pollutants in the hypoxia and aeration pool and then precipitation in the secondary clarification pool to separate. With activated sludge treatment, 96% of the organic matter in the sewage can be removed as a whole, and various odorous compounds can be fixed by adsorption and bio-oxidation. In nitrogen oxide technology, for example, ammonia gas is converted to nitrogen gas for discharge; first, ammonia gas is oxidized to nitrite using ammonia oxidation bacteria, then nitrite oxidation bacteria to convert it to nitrate. Nitrate converts nitrite and nitrate ions into gaseous nitrogen or nitrogen dioxide by denitrifying bacteria (Zhang et al. 2017a). Hydrogen sulphide is treated using sulphur-reducing bacteria combined with acetic acid in an anaerobic environment to convert them to sulphate, which avoids the pollution of hydrogen sulphide to the climate (Pang et al. 2017). Using activated sludge recovery and nitrogen oxide recovery technologies, emissions of odour compounds from sludge can be reduced by 95%. And, technologies do not require the construction of additional dedicated facilities, which are easy and reliable to operate to minimize irritating odour emissions and protect the health of nearby residents.

The sludge is carbonized to consume organic pollutants and avoid infiltration into water sources. Most of the sludge after dehydration is treated in landfills or composting, but landfills take up many land resources, and compost produces a smell. As a result, sludge is carbonized to reduce its volume and decompose organic pollutants (Singh et al. 2020). Sludge carbonization is a dry sludge as a raw material in a 300–900 °C hypoxic environment to cause a thermal cracking reaction, organic matter into helpful bioenergy. Dry sludge can obtain tar and non-condensed combustible gases during thermal cleavage, which can be used to produce biochar from rice poles (Xu et al. 2018). The high heat value combustible gas and biochar were cracked in the high-temperature condition. The heat generated by combustible gases during straw carbonization and sludge carbonization accounts for about two-thirds of the fuel energy, which increases energy recovery efficiency and reduces sludge treatment costs. Sludge carbonization products are rich in stable carbon, which can be preserved in soil for more than a hundred years, and sludge carbonization products can also be used as feedstock for carbon-based fertilizers, thus enhancing soil fertility and further promoting the carbon cycle (Räty et al. 2023). This method combines sewage sludge and corn straw for carbonization, not only to achieve the system's internal thermal self-sufficiency but also the resulting products can be used as soil improvement agents. This way, the cost of treating sludge per ton was reduced by 23.1 USD and greenhouse gas emissions by 126.7 kg/ton. The sludge incineration process is compared by Zhou et al. (2023). The carbonization of sludge produces little solid waste, and the resulting soil modifiers can be profitable.

Sewage sludge from incineration can be recovered as an alternative to building materials. Incineration is a feasible way to treat sewage sludge, especially where sewage sludge production is high. Incineration can effectively reduce the amount of waste, eliminate pathogens and volatile organic matter, and profit from energy recovery in the process of combustion (Tripathi et al. 2023). However, the transportation and landfill of sewage sludge can consume large sums of money and provide no additional benefits, so it is proposed that sewage sludge be used as an alternative to building materials for recycling. Sewage sludge consists of irregular silt and fine sand particles with porous microstructure and acceptable sand density, and its structure determines its use as a gelling material (Smol et al. 2020). Other wastes, such as fly ash, rice husks and copper residue, can be used as additives to improve the mechanical properties of sewage sludge materials (Tutur et al. 2019). Gelling materials from sewage sludge can be used in various applications, such as raw material mixing components used in cement production, active additives for cement-based inorganic adhesives and raw material-bearing components in building ceramics. Due to the similarity between sewage sludge and the main chemical composition of cement, sewage sludge may replace cement. The optimal percentage of sewage sludge substituted without reducing cement performance is 5–10% (Chen et al. 2021). Recycling sewage sludge for building materials will further enhance the circular economy in this way.

Generally, the primary pollutants and heavy metals are concentrated in sludge in recycled water technology, so if people choose to treat them suitably, they can reduce environmental safety risks. Firstly, volatile gases are fixed during wastewater treatment to avoid damage to the human body from volatile organic matter. Then, for the sludge dehydration treatment, the use of the carbonization process of sludge and rice rod combined heat energy recovery, in this way to further reduce the cost of sludge treatment. Finally, the sewage sludge obtained after incineration is mixed with building materials to be recovered.

Public perception issues related to recycled water systems

With the continued growth of cities and climate change, the public demand for water resources has increased exponentially, far exceeding the carrying capacity of water resources; water scarcity poses a severe threat to human existence, constrains the development of the national economy, and becomes a global strategic issue (Zhang et al. 2019b). Recycled water is an effective way to promote environmental protection as an alternative water source that is more stable than rainwater. The head of rainwater is mainly rainfall, and the start of recycled water is people's living wastewater (Zhang et al. 2021a). And in recycled water, increase sewage treatment to reduce water pollution. Compared to long-range water transfer and desalination, regenerative water technology stands out as a more environmentally friendly option, as it circumvents the impact of large-scale construction of water conservancy facilities on the natural environment. People use treated wastewater with many potential benefits, as depicted in Fig. 4.

The biggest obstacle to promoting recycled water is not the immaturity of technology but the psychological inadmissibility of the public. Although pollutants in sewage can be eliminated through technical solutions, negative perceptions of sewage have remained with progress. Most people are reluctant to use recycled water and are concerned that it may threaten their health (Etale et al. 2020). And with news coverage of water pollution, the public doubts the safety of recycled water. In Toowoomba, Australia, in 2016, the government's proposal to replenish the dam's cistern with clean recycled water met with strong opposition. Although the water in the cistern was already low and there was a risk of water scarcity, more than half of the population abandoned the project under the slogan "Citizens Oppose the Use of Sewage" (Hou et al. 2021a). The public has a strong negative stereotype about using recycled water, which is the product of living wastewater. The perception of sewage is deeply entrenched, and no matter how clean the quality of the treated water becomes, this cannot change quickly. This negative stereotype creates an aversion to the use of recycled water, and the negative emotions of people exposed to them become more intense (Hartley et al. 2019). People do not know enough about recycled water, so developing recycled

Fig. 4 Potential benefits to human society from the use of recycled water. This chart shows the six benefits of using recycled water for human society and promotes the sustainable development of human resources. It shows that using recycled water can ensure the safety of people's water and promote the circular economy. In addition, this image shows that using recycled water can also call for awareness of protecting the environment and conserving resources. Reclaimed water technologies can mitigate climate change and positively impact the environment as a wastewater treatment technology

water technology should focus on eliminating pollutant components in sewage while strengthening education and guidance to residents. Suppose regenerative water technology is acquired without paying attention to the acceptance of recycled water. In that case, the result can only be an excess of recycled water and no use by the population.

So, the government needs to guide people from multiple perspectives to make them accept and become accustomed to using recycled water. First and foremost, make people aware of recycled water and related treatment technologies. With the advancement of the information age, the degree of information disclosure has become an essential basis for public decision-making (Takagi et al. 2019). So, first of all, the government needs to use public media to make people aware of the lack of water resources, and by communicating this message, they need to create awareness of water conservation and the use of recycled water. At present, most people think that the current environmental problem is severe. Still, the ecological crisis is relatively broad. Hence, people need to learn the urgency of the environmental situation so it is natural not to change daily activities due to ecological problems (Ricart and Rico 2019). Thus, environmental issues are refined through the public media, and broad environmental issues are brought to people's attention, thus stimulating a sense of ecological responsibility. The process of improving water quality, the amount of water and the cost are then made known to the public through multimedia campaigns that allow recycled water to be used in activities that have less contact with the human body, such as horticulture or toilet flushing (Hou et al. 2020). The campaign aims to change the attitude of those who feel that recycled water is unavailable, thereby accepting the partial use of recycled water. According to Hou et al. (2021b) survey in Xi'an, 46.7% of households in the sample experienced water scarcity, and their acceptance of recycled water was 0.2% higher than households without such experience. Thus, the more deeply the public perceives environmental risks, the more they are willing to engage in environmental behaviours.

At present, the public is in the wait-and-see stage of recycling water use; whether the use of recycled water will cause harm to the human body is the main factor in their wait-and-see. Therefore, at this stage, the promotion should choose the negative stereotype of the public less water reclamation technology to start by building a decentralized water purification device and calling on community volunteers to manage it. Residents should observe the principle and effectiveness of decentralized water purification devices. Enabling residents to establish recycled water if appropriately treated, recycled water is the concept of clean and usable water resources (Mu'azu et al. 2020). And because recycled water is in the building or next to the building, recycled water is available at your fingertips, creating a social atmosphere in which recycled water is widely used, thereby enhancing residents' acceptance and recognition of recycled water. The government may also hold events inviting residents to visit extensive regenerative water facilities and camp in reservoirs made up of recycled water and other field activities, thus increasing the appeal of recycled water (Hopson and Fowler 2022). Regenerative water technology needs to be upgraded further in the promotion process and ensure the efficiency of purification in the process of the building-based pilot. When people start using recycled water, if the quality of the recycled water produced by the purification device is not satisfactory to the population, this will undoubtedly be a fatal blow to people's confidence in recycled water (Guo et al. 2023). And people need to reduce the price of recycled water further by optimizing processes to reduce costs. The cost of recycled water is lower than pure water due to social acceptance problems. But maintaining water purification equipment and related maintenance work is also expensive. Therefore, regenerative water technology still needs to optimize the process so that more people can accept using recycled water.

In short, people are currently on the sidelines about recycled water because people still have the wrong perception that recycled water is sewage. Under the influence of stereotypes, water-related facilities must be faster to advance. Therefore, the government should start from the point of view of water scarcity and call people to conserve water responsibly. At the same time, the arrangement of decentralized water purification devices can help people feel the effect of water purification. In this way, people receive recycled water and gradually apply it to their lives.

Perspective

To improve resource security, saving water in urban areas via recovery and effective energy usage is crucial. Greywater pollutants may be filtered using plant walls and column material in green roofs. The vegetation will function as a biofiltration system and offer a treatment process of microbial absorption and microbial activity through the media and plants (Pradhan et al. 2019). Due to weathering processes and chemical and physical interactions between rainfall and materials, roofing materials can cause dissolved particulate matter in roof runoff to be a source of contaminants. As greywater output is independent of climatic circumstances, adding greywater recycling systems to current rainwater collection systems will assist in counterbalancing the seasonality of rainfall (Leong et al. 2017). The greywater recycling system has a huge potential to improve water and energy security by assuring effective energy use while also conserving water, which was created by Wanjiru and Xia (2017).

It has been discovered that greywater recycling systems for construction projects that connect to secondary treatment processes and involve pretreatment systems are relatively complex, pricey, and sensitive to environmental changes. Additionally, the absence of nutrients in greywater can reduce the effectiveness of biological treatment systems (Oh et al. 2018). Greywater recycling must combine user safety, economic feasibility, usefulness, and political concerns with environmental sustainability. Widespread public hostility to such systems might result from a lack of public understanding and proof that they operate (Wanjiru and Xia 2017). Current recommendations and standards frequently only consider system design regarding water-saving goals, failing to contemplate the numerous other benefits of installing rainwater collecting systems. The financial viability of rainwater harvesting systems for buildings appears to be far from acceptable, as the payback period is still too long to provide an adequate return on investment (Campisano et al. 2017).

The objective of water sustainability is finally achieved through the monitoring of greywater recycling systems and the provision of financial incentives such as rebates and subsidies. For the best management of the resources of stored rainwater, equipment based on monitoring and data-collecting systems can enhance the automation and control of rainwater harvesting systems (Gee and Hunt 2016). To enhance the evaluation of the overall performance of rainwater harvesting systems, trustworthy multi-purpose modelling tools with improved connection to real systems must be developed in the future (Campisano et al. 2017). In order to provide favourable regulations and incentives to build a market for greywater systems, governments should formulate and enforce clear policies for the general public, whose opinions may be readily modified by giving explicit safety requirements. Optimized greywater recycling systems are required in cities with intermittent or no water supply to lower the cost of acquiring water from providers while guaranteeing resource efficiency and safety (Wanjiru and Xia 2017).

This section summarizes future trends in building water recycling systems. Advances in rainwater harvesting systems are an important factor in improving water recycling systems, and the development of biofiltration systems with greenery and microorganisms needs to be considered not only in terms of the complexity of the system, but also in terms of its acceptability to the public. Financial incentives can help to improve the technical support for rainwater harvesting systems, and the public will also have a better perception of new water recycling systems due to regulations.

Conclusion

This review discusses that building water recycling systems offer water conservation, reduced environmental impact and cost-saving benefits, but there are issues with water quality assurance, dual piping infrastructure, and regulatory compliance. Government incentives or mandates for installing water conservation and recycling systems, as well as government subsidy policies, are powerful interventions. The implementation of water recycling policies promotes information systems and energy efficiency. There is still a lack of effective policy guidelines to promote public interest in building water recycling systems. This review also evaluates a variety of technological advances in building water recycling, focusing on the strengths and weaknesses of the various technologies. Membrane filtration technologies that are easy to operate need to focus on the negative effects of membrane fouling. Whereas advanced oxidation processes are difficult to remove toxic organics, combining them with other novel processes can improve the oxidation efficiency of organics. In the future, more environmentally friendly methods need to be developed to optimize the energy consumption of electrochemical processes. Ultraviolet disinfection has also been used in treatment technologies for building water recycling to help reduce the use of chemicals to reduce the production of disinfectant by-products. Technological advances are needed to optimize reclaimed water systems and increase the efficiency of treating building wastewater, thereby reducing the economic cost of building wastewater treatment. The combination of reclaimed water technology and digital intelligence responds to the principles of a circular economy, controlling the balance between water purification and chemical consumption more efficiently and intelligently. While building reclaimed water systems offers the potential to purify water, there is also the threat of contaminants going unpurified and damaging human health. Resource utilization of sludge can effectively limit the pollution of a water recycling system. Government support is essential for advancing water recycling technology and enhancing public acceptance.

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