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Towards Sustainable Urban Water System: A Strategic Approach to Advance Decarbonizing Water Management



Xinyu Pan^a, Yumeng Zhao^{a,*}, Xinlu Lin^a, Nianyi Zhao^a, Meng Sun^b, Jun Ma^a

^aState Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology, Harbin 150090, China

^bState Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

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ABSTRACT

The decarbonization of urban water systems is critical for achieving global climate goals, and reducing the carbon intensity of urban water systems necessitates a paradigm shift from traditional end-of-pipe treatment approaches to alternative technological solutions and holistic planning. This study explores a comprehensive strategy for achieving sustainable urban water management that integrates a decentralized water system (DWS), source separation, and low-carbon water treatment technologies. DWS is fundamental to implementing a sustainable urban water system. This study addresses the social contexts, costs, approaches, and benefits associated with DWS implementation, emphasizing the importance of its construction. Subsequently, the analysis focuses on the on-site source separation of grey water, feces, and yellow water in the DWS, which serves as the primary approach for wastewater reuse and N/P recovery for a sustainable urban water system. Following source separation, low-carbon water treatment technologies based on resource conservation and recovery are thoroughly discussed. Specifically, resource conservation can be achieved through rainwater control, efficiency improvements, and low energy consumption, while resource recovery can be attained through carbon capturing and energy/nutrient recovery. Overall, in response to the challenges in current urban water management, this study proposes a comprehensive strategy that supports a sustainable urban water system, providing theoretical guidance for reducing carbon emissions.

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1. Introduction

Reducing carbon emissions and achieving carbon neutrality are critical strategic objectives that have garnered global attention [1,2], placing greater demands on the development of sustainable urban water systems. In the context of urban agglomeration, current urban water systems are typically centralized water systems (CWS), which adhere to a linear design trajectory [3,4]. This trajectory encompasses urban water conveyance, treatment, and distribution, followed by water usage, culminating in wastewater treatment and discharge. The energy consumption of urban water systems accounts for 2%–7% of total emissions associated with electricity generation annually [5,6]. Although urban water systems are region-sensitive, varying by geographical location, treatment process, and management strategies, the water distribution

and wastewater treatment stages are considered the largest contributors to multiple categories of environmental impact (e.g., ozone depletion and eutrophication) according to life cycle assessment (LCA) analyses [7–9]. The high carbon intensity of the water distribution stage results from the low-quality, non-potable end-use of drinking water and the long-distance distribution of water in the context of urban agglomeration. This renders the process more energy-intensive and the largest contributor to the overall environmental impact of urban water systems under the LCA category of metal depletion. On the other hand, wastewater treatment contributes significantly to global greenhouse gas (GHG) emissions. Based on previous studies [10–11], 9% and 3% of global CH₄ and N₂O emissions, respectively, are derived from wastewater treatment plants (WWTP).

Accordingly, growing concerns regarding the sustainability of end-of-pipe treatment approaches have arisen. The prevailing reliance on end-of-pipe approaches, primarily centered on terminal purification, engenders barriers to recycling effluent or value-added products. The advanced treatment of nutrients (e.g., N and

* Corresponding author.

E-mail address: zhaoyumeng@hit.edu.cn (Y. Zhao).

P) incurs extensive costs, and the resulting sludge poses challenges in terms of disposal and reuse. Importantly, underscoring that a terminal treatment approach does not necessarily equate to a comprehensive remedial measure is imperative; instead, it frequently leads to pollutant transference. For instance, desulfurization yields significant waste accumulation [12], and centralized wastewater treatment culminates in the generation of sludge [13]. In this regard, re-evaluation of urban water systems is necessary, emphasizing the imperative to address water quality and environmental repercussions. Such a paradigm shift requires a departure from established practices and the exploration of alternative technological solutions and holistic planning.

Herein, a comprehensive approach for a sustainable urban water system is proposed that integrates decentralization, source separation, and low-carbon water treatment technologies. The primary emphasis is developing a decentralized water system (DWS) in urban management and infrastructure planning, involving the transition from conventional water treatment systems to non-grid (e.g., households or rural areas), small grid (e.g., neighborhoods), or hybrid (e.g., communities) systems (Fig. 1(a)). Subsequently, based on decentralized infrastructure, source separation of wastewater (grey water, yellow water, and feces) is implementable during the water usage process (Fig. 1(b)). By integrating storage and conversion infrastructures, an environment conducive to water treatment and resource recovery is established. After source separation, this system can integrate low-carbon water treatment technologies that enable rainwater control, efficiency improvements, carbon capture, low energy consumption, and energy/nutrient recovery (Fig. 1(c)). These approaches facilitate resource conservation and recovery, providing water, fertilizer, and energy to both urban and surrounding rural areas, thus promoting a low-carbon cycle. Overall, this strategy could contribute to establishing a sustainable urban water system that recovers

resources, swiftly adapts to changing conditions, and mitigates carbon emissions from water systems.

2. DWS

Currently, an increasing number of countries are directing their attention towards the transition from conventional urban water systems to DWS [14,15]. DWS advocates a shift from traditional linear treatment approaches and disposal methods to circular models. This approach prioritizes treating small quantities of water as close to the source as possible [16]. First, before implementing a DWS, comprehensively considering both the social context and technical system is essential [17]. With regard to social context, the key considerations, from the macro to micro levels, include institutional frameworks (e.g., changing societal regulations), governance structures (e.g., reforming organization and industry structures), and individual behaviors (e.g., changing water usage behaviors and routines), as they shape stakeholder engagement and determine the effectiveness of innovative solutions. On the other hand, from the perspective of technical systems, from the macro to micro levels, considering the goals of water management frameworks (e.g., defining the service of water systems), deciding spatial organization of technical systems and their governance structures (e.g., defining system type and size), and selecting technologies suitable for integration at the household and/or small grid levels (e.g., anaerobic–anoxic–oxic (A²O)-membrane bioreactor (MBR), facultative MBR (FMBR), and constructed wetlands) are crucial (Fig. 2(a)). To manage transitions considering both the social context and technical system, long-term visions are required. In the short term, new technical solutions should be implemented within protected niches and gradually receive feedback from utilities, technology providers, governments, and users. In the long term, after gaining sufficient recognition, insights and lessons

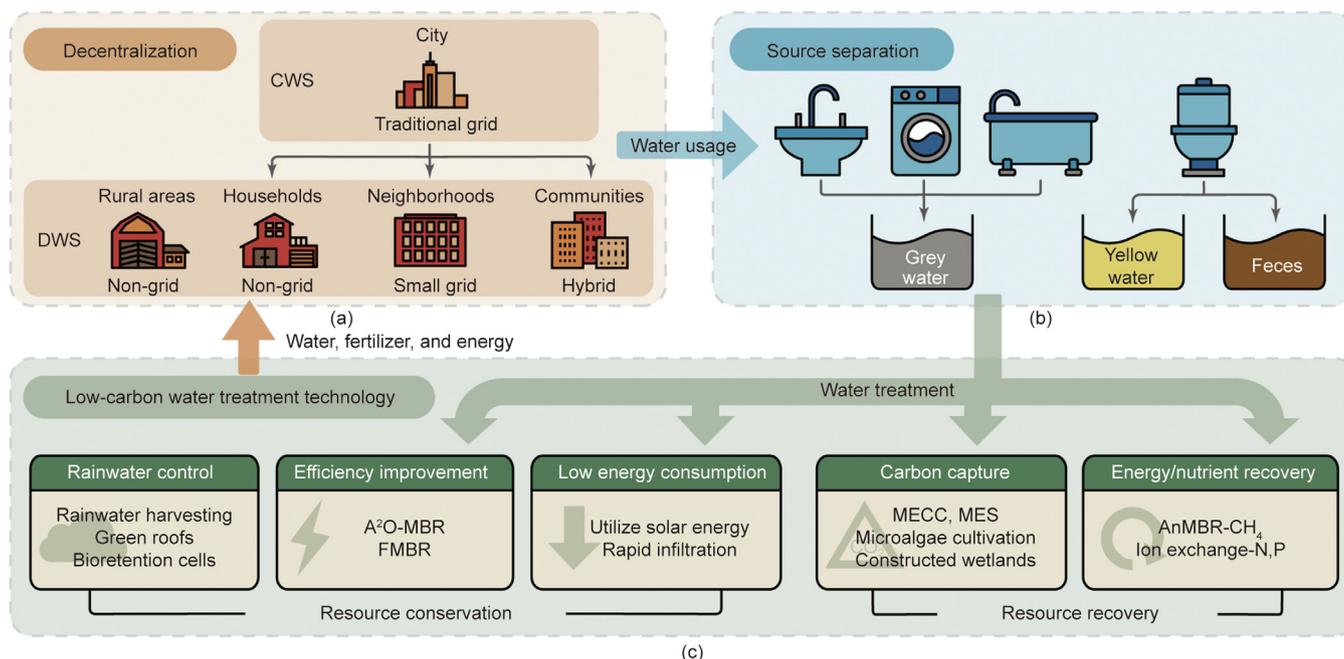


Fig. 1. Diagrams illustrating the relationships between decentralization, source separation, and low-carbon water treatment technologies in low-carbon urban water systems. (a) Schematic diagram depicting the transition from CWS to DWS. The image in the first line represents CWS, while the image in the second line depicts the components of DWS. The second row illustrates, from left to right, rural areas (non-grid), households (non-grid), neighborhoods (small grid), and communities (hybrid). (b) Schematic diagram illustrating the source separation of grey water, yellow water, and feces. Grey water mainly results from washbasins, laundry, and bathing, while urine and feces can be separated from toilets. (c) Classification of low-carbon water treatment strategies, including rainwater management, efficiency improvements, and low-energy consumption for resource conservation, as well as carbon capture and energy/nutrient recovery for resource recovery. A²O-MBR: anaerobic–anoxic–oxic membrane bioreactor; FMBR: facultative membrane bioreactor; MECC: microbial electrolytic carbon capture; MES: microbial electrosynthesis; AnMBR: anaerobic membrane bioreactor, CH₄: methane.

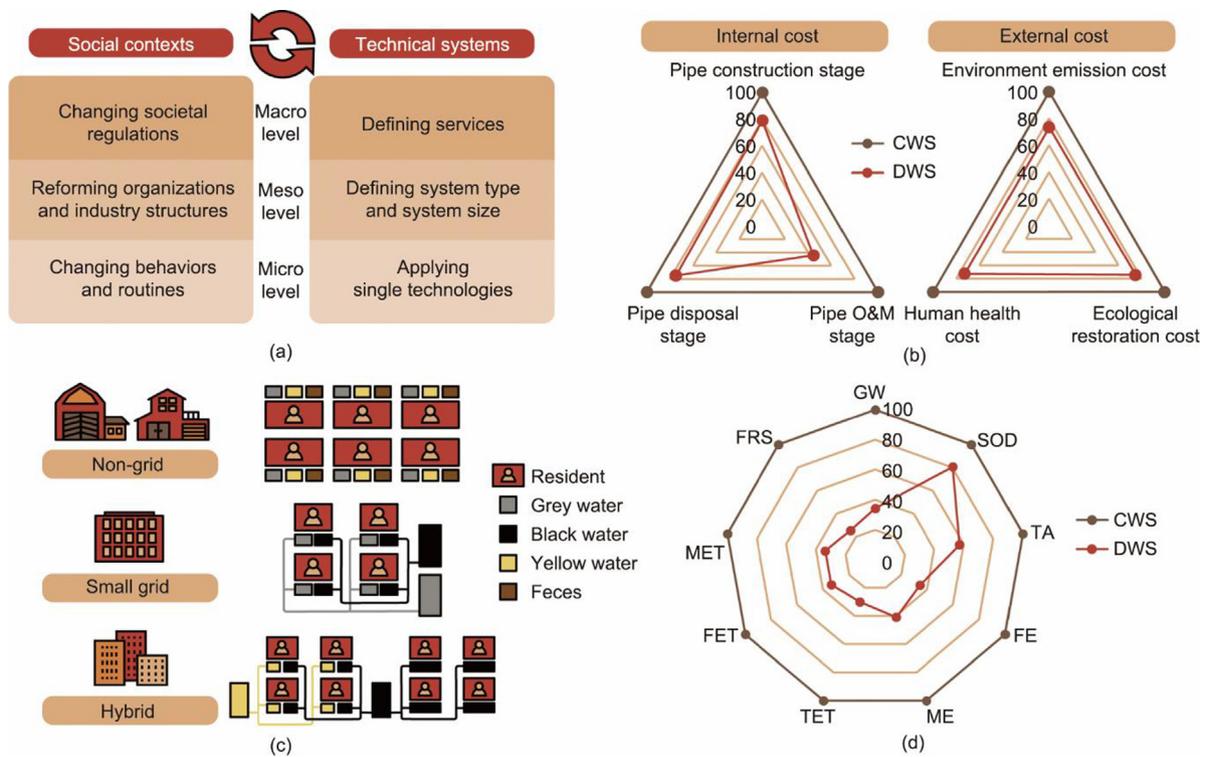


Fig. 2. Implementation of decentralization in sustainable urban water systems. (a) Factors to consider in both social contexts and technical systems when implementing decentralized systems. (b) Cost comparison between CWS and DWS, O&M: operation and maintenance. (c) Diagrams illustrating non-grid, small grid, and hybrid systems. (d) Comparison of environmental impacts between CWS and DWS. The coordinates represent relative contribution (%), with CWS set to 100% and DWS shown accordingly. The evaluation parameters are commonly used within an LCA framework to represent environmental impacts, namely, GW: global warming; SOD: stratospheric ozone depletion; TA: terrestrial acidification; FE: freshwater eutrophication; ME: marine eutrophication; TET: terrestrial ecotoxicity; MET: marine ecotoxicity; FET: freshwater ecotoxicity; FRS: fossil resource scarcity.

gained from these experiences should be integrated into mainstream technical practices [18]. These considerations are significant for ensuring optimal system performance and minimizing technological lock-in effects in urban water management [17].

Cost is also a key consideration before implementing DWS. According to a case study in Guangzhou, China, when comparing CWS and DWS, both of which use grey infrastructure (designed to intercept, collect, and channel stormwater runoff through effective urban drainage system utilization), the internal and external costs associated with DWS could be 40% and 35% lower than CWS, respectively [19]. Internal costs refer to direct economic expenditures during implementation. The implementation process is divided into three phases in chronological order: the pipe construction stage, the pipe disposal stage, and the pipe operation and maintenance (O&M) stage. External costs are generated by indirect impacts on the environment and society. These costs include economic losses caused by releasing pollutants into the environment (i.e., environment emission costs), the medical and economic losses resulting from the impact of environmental pollution on human health (i.e., human health costs), and the financial expenditure required to restore damaged environments (i.e., ecological restoration costs) (Fig. 2(b)). In addition, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) reported that the investment, operation, and maintenance costs associated with DWS are lower than conventional centralized treatment plants by a minimum of 20%–50% [20]. Additionally, since DWS demonstrates smaller pipeline scales and lower maintenance frequencies, the costs associated with DWS are significantly lower. Based on divide-and-conquer strategies, in areas with plains, hills, or plateaus, the costs of DWS decrease by 20%, 78%, and 72%, respectively, compared with CWS [21]. Moreover, in

wastewater treatment applications, DWS combined with source separation offers greater cost-effectiveness. By diverting 90% of urine from wastewater, the energy required for aeration can be reduced by up to 33%, further lowering the overall cost of water treatment [22].

During the implementation of DWS, three approaches can be employed for its establishment: non-grid systems, small grid systems, and hybrid systems based on the type of household and the existing pipeline network [17]. The grid is a component of CWS, whose capital expenditure on pipes and sewers typically amounts to 70%–80% of total capital expenditures [23]. Extensive initial investments have resulted in technological lock-in effects, complicating the implementation of DWS. Comparatively, non-grid and small grid systems are more suitable for implementing DWS. Non-grid systems lack pipes or sewers between individual buildings. In contrast, small grid systems have sewers and pipes connecting only a small number of individual buildings compared with a grid system. From a construction standpoint, these two systems offer greater flexibility. When incorporating a traditional grid into DWS, the hybrid system approach can be adopted by combining a traditional grid system with non-grid or small grid systems (Fig. 2 (c)). The reason for this approach is the significant technological lock-in effects associated with the traditional grid, including challenges in management, user acceptance, technology selection, and replacement costs. A hybrid system approach allows for the successful implementation of small-scale DWS, and in the long term, once the support of utilities, technology providers, governments, and users are secured, the lessons learned from this approach can be widely applied to promote the broader adoption of DWS in traditional grids. Additionally, for enhanced technological adoption, DWS is especially useful for treating non-traditional water sources

(e.g., agricultural wastewater, rainwater, mining wastewater, and grey water) [24–26], which are small in scale, geographically dispersed, chemically heterogeneous, and temporally varied compared with traditional freshwater or seawater sources. This approach can reduce the energy costs associated with water conveyance and distribution, which can account for approximately 50% of the energy demand in urban water systems [7].

Successfully implementing DWS can contribute to reducing carbon emissions. In an urban nutrient recovery scenario, DWS was compared to CWS, where land fertilization resources are recovered from combined black water and grey water treatment in a centralized facility instead of through hybrid treatment. The LCA calculations show that the environmental impact of DWS averages 56% lower than that of CWS (Fig. 2(d)). Notably, the environmental impact of DWS in the fossil resource scarcity (FRS) category is merely 25.2% of that of CWS, further indicating the effectiveness of DWS in reducing nutrient discharge and conserving energy when combined with source separation [27]. For instance, DWS typically involves the separate management of grey water, yellow water, and feces, avoiding the dilution of wastewater and enhancing resource recovery efficiency [28]. With regard to the energy trade-off in DWS, DWS often highlights high energy intensity for treatment and low energy consumption for distribution and discharge, while CWS demonstrates a contrasting trend. In this regard, integrating DWS with grey water recycling can simultaneously decrease water treatment energy consumption and reduce the load on CWS, thus promoting sustainable urban water management [29].

3. Source separation

The deployment of DWS establishes a robust foundation for source separation by fostering cross-sector collaboration among energy, water, and waste utility sectors, supported by social efforts during the decentralization process (Fig. 3(a)) [30]. The integration

of DWS with source separation offers the potential for reducing the environmental impacts associated with urban water systems (e.g., nutrient losses, greenhouse gas emissions, and energy consumption), thus promoting sustainable urban water systems. Source separation mitigates the increasing complexity of water quality along an urban water system’s linear trajectory, reducing the technical difficulty associated with subsequent treatment. Specifically, the distributions of volume, total nitrogen (TN), and total phosphorus (TP) in grey water, yellow water, and feces on a national scale in the Netherlands [31,32] (Fig. 3(b)) shows that grey water has the highest volume and the lowest pollutant content; thus, treating grey water separately allows for the rapid recovery of water resources with minimal pollutant removal. In contrast, urine contains the highest levels of TN and TP, rendering its separation a significant source of fertilizer. Meanwhile, feces have lower N and P contents compared with urine but still represent a valuable resource for nutrient recovery. By separately collecting and conveying grey water, yellow water, and feces at the source, cross-contamination of water quality can be prevented, allowing energy and resources to be recovered individually (Fig. 3(c)). The above measures facilitate the extraction of value-added products, serving as reclaimed water and fertilizer resources.

For grey water recovery during source separation, water is collected from bathrooms, kitchens, and laundry, then treated and utilized for non-potable uses, such as toilet flushing and irrigation [33]. Based on LCA, compared with treating combined sewage in conventional systems, treating grey water separately after the source separation of grey water, feces, and urine can reduce energy consumption (Fig. 3(d)). For example, the sequencing batch reactor and trickling filter processes treat grey water with 38% lower energy requirements compared with traditional activated sludge systems (the total primary energy consumption includes wastewater collection, wastewater treatment, urine and sludge transport, and the energy production associated with generated methane) [34]. Additionally, sludge from treating grey water can be further

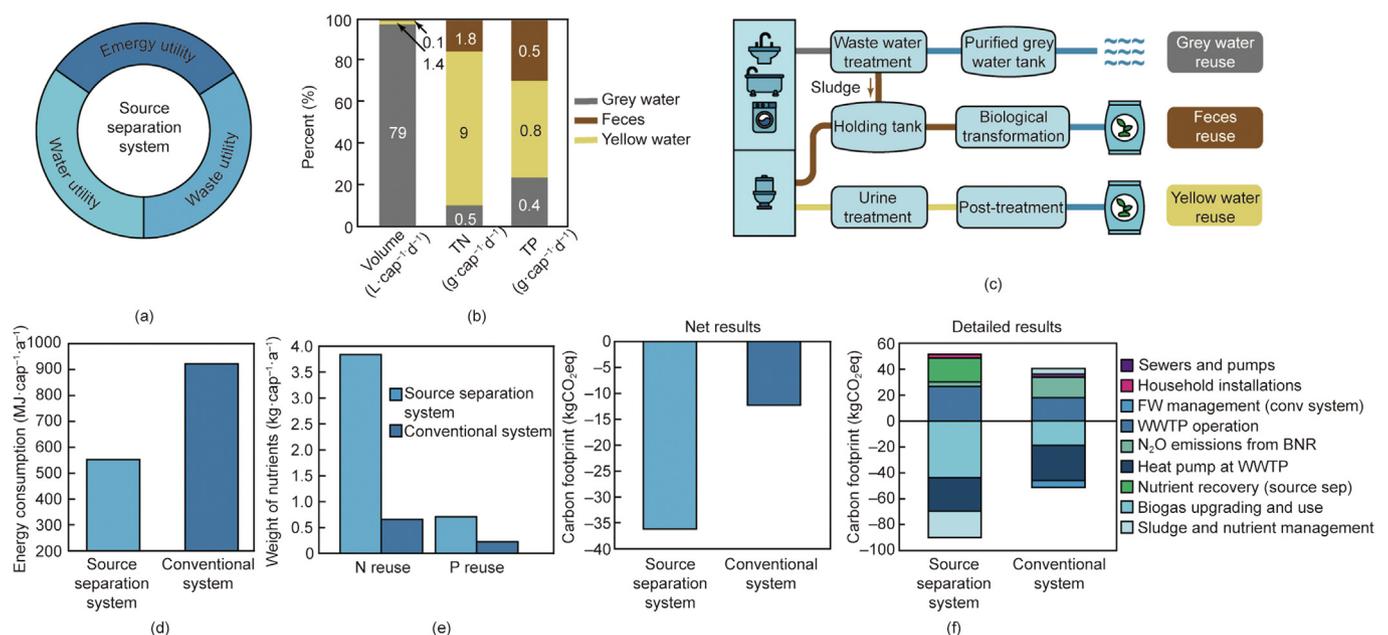


Fig. 3. Implementation of source separation in sustainable urban water systems. (a) Conceptual illustration of a source separation system requires the collaboration of conventionally separated infrastructure sectors. (b) Distributions of volume, TN, and TP across grey water, yellow water, and feces. (c) Schematic diagram of the resource recovery pathways for grey water, yellow water, and feces. (d) Comparison of per capita annual energy consumption between source separation systems and conventional systems. (e) Comparison of per capita annual N and P recovery between source separation systems and conventional systems. (f) Comparison of carbon emissions between source separation systems and conventional systems. FW: food waste; BNR: biological nitrogen removal; kgCO₂·eq.: kilograms of CO₂ equivalent. conv: conversion, sep: separation, cap: capita.

collected in feces storage tanks and used for fertilizer production, thus avoiding sludge transportation and enhancing energy efficiency [34,35].

Urine is the main component in separated yellow water and contains high N and P contents, contributing to approximately 80% N and 50% P in municipal wastewater from this single source while also exhibiting considerable potential for nutrient recovery [36]. The extracted nutrient-rich biomass derived from urine is instrumental in manufacturing sustainable fertilizers for crop cultivation, serving as an eco-friendly alternative to industrial fertilizer. The production of fertilizer from urine involves treatment (e.g., storage, acidification, alkalization, and nitrification) and post-treatment processes (e.g., volume reduction and the removal of pharmaceutical residues and pathogens) [37,38]. These processes are designed to reduce odor, increase nutrient concentrations, and enhance safety (Fig. 3(c)). Based on an LCA study focusing on managing and recovering energy and nutrients from household wastewater, the source separation system for wastewater treatment demonstrates higher recoveries of N and P compared with a CWS (Fig. 3(e), over seven times more N and three times more P are recovered). This is because the majority of N in the centralized system is removed as atmospheric N_2 during biological nitrogen removal (BNR), and the majority of P enters the dewatered sludge at the WWTP [39]. When treating urine on-site, the N removal rate reached 65%–80% in combination with struvite crystallization at the source. Such performance can compete with the majority of denitrifying treatment plants with N recovery rates of 70%–80% [40,41]. Notably, undiluted urine at the source is suitable for adsorption processes, and many micropollutants, including pharmaceuticals and hormones (50%–60% of pharmaceuticals and hormones are contained in urine), can be efficiently removed at the source rather than in the diluted wastewater [42,43].

The recycling of feces is a key method for source separation in DWS scenarios for recovering N and P, as each person produces approximately 0.52 kg of N and 0.21 kg of P annually in feces [35]. If collected, the P available in urine and feces could account for 22% of total global P demand [44]. The nutrients in feces can be converted into fertilizers through biological transformations, including composting using sanitary bark or biochar, vermicomposting, and lactic acid fermentation [45,46]. These treatments not only facilitate nutrient recovery but also reduce pathogens and contaminants (Fig. 3(c)). By recovering nutrients from feces, soil micronutrients are replenished, helping to mitigate biological pollution in urban sewage networks and wastewater treatment plants [47,48].

From a comprehensive perspective, source separation can also contribute to achieving low-carbon emissions. Based on LCA, a source separation system can achieve a threefold reduction in carbon emission than a conventional wastewater treatment system in a South Sweden urban study area (Fig. 3(f)). The minimal impact of this source separation system is mainly attributable to increased biogas production, reduced N_2O emissions, and enhanced replacement of mineral fertilizers, largely resulting from improved nutrient utilization [39]. Meanwhile, the source separation system allows for the recycling of nutrients, particularly N, back into agriculture. This reduces the need for synthetic N fertilizers, which are energy-intensive to produce and contribute to environmental degradation. Additionally, source separation systems contribute to a reduction in organic loading into effluents, which in turn lowers N_2O emissions during subsequent wastewater treatment.

4. Low-carbon water treatment technology

In the context of DWS, integrating low-carbon water treatment technologies following the source separation process serves as a key foundation for achieving a sustainable water system, enabling

effective water treatment while supporting carbon neutrality. With increasing awareness of climate change, a shift towards developing technologies that ensure the effective purification of water and minimize the carbon footprint associated with these processes has occurred. For low-carbon water treatment technologies, carbon footprint reductions can be approached by resource conservation and resource recovery. The former can be achieved through rainwater control, efficiency improvements, and low energy consumption, while the latter can be attained through carbon capturing and energy/nutrient recovery (Table 1 [49–58]).

Rainwater harvesting, green roofs, and bioretention cells play crucial roles in controlling rainwater and lowering carbon emissions from DWS. The installation of rainwater harvesting tanks increases water self-sufficiency in rural and household scenarios and reduces dependence on CWS [49]. In addition, rainwater can be harvested using permeable-base and permeable-surface pavements that can store infiltrated water for irrigation purposes. Based on a survey of 28 pilot sponge cities in China, the water savings achieved using these two methods are 433.8 and 304.1 $kg\cdot m^{-2}\cdot a^{-1}$, respectively [59]. An alternative approach to optimizing rainwater harvesting involves intelligent management, with decentralized household rainwater systems being centrally monitored. Through this method, rainwater tanks can be emptied before rainfall to maximize storage capacity for extreme weather events [18]. Green roofs possess strong environmental regulation capabilities. By reducing temperatures around buildings between 0.1 and 6.0 °C, green roofs provide natural insulation that reduces energy consumption and mitigates the urban heat island effect [60]. In addition, green roofs manage stormwater by decreasing runoff and flooding risks, as exemplified in cities such as Milan and across Germany, where green roofs are integrated into rainwater harvesting systems [50]. Bioretention cells share an equal level of importance by mimicking natural hydrological processes to filter pollutants and manage stormwater in urban settings such as parks, parking lots, and residential areas. Cities such as Portland and Seattle have successfully implemented bioretention cells that enhance water quality and support local biodiversity [51].

The A^2O -MBR and FMBR are efficient and cost-effective wastewater treatment technologies for off-grid scenarios such as rural areas and household applications. The A^2O -MBR integrates biological degradation with membrane filtration, effectively removing organic pollutants such as N and P, where the removal rates in treating domestic water at the pilot scale are exemplified as 75% and 82%, respectively [61]; thus addressing environmental concerns related to nutrient pollution. Communities in Beijing have successfully implemented A^2O -MBR to treat domestic wastewater, ensuring compliance with stringent discharge standards [52]. FMBR employs facultative anaerobic processes to mitigate biofilm formation, minimize sludge production, and reduce operational costs. The operation time of an FMBR before membrane cleaning is 3.5 times longer than anaerobic membrane bioreactor (AnMBR) that couples membrane separation with anaerobic biological treatments when treating activated sludge, rendering it a more efficient and cost-effective solution [53].

To reduce energy consumption, integrating solar power and utilizing water treatment methods such as constructed rapid infiltration (CRI) in decentralized areas provide a viable approach. The global solar irradiation on a horizontal surface, ranging from approximately 1500–3000 sunshine hours and 1.9–2.3 $MW\cdot h\cdot m^{-2}$ per year, highlights the significant potential for integrating solar energy with water treatment processes [62]. With regard to practicality, solar-powered systems (e.g., aeration and portable sterilization devices) have proven effective in lowering operational costs and GHG emissions while also providing clean water in remote areas lacking traditional infrastructure [54]. Different from integrating clean energy, CRI reduces energy requirements by

Table 1
Different technologies in low-carbon water treatment.

Purpose	Approaches	Main advantages	Major challenges	Reference
Rainwater control	Rainwater harvesting (RWH) RWH consists of the concentration, collection, storage and treatment of rainwater from rooftops, terraces, and other impervious building surfaces for on-site use	<ul style="list-style-type: none"> • Reduce consumption of drinking water from centrally supplied sources • Control water runoff 	<ul style="list-style-type: none"> • Limited by roof area • The utilization rate is affected by seasons and weather conditions 	[49]
	Green roofs The green roofs are partially or completely covered with vegetation and a growing medium planted over a waterproofing membrane	<ul style="list-style-type: none"> • Lower capital costs (compared with grey water reuse) • Reduce stormwater runoff • Delay the discharge of excess water • Ecological benefit 	<ul style="list-style-type: none"> • Limited by roof area • Subject to climatic conditions 	[50]
	Bioretention cells (BRCs) A landscaped area that uses soil, vegetation, and microbial processes to treat and infiltrate stormwater	<ul style="list-style-type: none"> • Reduce runoff volume and peak flow in urban areas, lowering the risk of flooding • Reduce the urban heat island effect • Effectively removing pollutants from stormwater • Ecological benefit • Strengthened function of denitrification and dephosphorization • Little sludge production 	<ul style="list-style-type: none"> • Require regular maintenance to prevent media clogging and ensure healthy plant growth • Can vary significantly across different regions and climatic conditions 	[51]
Efficiency improvement	Anaerobic–anoxic–oxic membrane bioreactor (A²O-MBR) A membrane bioreactor technology that combines anaerobic, anoxic, and aerobic processes	<ul style="list-style-type: none"> • Can reach the near zero discharging of the organic residual sludge • Can well deal with the organic contaminants and N removal 	<ul style="list-style-type: none"> • Relatively high initial investment • Membrane fouling • The cleaning of fouled membranes can be challenging 	[52]
	Facultative membrane bioreactor (FMBR) The FMBR combines the facultative anaerobe and MBR, which can remove the pollutants by controlling dissolved-oxygen concentration and forming high concentrations of the activated sludge with the facultative anaerobe	<ul style="list-style-type: none"> • Can reach the near zero discharging of the organic residual sludge • Can well deal with the organic contaminants and N removal 	<ul style="list-style-type: none"> • Relatively high initial investment • Membrane fouling • Weaker capability for removing phosphates compared with A²O-MBR 	[53]
Low energy consumption	Utilizing solar energy Water treatment technology powered by solar energy can be more cost-effective, particularly in places facing energy shortages and having an abundance of solar energy	<ul style="list-style-type: none"> • Reduce energy consumption • Enable clean water access in remote, off-grid locations • Decrease GHG emissions and pollution 	<ul style="list-style-type: none"> • Significant upfront investment • Solar energy availability depends on the weather • Difficulty in integrating solar system with existing water infrastructure 	[54]
	Constructed rapid infiltration (CRI) Sewage is placed on the surface of an artificially constructed infiltration medium, subjecting it to different physical, chemical, and biological effects in the process of downward infiltration, with subsequent sewage purification	<ul style="list-style-type: none"> • Low capital investment • Low operation costs • Simple operation and management • No excess sludge discharge 	<ul style="list-style-type: none"> • Difficult to fully remove refractory organic matter (e.g., pharmaceuticals and personal care products) • Large land area is needed 	[55]
Carbon capture/energy recovery	Microbial electrolytic carbon capture (MECC) Microbial electrolysis enables wastewater treatment, H ₂ generation, and CO ₂ mineralization to carbonate	<ul style="list-style-type: none"> • High-rate CO₂ capture and utilization • Energy positive due to H₂ production • CO₂ is sequestered as stable carbonates • Efficient organic removal with low sludge • Potential to produce high-titre chemicals 	<ul style="list-style-type: none"> • Low product value (carbonates) • High capital costs with current design • Limited nutrient removal • Need large-scale validation 	[56]
	Microbial electrosynthesis (MES) Electrons are recovered from wastewater in the anode for cathodic CO ₂ reduction to organic chemicals catalyzed by electrotrophs	<ul style="list-style-type: none"> • High conversion efficiency • Self-sustainable biocatalysts • Efficient organic removal with low sludge 	<ul style="list-style-type: none"> • Low rate of biocatalytic electron uptake • Poor selectivity of high-value products • High costs with current design 	[56]
	Microalgae cultivation Naturally occurring microalgal communities are enriched to take up N and P while also assimilating CO ₂ into biomass	<ul style="list-style-type: none"> • Effective nutrient removal with high carbon capture and utilization (CCU) • Biomass generation for biofuels and bioproducts • Achieve organics polishing 	<ul style="list-style-type: none"> • Uncertain performance reliability • Requirement of large land area • High costs/energy for biomass harvesting • Limited organics removal 	[56]
	Constructed wetlands Engineered wetland system that integrates vegetation, soils, and microbial ecosystems to treat wastewater and capture CO ₂ to plant biomass	<ul style="list-style-type: none"> • Simultaneous organic carbon and nutrient removal • Multifunction in addition to CCU and waste treatment • Easy maintenance, low energy consumption, and low costs • Mature process for centralized and distributed uses 	<ul style="list-style-type: none"> • Limited removal nutrient • Large land area and limited success in cold climates 	[56]

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of their ability in rainwater control, efficiency improvements, carbon capture, low energy consumption, and energy/nutrient recovery, showcasing the diverse pathways required to achieve a sustainable urban water system for resource conservation and recovery.

Overall, this study comprehensively discusses strategic approaches for circular urban water management with reduced carbon emissions. Notably, this strategy is limited to the current social and technological context, which will require a detailed implementation plan and technical specifications. In the future, several areas warrant further investigation. First, pipelines, the key components in water distribution and discharge systems, are typically considered in terms of water transport or construction and maintenance costs. However, pipelines also facilitate microbial reactions that can form greenhouse gases. The environmental impact of these processes in future DWS should be evaluated by considering factors such as pipeline materials, water conditions within the distribution system, and effluent water quality in order to provide a more targeted and comprehensive assessment. Additionally, chemicals of emerging concern, such as pharmaceuticals and personal care products, are increasingly detected in drinking water sources. In addition to conventional water quality indicators such as total organic carbon, nitrogen, and phosphorus contents, indicators of removing emerging contaminants should be considered for assessing the overall circular urban water system within the water–environment–health nexus. Last, the development of low-carbon water treatment technologies should extend beyond the current focus on operational metrics such as pollutant removal efficiency, faradic efficiency, and treatment duration. Additionally, assessing these technologies' performance within sustainable urban water systems, considering factors such as capital and maintenance costs, user acceptance, and applicability across different contexts, is of equal importance. This broader evaluation would provide more comprehensive support for these technologies' widespread adoption.

CRedit authorship contribution statement

Xinyu Pan: Writing – original draft, Methodology. **Yumeng Zhao:** Writing – review & editing, Supervision, Project administration. **Xinlu Lin:** Investigation. **Nianyi Zhao:** Data curation. **Meng Sun:** Validation. **Jun Ma:** Resources, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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