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Using water and wastewater decentralization to enhance the resilience and sustainability of cities

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The imperative to make energy and resource consumption more sustainable is prompting a critical reconsideration of all human endeavours. Within urban water management, the drive to enhance sustainability is grounded in the recognition that water services consume a substantial amount of energy and that wastewater contains valuable resources, including water, heat, organic matter and essential plant nutrients. To make urban water systems more sustainable, a paradigm shift is needed. Among the proposed strategies, source separation coupled with anaerobic co-digestion appears to be an effective means of recovering energy, water and nutrients. Here, as existing centralized infrastructure that serves tens to hundreds of thousands of people is difficult to alter and the technologies needed to realize this strategy are difficult to implement in single-family homes, we consider the scale of a city block. Using a quantitative model of unit processes that simulate energy, water and nutrient flows, we consider the technical and economic feasibility of a representative decentralized system, as well as its environmental impacts. To realize potential synergies associated with on-site use of the recovered resources, we complement the decentralized water system with vertical farming, photovoltaic energy generation and rainwater harvesting. Our analysis suggests that decentralized water systems can serve as a cornerstone of efforts to enhance resource efficiency and improve the resilience of cities.

A recognition that humanity's energy and resource consumption is unsustainable is prompting a critical re-evaluation of all human endeavours. In urban water management, the desire to enhance sustainability is driven by the recognition that the provision of water consumes large quantities of energy and that the wastewater produced by households, commercial activities and industries contains valuable resources. Wastewater represents an underutilized source of water, energy and plant-essential nutrients. However, most urban water systems were designed to treat and dispose of wastewater in a manner that minimizes surface water pollution and risks to public health. To achieve these goals, energy-intensive treatment processes that often dissipate energy and nutrients contained in wastewater are used[1–4]. Recognizing the limitations of traditional wastewater management approaches in achieving environmental and economic sustainability goals[1,5–7], the urban water cycle must change.

Most prior efforts to recover resources from wastewater have focussed on resource recovery at large, namely centralized treatment plants. This approach benefitted from economies of scale and was

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relatively easy to integrate into the institutions responsible for urban water management, but it was unable to take advantage of the efficiencies that could be gained through the collection and recovery of separate waste streams that were rich in specific resources. Centralized resource recovery systems also struggled to take advantage of the benefits of fit-for-purpose water treatment because expensive new pipe networks were required to distribute non-potable water. The convergence of information technology (IT) and modular technology advancements holds the potential to enable the safe operation of small-scale water treatment and water supply networks that can take advantage of source separation and its high resource recovery efficiency together with the reuse of water of different qualities[8,9]. These innovations also have the potential to enable flexible and resilient hybrid or 'off-grid' small-scale systems, where citizens enjoy access to high-quality water in a manner that is less expensive, more sustainable and less polluting than existing approaches[10–12].

Source separation enhances the efficiency of resource recovery

Separation of wastewater into three different components, namely yellow water (that is, urine), brown water (that is, faeces and flush water) and grey water (that is, everything else), has the potential to reduce the costs of recovering water, energy and nutrients relative to the conventional approach of treating the combined wastewater streams[11,13–16]. Slowly but steadily, the number of initiatives taking advantage of this approach is increasing[17–22]. Black water (combined brown and yellow water), which constitutes roughly 20% of the volume of household wastewater, contains about 90% of the carbon and nitrogen and 80% of the phosphorus discharged by households. Treating this resource-rich stream separately (for example, by anaerobic digestion) is a proven means of recovering energy and water[2,13,16,23–27]. Anaerobic digestion, despite its lower energy conversion efficiency[28–30] (<15%) compared with incineration[31,32], provides a sustainable solution for energy and nutrient recovery from black water, offering a substantial improvement over the energy-intensive aeration processes owing to low oxygen transfer efficiencies[33–36] commonly used in conventional wastewater treatment. The grey water remaining after the black water is separated can be treated with less energy-intensive approaches to a point at which it is suitable for reuse within the home (for example, for laundry) or irrigation of plants[20,37,38].

Digital tools support a beneficial spread of distributed water treatment

New advancements in IT, such as Digital Twins, the Internet of Things and application programming interfaces, are revolutionizing the control, monitoring and operation of wastewater and resource recovery facilities[39–41]. While advances in remote monitoring, process modelling and real-time control of processes have addressed certain of the limitations that previously hindered the operation of decentralized or distributed water and wastewater treatment systems[42–44], it is important to recognize that IT is just one piece of the puzzle. Nonetheless, IT advancements represent a powerful toolkit with immense potential that can support transformative changes in water and wastewater management when coupled with better sensors and actuators, communication devices, modular approaches and new ways of thinking.

Similarly, reliance on centralized sewer networks is being re-examined owing to costs, maintenance challenges and vulnerability to extreme weather events. In centralized urban water systems, over 90% of the wastewater collection and treatment costs can be attributed to the construction and maintenance of sewers[45–48]. Moreover, the existing sanitation infrastructure, particularly sewers, is reaching its operational limits as utilities confront the challenges associated with ageing infrastructure, population density changes and the increasing frequency of large rain events driven by a changing climate[49–51]. To cover the necessary repairs and replacements, the costs of water services have been increasing at rates that are faster than those of other essential services. These costs are projected to grow as infrastructure deterioration continues[52–57]. Therefore, decentralized systems could alleviate some of the burden of increasing flows on these systems.

Research needs

Hybrid centralized–decentralized systems—the practice of integrating building or city block-scale water and wastewater management within existing centralized water systems—is attractive because it has the potential to reduce the costs of resource recovery while simultaneously providing a means of exploiting fit-for-purpose water that supports broadly shared societal goals related to resilience and can enhance water security, food supply chains and water self-sufficiency[1,6,58,59]. These systems also have the potential to be more compatible with existing water governance because they provide a means for cities facing water stress to reduce the quantity of water delivered and treated without abandoning existing infrastructure or making large investments to rapidly transition away from existing approaches[15,58,60]. The term 'decentralized' is used throughout the manuscript to highlight localized resource recovery. Still, it is important to note that these systems would probably function as 'distributed' components within a larger centralized management network, enabling local benefits and broader integration.

Acknowledging the potential advantages of decentralized urban water and wastewater systems, this study provides a cost, technical and environmental evaluation of decentralized source separation to facilitate efficient energy, water and nutrient recovery. The magnitude of recovered nutrients is illustrated using the produced fertilizers to support local food production while exploring potential payback mechanisms through synergistic strategies. A theoretical urban cluster of housing blocks was selected for this analysis because the size of the developments is consistent with initiatives such as Barcelona's Superilles (Superblocks)[61] that have broad appeal in cities seeking actions to achieve a shared social commitment to the circular economy and the desire to live in a green community.

Results and discussion

Decentralized water systems can bring water, energy and plant-essential nutrients directly into the urban landscape. Although the prospect of recovering a large fraction of the energy and resources flowing through these systems is attractive, adoption of this approach in full-scale systems has been limited[1]. Nevertheless, several high-profile proof-of-concept projects have been built recently[17–19]. As first-generation demonstration projects often receive grants and subsidies and are often designed in a manner that minimizes risk, cost and energy, the data obtained from them may not be readily extrapolated to projects that would be built as the concept is implemented in multiple locations within a city. To address this limitation, we evaluated a representative block-scale water and wastewater management system that employs source separation as part of a larger effort to make urban areas more resilient and attractive while supporting a circular economy.

A new paradigm of decentralized source separation and reuse

The proposed system considers a city block with approximately 2,000 people living in eight 12-storey medium-rise apartments (Fig. 1). Each building has a total area of 670 m^2 available as a rainwater collection surface (Supplementary Tables 2.1 and 2.2). Nutrients recovered by the wastewater treatment system are supplied to a vertical farming system located in semi-automated containers within, adjacent to or on the exterior of the buildings (Supplementary Table 26.1). The buildings share a common basement/parking area accommodating the water treatment system. The space required for the treatment system occupies 6–8% of the basement/parking area, allowing for additional equipment or future expansions (Supplementary Table 14.6).

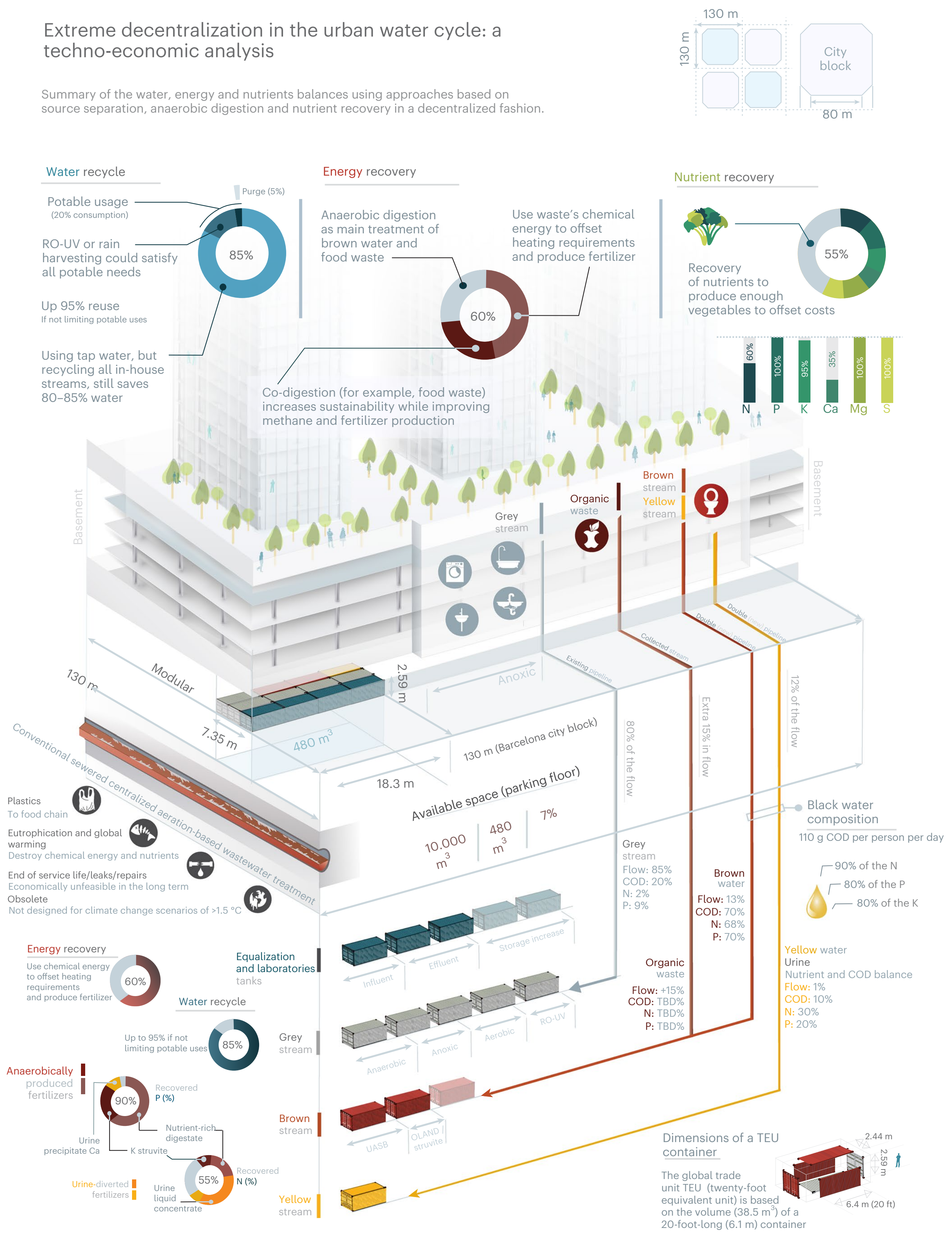

Fig. 1 | Proportional representation of the space requirements for decentralized wastewater treatment in a typical city block. The internationally standardized dimensions of twenty-foot equivalent unit (TEU) containers were used to visually compare the space requirements. The decentralized source-separation modules only require approximately 480 m^3 (7%) of a basement parking floor. COD, chemical oxygen demand; TBD, target bio-load dependent.

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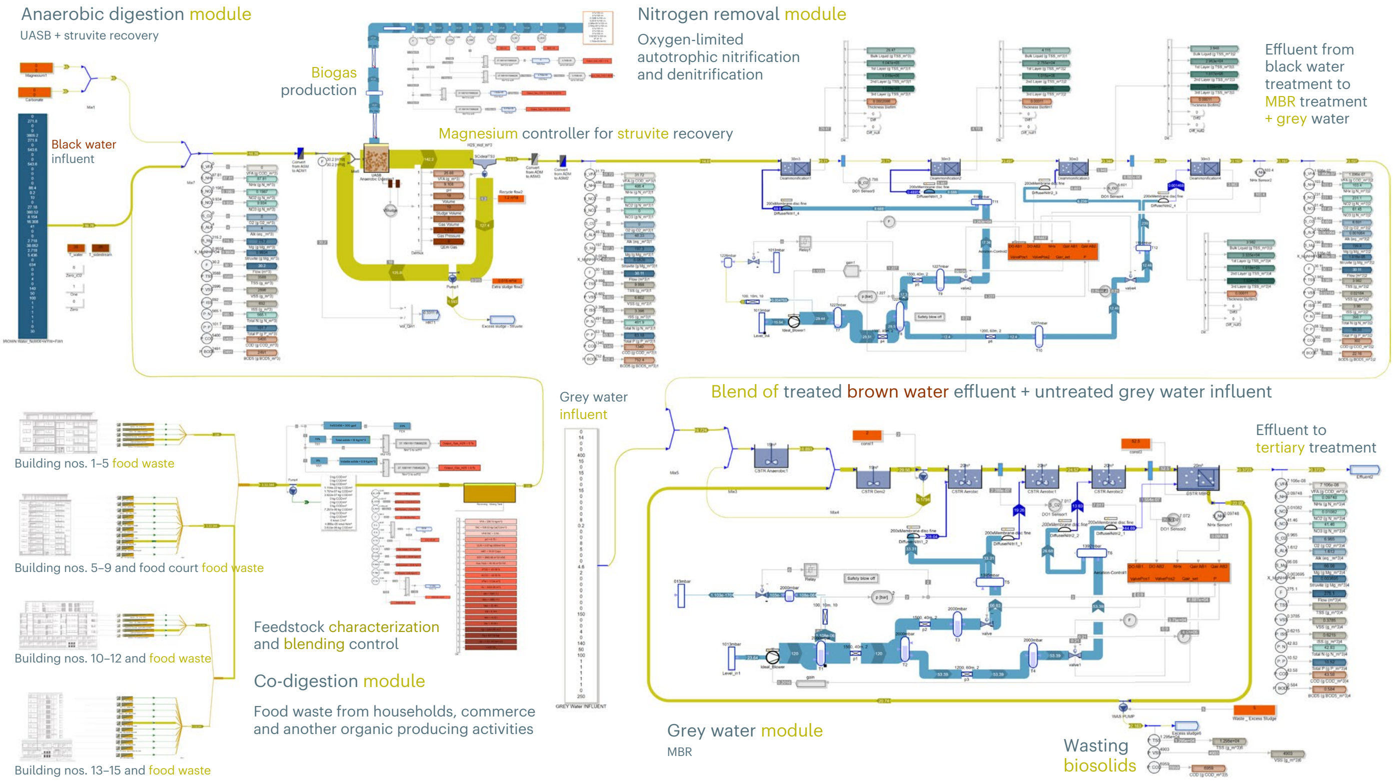


Fig. 2 | The source separation-based model in the city block was simulated with the modelling software SIMBA#. The Sankey diagram represents the TKN mass flow, grams of N per day (green), and the biogas and air flows, m^3 per day (light blue). The model includes three main types of controllers: (1) chemical dosing of magnesium for struvite recovery; (2) aeration controllers for oxygen requirements (deammonification and MBR); and (3) co-digestion module for the appropriate blending of feedstocks properties (that is, organics from households, commerce, restaurants and so on). The depicted buildings represent the different organic blends from each group of buildings within the urban cluster. nrYW, non-recovered yellow water; FW1, fresh water parameter; T_{Water}, temperature water; $T_{sidestream}$, temperature sidestream; $Zero_{iO2}$, oxygen initialization parameter; VFA, volatile fatty acids; BOD, biochemical oxygen demand; COD, chemical oxygen demand; TSS, total suspended solids; VSS, volatile suspended solids; ASM, activated sludge model; ADM, anaerobic digestion model.

Wastewater produced within the buildings is separated into black and grey water (Figs. 1 and 2). The black water is further separated into yellow and brown water with urine-diverting toilets (Supplementary Information Section 11). The yellow water (1–2% of the flow) is directed towards additional equipment designed to extract nitrogen (N)- and phosphorus (P)-based fertilizers, which satisfies about 45% and 7% of the N and P demand of the vertical farm, respectively (Supplementary Table 26.1). The brown water (10–15% of the flow) is enriched with food waste produced within the buildings before being fed into an upflow anaerobic sludge blanket (UASB) reactor (Supplementary Table 4.3). The UASB is designed and operated for struvite precipitation, which recovers about 90% of the P needed by the vertical farm as struvite and liquid digestate (Supplementary Table 10.4). It also enables the recovery of more than 50% of the whole treatment system energy requirements through biogas (Supplementary Information Section 7.2). The effluent of the UASB is further treated to lower the N concentration (via deammonification), but the layout could be modified to allow further N recovery. A membrane bioreactor treats the low-strength grey water (85% of the flow). Four other alternatives, that is, moving bed bioreactor, membrane aerated bioreactor (MABR), aerobic granular sludge and electro-oxidation, also were considered and proved to be potentially more cost effective (Supplementary Table 9.16). We selected a membrane bioreactor (MBR) for our analysis owing to its well-documented cost, technical data and combined biological treatment and filtration process. The treated grey water complies with the guidelines of the United States Environmental Protection Agency (US EPA) (EPA/600/R-12/618), World Health Organization (WHO) (GDWQ, 2011 and 2006) and the European Union (regulation 2020/741) for reuse in urban and bathing applications (Supplementary Table 20.1). To further ensure safety and optimize treatment standards, we not only adhered to the recommendations of the National Blue Ribbon Commission's Health Risk-Based Benchmarks for Onsite Treatment of Water and the regulations for on-site treatment and reuse of non-potable water of the California State Water Resources Control Board[62,63], additionally, we incorporated state-of-the-art research and adapted all risk measures following similar approaches to ensure alignment with the most current and rigorous practices[20,64].

Potable water could be partially sourced through the collection and treatment of rainwater, employing a multi-stage process consisting of pre-treatment, reverse osmosis (RO), ultraviolet (UV) disinfection and remineralization to ensure the highest standards of purity and reliability even in polluted environments (Supplementary Information Section 13.1). In situations where rainwater is insufficient, the system can draw from the existing centralized supply or expand the capacity of treated grey water to fulfil drinking water needs (similar to a direct potable reuse scheme). This decentralized approach offers the potential to substantially decrease water demand on the central supply by up to 90–95%. However, regulatory constraints on potable grey water usage must be addressed to fully realize this potential and alleviate the burden on existing centralized systems.

Model development and system performance assessment

The model applied in one of the scenarios is illustrated in Fig. 2. System performance was simulated with the modelling software SIMBA# (ifak)[65], which was augmented using manufacturing specifications and available technical data. The model integrates co-digestion, anaerobic digestion with simultaneous struvite recovery, grey water treatment process, chemical dosing, aeration systems for aeration-based processes (for example, MBR and biofilm-based biological treatment), rainwater harvesting and water purification systems (Supplementary Information Section 19). Mass balances and volumetric flows were obtained under different scenarios, as exemplified in the Sankey diagram (Fig. 2) of the total Kjeldahl nitrogen (TKN) mass flow as well as the biogas and supplied air flows (m^3 per day). The source separation-based model supports the estimation of monitoring needs, equipment sizing, unit selection, energy requirements, maintenance and overall cost analysis.

Simulation results were cross-checked with a specialized software package designed for source separation modelling (SampSONS)[66] and a detailed mass and energy flow analysis[67] (Supplementary Information Section 21). To obtain realistic cost estimates and ensure the highest safety standards, the study includes monitoring requirements (Supplementary Tables 24.1, 24.2, 24.3 and 24.4), associated maintenance and costs of all the equipment (Supplementary Table 18.9), and necessary flow metres, sensors, pumps, valves, storage units and tank capacities (Supplementary Tables 14.5 and 14.6), as well as performance outputs, such as efficiency metrics and effluent quality (Supplementary Information Section 20.1), together with risk mitigation strategies (Supplementary Information Section 25).

To gain insight into the performance of the decentralized system, water demand, energy production, nutrient recovery and environmental impacts were compared with a conventional centralized system (Fig. 3). To represent the conventional centralized system, data from two conventional activated sludge models were analysed (firstly, a detailed conventional activated sludge system with a modified Ludzack–Ettinger (MLE) configuration with primary and secondary clarifiers and, secondly, a conventional activated sludge system using a MBR in an MLE configuration), along with insights from a comprehensive literature review and the corresponding piping network calculations (Supplementary Discussion 23). Employing decentralized treatment could reduce the amount of water obtained from the centralized water supply network by up to 90–95% (Fig. 3a) under the scenario in which no potable water demand was met by rainwater harvesting. As indicated in our previously published analysis[11], the potential for rooftop rainwater harvesting to satisfy a portion of the potable water needs of people living in medium-rise buildings depends upon local climactic conditions. For example, rainwater harvesting could meet about 30–40% of the annual potable water demand of people living in a 15-storey building in Miami or Hong Kong, but only 5–10% of the water needs of people in the same type of building located in Barcelona or Santiago de Chile.

On a per capita basis, energy production in the decentralized system would be approximately twice as high as the amount produced in a centralized facility (Fig. 3b and Supplementary Discussion 22.13). The higher energy yield of the decentralized system is due to the fact that organic matter from the black or brown water is sent directly to the digestor in the decentralized system, whereas some of the energy associated with the organics is mineralized (that is, converted into carbon dioxide and water) through the biological treatment process used in the centralized system. In addition, the decentralized system could benefit from a more efficient co-digestion of food waste, which can increase energy production for the considered conservative scenario by about 35% in comparison with a value ranging from 18% to 25% in a centralized system (Supplementary Discussion 6.5).

Decentralized systems that employ source separation recover about twice as much N as centralized systems (Fig. 3c), mainly because they can efficiently recover N contained in liquid streams (for example, source-separated urine). The proposed decentralized system could recover as high as 90% of the N present in wastewater if less cost-effective technologies such as air stripping-absorption were employed[68–70].

P recovery is above 90% in both the centralized and the decentralized approaches (Fig. 3d). However, decentralized systems offer advantages over centralized nutrient recovery systems with respect to the potential uses of the recovered nutrients for two reasons. First, the fertilizer obtained in the anaerobic digestion process (that is, struvite) exhibits a higher purity (>85%) than the solids obtained by centralized systems (that is, biosolids that contain about 4.6% and 2.3% N and P, respectively[71,72]). Urine-derived fertilizers obtained from yellow water, such as P precipitates (that is, $Ca_3(PO_4)_{2(s)}$) and stabilized urine liquid concentrate, also exhibit higher purity than conventional biosolids[73,74]. Thus, both types of minerals obtained from small-scale systems can be used as fertilizers with little additional treatment. Second, the production of fertilizers in proximity to their point of use reduces costs associated with transportation and integration of the nutrients into a larger fertilizer supply chain.

The environmental impact of both approaches was evaluated through a life-cycle analysis that considered 15 mid-point indicators within different European cities as derived by the ReCiPe method[67]. Global warming potential (GWP) and eutrophication potential (EP) categories, considered the most used and well-understood environmental impact categories in the framework of wastewater management[75], were examined in detail (Supplementary Discussion 22). GWP was reduced mainly owing to the lower net energy usage due to the anaerobic digestors (Supplementary Tables 22.13 and 22.14). EP was also substantially diminished for the decentralized system because more than 80% of the treated water was recycled and the nutrients recovered (Supplementary Table 22.15), which reduced the nutrient-containing effluent discharged to surface water bodies (Fig. 3f).

Decentralization creates synergies that enhance resource circularity

After assessing water, energy and plant-essential nutrient production within the decentralized system, we considered synergies that could enhance environmental sustainability, reduce costs and promote circular economy practices. Owing to the interest expressed by many decision-makers and members of the public in the water–energy–food nexus, we focussed on practices that reinforce the spread of renewable energy and contribute to local food production. The potential synergies that we identified from the simultaneous adoption of vertical farming, local solar photovoltaic energy production and rainwater harvesting are strongly supported by many communities and could strengthen the case for investing in these more resilient urban water systems.

Vertical farming. The nutrients recovered by the decentralized treatment systems can serve as fertilizers used locally for landscaping purposes (for example, creating a verdant environment in courtyards and public spaces around buildings) or the local cultivation of food[76–78]. Although urban landscaping might be the easiest way to reuse the nutrients with current practices, using buildings as a means of producing fresh foods was investigated because it is an idea that captures the imagination of the public, can be a vector to promote public awareness and has the potential of generating revenue that could offset some of the costs of operating distributed treatment system.

The combination of wastewater treatment and hydroponic food cultivation has been a subject of considerable interest recently[74,79–82]. To address the potential for using recovered nutrients for the cultivation of high-value crops, we considered commercially available modular, hydroponic systems (for example, Boxfarm, Freightfarms and Urbancropsolutions) capable of growing tomatoes (*Solanum lycopersicum*), lettuce (*Lactuca sativa*), strawberries (*Fragaria ananassa*), spinach (*Spinacia oleracea*) and mushrooms (*Agaricus bisporus*) (Fig. 4). The allocation of production area for each crop was determined with an optimization model that factors in capital and operational costs, marketable weight per plant, crop harvest cycle, consumer pricing and per capita consumption[83–88]. The relative quantities of these five crops were

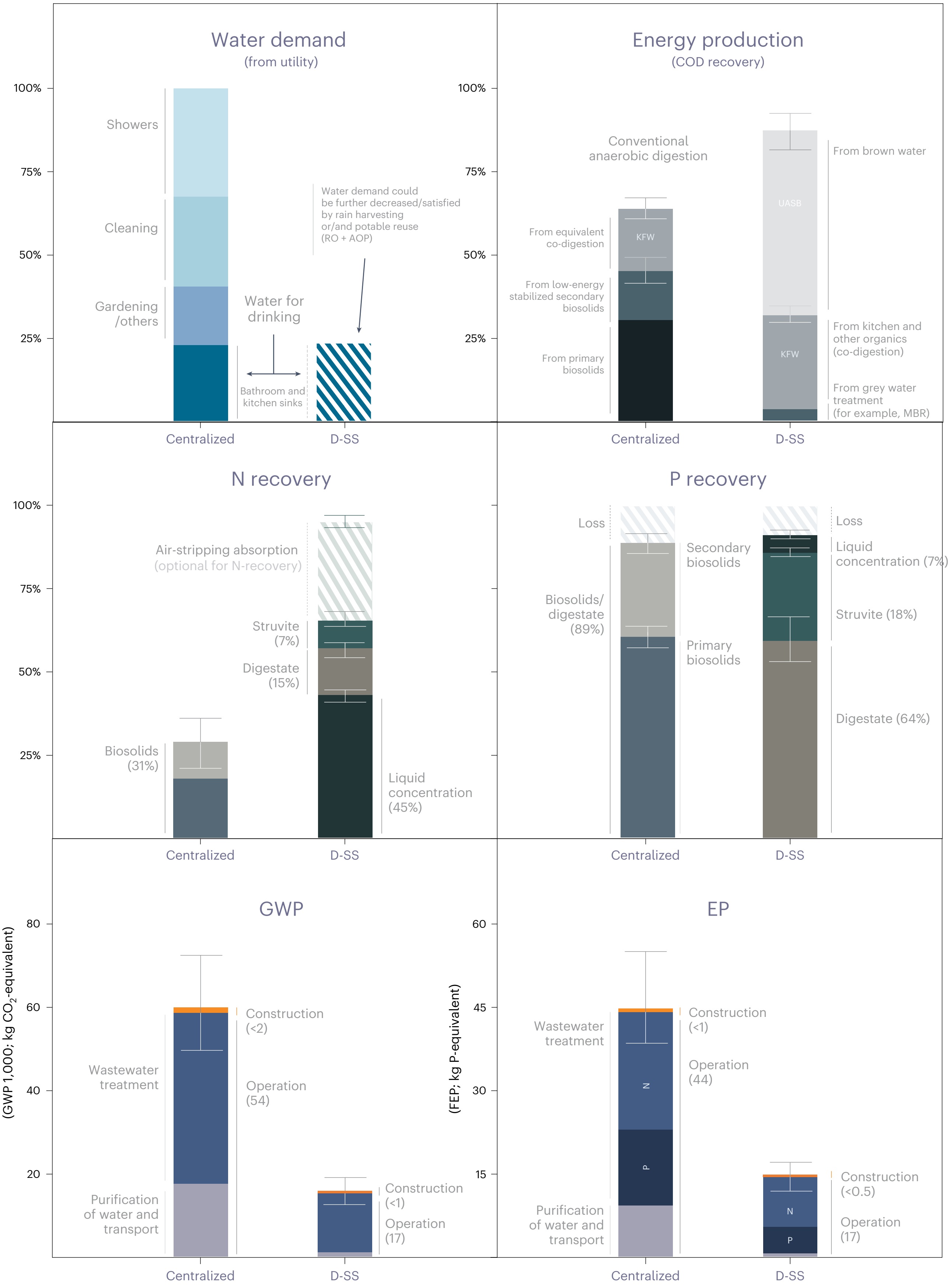
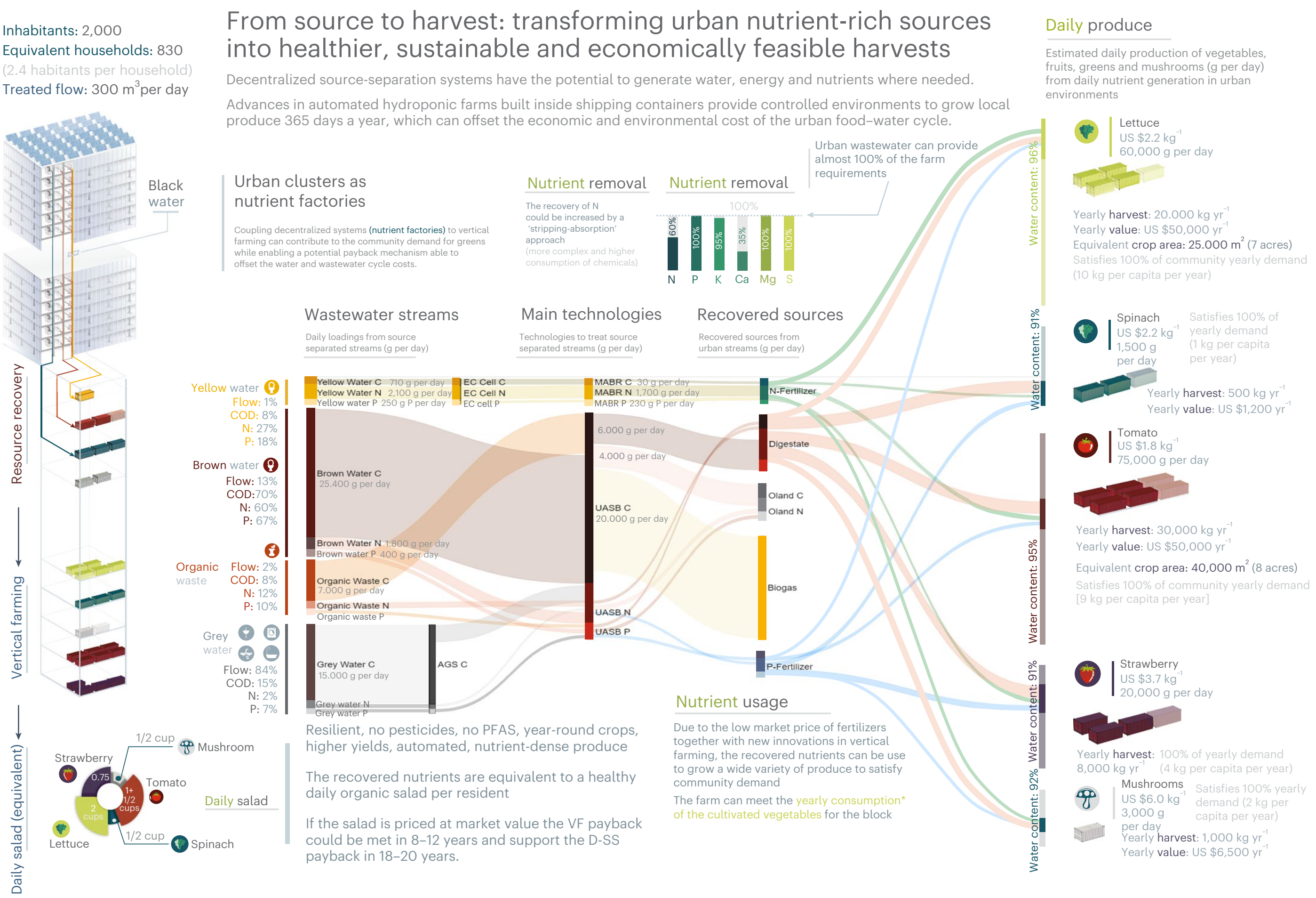


Fig. 3 | Comparison of the resource recovery potential and two life-cycle assessment categories for the proposed decentralized system (D-SS) and a conventional centralized treatment system (centralized). Data are presented as mean values ±90% confidence intervals, calculated using the s.e.m., to illustrate the range of uncertainty associated with each data point, which is derived from variations in model parameters, assumptions or input values. COD, chemical oxygen demand; AOP, advanced oxidation processes; FEP, freshwater eutrophication potential.



From source to harvest: transforming urban nutrient-rich sources into healthier, sustainable and economically feasible harvests

Decentralized source-separation systems have the potential to generate water, energy and nutrients where needed.

Advances in automated hydroponic farms built inside shipping containers provide controlled environments to grow local produce 365 days a year, which can offset the economic and environmental cost of the urban food–water cycle.

Urban clusters as nutrient factories

Coupling decentralized systems (nutrient factories) to vertical farming can contribute to the community demand for greens while enabling a potential payback mechanism able to offset the water and wastewater cycle costs.

Nutrient removal

The recovery of N could be increased by a 'stripping-absorption' approach (more complex and higher consumption of chemicals)

Urban wastewater can provide almost 100% of the farm requirements

Resilient, no pesticides, no PFAS, year-round crops, higher yields, automated, nutrient-dense produce

The recovered nutrients are equivalent to a healthy daily organic salad per resident

If the salad is priced at market value the VF payback could be met in 8–12 years and support the D-SS payback in 18–20 years.

Nutrient usage

Due to the low market price of fertilizers together with new innovations in vertical farming, the recovered nutrients can be use to grow a wide variety of produce to satisfy community demand

The farm can meet the yearly consumption* of the cultivated vegetables for the block

Daily produce

Estimated daily production of vegetables, fruits, greens and mushrooms (g per day) from daily nutrient generation in urban environments

Fig. 4 | Source-separated decentralized system's mass flow analysis (g per day). The daily loadings (g per day) of the main constituents (that is, carbon, nitrogen and phosphorus) in each source-separated stream (that is, yellow, brown, grey and organics) and how these contribute to source recovery in the form of fertilizers that can be used in automated vertical farms to produce a variety of valued products in g per day and including water content (that is, green, vegetables, fruits and mushrooms) to offset the economic and environmental costs of the urban water cycle. COD, chemical oxygen demand; PFAS, per- and polyfluoroalkyl substances; EC, electrochemical cell; AGS, aerobic granular sludge; VF, vertical farming; WC, water content.

based on yearly average consumption, as reported by the United States Department of Agriculture[89]. The additional costs associated with semi-automated modular containers or the external facades that could house the vertical farming modules were included in the cost model (Supplementary Tables 26.1 and 26.2). Although we did not attempt to take them into account, facades of this type can serve aesthetic, health and energy efficiency goals[90–94].

By efficiently using the recovered plant-essential nutrients, which are relatively inexpensive owing to the low cost of obtaining fertilizers on the open market[95–97], the amount of these selected crops produced by the vertical farming operation would exceed the United States national average consumption for residents of the housing block[89]. The production would be equivalent to a daily salad per resident containing roughly two cups of lettuce, half a cup of spinach, one medium tomato, a few mushrooms and, occasionally, a few strawberries (Fig. 4). This low-calorie salad (<5% daily adult intake) would contain vitamins, minerals and fibre, which are essential for a healthy diet (Supplementary Tables 26.4, 26.5 and 26.4). Assuming current market prices, the value of the theoretical daily (organic and locally grown) produce would offset the vertical farming investment and operational costs (CapEx and OpEx) in approximately 10–12 years (Supplementary Table 28.3). After the payback period and also considering the revenue generated by selling surplus crops (which roughly correspond to the vertical farming OpEx), the produce value could represent a potential payback mechanism for offsetting the costs associated with the decentralized system (Fig. 5 and Supplementary Tables 28.7 and 28.8). Therefore, although the inclusion of vertical farming would increase the initial investment by roughly 3.1 ± 0.3% (Supplementary Table 18.11), the operation and deployment costs could be offset in less than 8–13 years if the produce is valued at market prices, and it could support the economic feasibility of the decentralized system by providing an indirect revenue stream (Supplementary Table 28.8).

The nutrients recovered by the decentralized treatment system would not exactly match the amount needed to grow the produce. Using the optimal mix of crops, the recovered nutrients could supply all the necessary phosphorus, magnesium, potassium and sulfur for the vertical farm, as well as 56% nitrogen and 31% calcium. To ensure optimal growth, nitrogen, calcium and other trace nutrients must be added to the system[74] (Supplementary Table 26.1).

Photovoltaic system. The use of decentralized energy resources (that is, small-scale power generation located in proximity to consumers) is gaining interest as an integral part of the transition towards renewable energy sources[98–101]. This approach has the potential to satisfy about 20% of a country's electricity demand while simultaneously enhancing grid reliability and resilience[100,101]. To evaluate possible synergies between the energy demand of the decentralized water system and the added capacity provided by decentralized energy resources, we considered a photovoltaic system integrated into the city block containing the decentralized water system. Representing diverse Köppen–Geiger climates, the cities of Barcelona, Toronto, Santiago de Chile, Hong Kong and Miami were selected for analysis. Energy consumption within the block was categorized into three categories based on demand: (1) the water recycling system (D-SS), (2) the vertical farm and (3) household energy consumption.

The installations are anticipated to offset an average of 12 ± 3% of the estimated total domestic electricity demand (Supplementary Table 28.9). The decentralized system and the vertical farm represent approximately 2.0 ± 0.7% and 2.4 ± 0.2% of the total annual energy demand of the considered development (Supplementary Table 28.9). Consequently, the integrated photovoltaic installation would reduce grid energy consumption by approximately 8–11% compared with a development lacking these features. This allows for the payback of initial investment costs (approximately 4% of a new development cost) in 10–18 years, with the exact timeframe influenced by urban location (for example, Toronto, Miami and so on) (Supplementary Table 28.3). Following this payback period, the ongoing energy cost savings could then support offsetting the investment costs of both the vertical farm and decentralized approach.

Cost and energy comparison with centralized systems

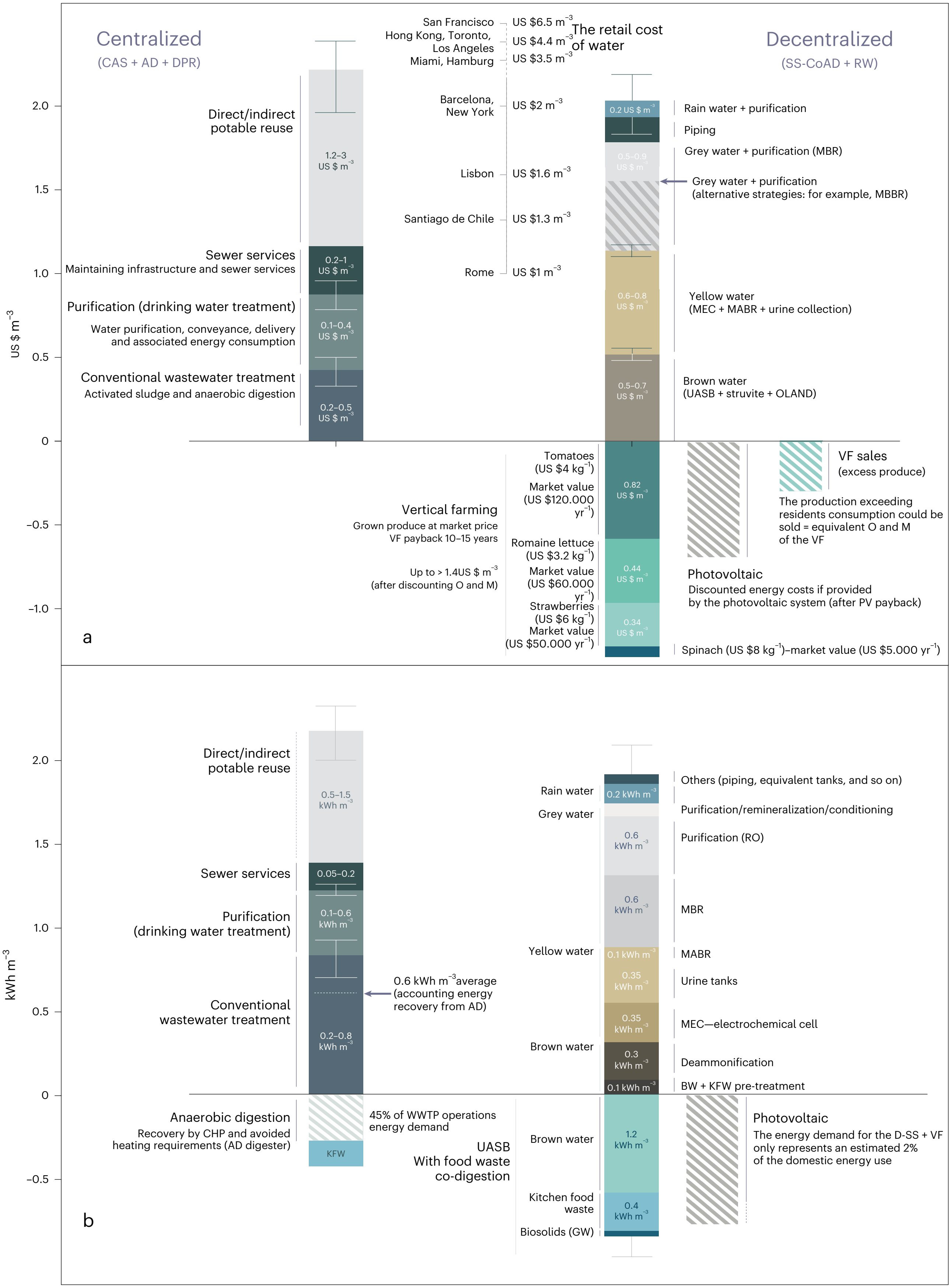
A detailed cost and energy analysis, which builds upon approaches used in previous studies[11,12], indicates that the performance of the decentralized system is similar to that of the centralized system (Fig. 5). However, when factoring in cost offsets from food production, rainwater harvesting and energy generation, the decentralized system becomes substantially more cost effective, potentially reducing costs by half or more compared with the centralized system. Similarly, considering energy produced through photovoltaics and food waste digestion, the decentralized system demonstrates a substantial decrease in grid energy consumption, potentially using half or less than the centralized system.

Our analysis of energy consumption (Fig. 5b) indicates that both modes of providing water services require approximately 2 kWh m^{-3}. To enable a fair comparison of both systems, the centralized system incorporated direct/indirect potable reuse, ensuring both systems provide the same functionality—delivering drinking-quality water without developing new traditional supplies (Supplementary Discussion 28.8). Considering the cost of potable water, wastewater treatment, water reuse and sewer services for centralized treatment systems[102–105], the overall cost of water from the centralized system would be approximately US $2.2 m^{-3}, compared with US $1.8 m^{-3} for the decentralized system before accounting for offsets from food production. Much of the energy use for the centralized water system is associated with operating conventional wastewater treatment plants (60%), and advanced treatment plants are needed to prepare the water for potable reuse (Fig. 5a). On the other hand, grey water treatment and purification represent the largest energy demand for decentralized systems (50% of total use). Implementing innovative technologies such as the moving bed bioreactor, MABR or electro-oxidation instead of the selected MBR holds considerable potential for energy reduction (Supplementary Discussion 9.4). The anaerobic digester's ability to recover energy and heat from brown water and food waste gives decentralized systems the potential to offset over 50% of their total energy demand (Supplementary Table 7.4). This substantial energy recovery advantage differentiates them from centralized systems (Supplementary Tables 7.1. and 7.2). The decentralized system's appeal further increases when considering energy from photovoltaic systems (with potential for free energy after payback), especially in locations with high energy costs for water import and distribution. While centralized systems could also benefit from photovoltaics, the diverse range of potential solutions makes a detailed comparison beyond the scope of this urban-focussed paper and a subject for future research. For comparison purposes, the gross cost of these two systems is examined against the cost of water in the representative cities[106,107]. Our results indicate that both modes of water provision have similar costs expressed through volumetric tariff rates relative to typical volumetric costs for several United States cities, such as Barcelona and Hong Kong. Costs in Lisbon, Santiago de Chile and Rome are about 25% lower than our projected costs (Fig. 5a).

This comparison highlights a crucial aspect of water costs and prices: much of the water utilities' actual costs are fixed (mainly asset costs, staffing, overhead costs and so on) and, therefore, independent of the actual amount of water produced. Most of the utilities charge both a fixed cost (for example, 'service fee' or 'connection fee') and a consumption-based variable cost (US $ m^{-3}). Consequently, the fixed costs can easily represent up to 75% of the total cost. Further differences between the cost of water treatment and supply (Fig. 5a, left column) and the final price paid by consumers in different cities (Fig. 5a, middle column) can also be attributed to a range of interconnected factors, including the need to recover costs of investments in water infrastructure and efforts to encourage water conservation, as well as the need to subsidize water users who are unable to pay the full costs of service[108–110]. External elements such as energy cost fluctuations and unforeseen events (for example, drought and chemical contamination) further influence the pricing structure, uniquely shaping the variation between actual costs and consumer prices within each region and utility[111,112]. Therefore, water price comparisons are inherently complex, but they reveal a crucial aspect: the need to share the 'net loss' cost of the provided service due to the absence of payback paths. In contrast, decentralized systems hold the potential to tap into two payback mechanisms powered by synergistic strategies. Decentralized system initial costs are approximately 3.5% of the cost of a new building (Supplementary Tables 18.1, 18.2 and 18.4), and the initial cost of the photovoltaic infrastructure and the vertical farming account for approximately 4% and 3.5% of the total cost, respectively (Supplementary 18.11). Nevertheless, as is the case for all solar power installations and urban farming initiatives, there is an expectation of payback on the initial investment. The proposed concept is not an exception; while photovoltaic power has an expected payback period of 8–12 years depending on location (Supplementary Table 27.4) and vertical farming, the initial investment is expected to be (indirectly) covered in 12–15 years (Supplementary Table 28.8), the distributed water system stands in an intermediate position because two indirect payback mechanisms could deliver a return on investment in about 10–15 years (Supplementary Table 28.3).

The first payback mechanism involves potential indirect savings generated by the availability and sale of locally grown, water-efficient and organic produce. The efficient in situ recovery of nutrients holds the potential to bypass the competitive disadvantage associated with artificial fertilizer prices (Supplementary Discussion 28.5.1) and would price the recovered nutrients based on their ability to produce food

Fig. 5 | High-level comparison of the costs and energy requirements per cubic metre of treated water between the source separation system (decentralized) and the centralized conventional treatment (centralized). **a**, Detailed cost comparison in $ m^{-3} between centralized and decentralized source-separation. **b**, Energy demand contributors in kWh m^{-3} between centralized and decentralized source-separation. Advanced monitoring and risk mitigation strategies are already incorporated in the cost and energy analysis of the decentralized system. Data are presented as mean values ±90% confidence intervals, calculated using the s.e.m., to illustrate the range of uncertainty associated with each data point, which is derived from variations in model parameters, assumptions or input values. AD, anaerobic digestion; MBBR, moving bed biofilm reactor; CHP, combined heat and power; SS-CoAD, source separation co-anaerobic digestion; RW, rainwater; BW, black water; WWTP, waste water treatment plant.


Centralized
(CAS + AD + DPR)
Decentralized
(SS-CoAD + RW)
The retail cost of water
San Francisco US $6.5 m⁻³
Hong Kong, Toronto, Los Angeles US $4.4 m⁻³
Miami, Hamburg US $3.5 m⁻³
Barcelona, New York US $2 m⁻³
Lisbon US $1.6 m⁻³
Santiago de Chile US $1.3 m⁻³
Rome US $1 m⁻³
US $ m⁻³
2.0
1.5
1.0
0.5
0
−0.5
−1.0
Direct/indirect potable reuse
1.2–3 US $ m⁻³
Sewer services
Maintaining infrastructure and sewer services
0.2–1 US $ m⁻³
Purification (drinking water treatment)
Water purification, conveyance, delivery and associated energy consumption
0.1–0.4 US $ m⁻³
Conventional wastewater treatment
Activated sludge and anaerobic digestion
0.2–0.5 US $ m⁻³
0.2 US $ m⁻³
Rain water + purification
Piping
0.5–0.9 US $ m⁻³
Grey water + purification (MBR)
Grey water + purification (alternative strategies: for example, MBBR)
0.6–0.8 US $ m⁻³
Yellow water (MEC + MABR + urine collection)
0.5–0.7 US $ m⁻³
Brown water (UASB + struvite + OLAND)
Vertical farming
Grown produce at market price
VF payback 10–15 years
Up to > 1.4US $ m⁻³ (after discounting O and M)
Tomatoes (US $4 kg⁻¹)
Market value (US $120.000 yr⁻¹)
0.82 US $ m⁻³
Romaine lettuce (US $3.2 kg⁻¹)
Market value (US $60.000 yr⁻¹)
0.44 US $ m⁻³
Strawberries (US $6 kg⁻¹)
Market value (US $50.000 yr⁻¹)
0.34 US $ m⁻³
Spinach (US $8 kg⁻¹)–market value (US $5.000 yr⁻¹)
VF sales (excess produce)
The production exceeding residents consumption could be sold = equivalent O and M of the VF
Photovoltaic
Discounted energy costs if provided by the photovoltaic system (after PV payback)
a
kWh m⁻³
2.0
1.5
1.0
0.5
0
−0.5
Direct/indirect potable reuse
0.5–1.5 kWh m⁻³
Sewer services
0.05–0.2
Purification (drinking water treatment)
0.1–0.6 kWh m⁻³
Conventional wastewater treatment
0.2–0.8 kWh m⁻³
0.6 kWh m⁻³ average (accounting energy recovery from AD)
Anaerobic digestion
Recovery by CHP and avoided heating requirements (AD digester)
KFW
45% of WWTP operations energy demand
Rain water
0.2 kWh m⁻³
Others (piping, equivalent tanks, and so on)
Grey water
Purification/remineralization/conditioning
0.6 kWh m⁻³
Purification (RO)
0.6 kWh m⁻³
MBR
Yellow water
0.1 kWh m⁻³
MABR
0.35 kWh m⁻³
Urine tanks
0.35 kWh m⁻³
MEC—electrochemical cell
Brown water
0.3 kWh m⁻³
Deammonification
0.1 kWh m⁻³
BW + KFW pre-treatment
UASB
With food waste co-digestion
Brown water
1.2 kWh m⁻³
Kitchen food waste
0.4 kWh m⁻³
Biosolids (GW)
Photovoltaic
The energy demand for the D-SS + VF only represents an estimated 2% of the domestic energy use
b

valued at market prices. While food production might not be among the main goals of the first decentralized source separation systems (initiatives such as landscaping, urban forestry and community gardens might be first considered), the theoretical value of nutrients (as produced crops) illustrates the potential for nutrient recovery potential to enhance the economic viability of these systems.

Results from this study suggest that the proposed concept could meet approximately 5–8% of the nutritional daily needs of residents through organic produce (that is, lettuce, tomato, spinach, strawberry and mushrooms) that will not only support a circular economy, but has a market value that if accounted for as money saved by the residents, offers a payback for the vertical farming investment in less than 15 years and the (indirect) revenue after the vertical farming payback could be used towards the pay off of the decentralized system costs. Similarly, the proposed photovoltaic system has an estimated payback period in the range of 6–15 years, depending on location. This means that the energy would be at no cost after the payback period, further decreasing the payback period of the decentralized system (even if 50–60% of the decentralized system energy is already being recovered using anaerobic digestion).

The decentralized system also taps into another payback mechanism that holds the potential to reduce the payback period to less than 10–15 years, thus avoiding the costs associated with the expansion of the existing potable water supply (Supplementary Discussion 28.8). Separating grey water allows for a more efficient treatment with reverse osmosis treatment, making it cheaper than treating mixed wastewater or even desalted seawater. Therefore, the ability of the decentralized system capacity to efficiently provide drinking water enables a direct comparison with similar approaches achieving the same functionality. A direct comparison with traditional water sources is not feasible owing to the diversity of potential sources (that is, reservoirs, groundwater and rivers) and the combination of amortized infrastructure and ageing needs. However, many urban areas grappling with the effects of climate change and rapid urbanization cannot meet their projected needs through the expansion of traditional potable water supplies. For this reason, the most practical solution will probably involve efforts to progressively augment the water supply with potable water reuse. Thus, the costs of producing drinking water will include the wastewater treatment costs and the required extra processes to achieve clean drinking water (Supplementary Discussion 28.8). When the same functionality is considered (that is, providing drinking-quality water without developing new forms of traditional supplies), decentralized systems can cost about half as much as the centralized treatment approach.

The role of increasing water scarcity is important because expanding existing systems is much more expensive per unit of water than the average cost used in these comparisons. This means that presented cost analyses probably underestimate the economic value of decentralized systems because the increasing costs of expanding the centralized system as population growth and climate change add additional stress were not considered. Future economic analyses should incorporate the avoided cost of expanding centralized infrastructure as a key factor, alongside other potential benefits such as improved water security and resilience. Nevertheless, the presented approach provides insights into decentralized water systems' true economic value proposition. Therefore, while the decentralized system payback is initially estimated at 18–22 years, valuing the avoided cost of expanding existing water infrastructure could drastically reduce the payback period. Conservative estimates (only comparing the price difference with that of direct potable reuse (DPR) strategies) suggest a payback period of 10–14 years.

Ancillary benefits of decentralized water systems to green developments. The concepts proposed in this study not only bring forth economic, environmental and technical advantages but also hold the potential to captivate the public's attention through their alignment with concepts associated with sustainability and the circular economy. While our primary focus has been on demonstrating the cost effectiveness, environmental impacts and energy implications, decentralized treatment systems can be configured in ways that are attuned to local conditions and community values. For example, recycled water and recovered nutrients could be used for the cultivation of trees and gardens, creating a neighbourhood that realizes the reduction in land surface temperatures (that is, mitigation of the urban heat island effect while maximizing the health benefits of being surrounded by vegetation)[113–115]. This holistic approach to urban planning promotes environmental sustainability and prioritizes the community's mental and physical health, fostering a sense of belonging and cohesion among residents[116–118]. Other neighbourhoods might opt for sending recovered water and nutrients to existing operations, such as farms, golf courses and industry.

Neighbourhoods that embrace technological advancements may command higher property values and rents owing to their inherent appeal[114]. The integration of sustainable practices and innovative technologies within the community enhances the overall attractiveness and desirability of the neighbourhood. The combination of resource-efficient infrastructure, abundant greenery and forward-thinking technologies creates a unique urban ecosystem that resonates with the values of modern urban dwellers and could shape a more sustainable and fulfilling urban lifestyle.

Finally, neighbourhoods equipped with decentralized water systems, photovoltaics and green spaces may also exhibit enhanced resiliency. They may recover more quickly when water or power is interrupted by natural hazards and be better prepared for extreme heat, droughts or floods.

Barriers and drivers of a paradigm shift

From 'lock in' to a green transition

Many innovative decentralized urban water solutions have been around for years, but real implementation of these practices at scale remain challenging[17–19,37,119–122]. Over the past two decades, architects, developers and utilities have shown that it is feasible to construct buildings or neighbourhoods that are capable of recovering and recycling a marked fraction of the water and nutrients that would otherwise be discharged as waste. Although advancements in the technologies employed for water treatment and resource recovery have improved to the point at which decentralized treatment systems are often more attractive than centralized systems[20,47,64,123–127], translating demonstration projects into widespread adoption remains a substantial challenge[128–132] because decisions about whether or not to invest in new approaches to infrastructure management usually depend on factors other than technological feasibility and economic performance[1].

Researchers have identified several key barriers to the diffusion of decentralized water system technologies[1]. Arguably, the most challenging is the lack of broad institutional support, which is primarily rooted in technological inertia reinforced by the institutions responsible for urban water management. The near absence of existing buildings with dual plumbing and the limited experience of builders and building operators with such building-scale water recycling systems combined with concerns about public perception of the risks of exposure to unsafe water are sometimes offered as reasons for a lack of support. Although these issues could be addressed readily, the larger problem of technology 'lock in' probably explains much of the hesitancy about decentralized water systems[1,10,38,133]. This phenomenon, which has been observed in numerous social-technical systems, often occurs when an approach that has an early lead in innovation acquires dominance in a market that restricts the advancement of other technologies[134]. When the technical approach that receives the initial investments involves capital-intensive centralized infrastructure, the lock-in effect is often extremely difficult to overcome because sunk investment costs are large and institutions (for example, equipment providers, contractors and utilities) that benefit from the status quo resist change. Furthermore, an inability to fully account for the societal, economic and environmental benefits of alternative approaches often thwarts efforts to break the lock-in effect.

Technology lock-in is not restricted to urban water management[135,136]. For example, rooftop solar power took approximately four decades to progress from a state in which it was employed mainly in projects that sought to demonstrate the feasibility of the technology to a state in which it is often a standard feature of new homes, offices and retail developments. Some of the delay in implementation of the technology was due to the high costs of solar panels during the initial phase of its development, but delay in technology diffusion was also attributable to the lock-in effect, which was perpetuated by centralized utilities concerned about revenue losses if distributed electricity generation became popular. Similar to the early days of the adoption of rooftop-scale photovoltaic energy production, the lock-in effect coupled with incomplete accounting for the social and economic benefits may slow the rate of uptake of distributed water solutions.

Aligning with a broader recognition that the existing system of centralized water supply and treatment is inconsistent with society's sustainability goals and mirroring the eventual economic advantages of rooftop photovoltaics, decentralized water systems offer a compelling case for breaking the lock-in effect in urban water management, promising solutions to water and sanitation challenges while contributing to broader goals of resilience, reduction in pollution and economic gain.

There are several mechanisms through which the lock-in effect can be overcome. In addition to supporting the creation of iconic projects that demonstrate the feasibility of new approaches, government can play an important role through subsidies that lower the costs of new approaches during their early phase of development, when costs are likely to be highest. They also can create ordinances that require the use of new technologies and mandate institutional reforms that assure smoother financing, permitting and monitoring of new approaches. In addition, research and development efforts that document the financial and social benefits associated with the use or sale of recovered nutrients, lower water bills, reduced consumption of chemicals, lower energy requirements and reduced waste disposal can help build political support, public interest and institutional support[13,15,38,132]. Recognition that the cost of new approaches tends to drop as experience is gained and that institutional challenges decrease as stakeholders gain experience is critical to navigating from demonstration projects to widespread adoption. Rabaey et al.[10] proposed learning from solar power's successful adoption to guide the implementation of distributed water systems. Similar to solar energy, the first installations could start with environmentally motivated early adopters, leading to cost reductions through innovation. However, these concepts offer additional advantages beyond cost competitiveness, such as increased resilience, local water independence, waste reduction and sustainable water management. Despite these benefits, decentralized water approaches could face competition from other drought-resistant options such as centralized water reuse and desalination. These centralized approaches align better with existing water institutions and do not require dual plumbing systems but face public opposition due to cost, environmental concerns (desalination) and the perception of treated wastewater (reuse).

A hybrid transition helps overcome the lock-in effect

Although many of the communities that will ultimately find distributed water systems more attractive than centralized systems will be in low- and middle-income countries where water service is less reliable or in rural communities that lack piped water and sewers, the initial adoption of this approach is likely to take place in cities in high-income countries, where a desire for achieving resource circularity coupled with the wealth needed to fund new forms of infrastructure exist. Centralized water services in these cities could play an important role in supporting the decentralized systems, providing access to tap water that can augment the supply of distributed systems when needed, as well as sewer systems for disposal of excess water and residuals (for example, solids and salts). As was the case for rooftop solar power, the initial market for distributed water systems will probably be part of a hybrid approach, where investments in decentralized solutions reduce the need for new centralized water projects and make up for the decreasing reliability of imported water supplies or to expand the capacity of existing sewage treatment plants. As decentralized projects are being added to the urban water system, their integration into the existing infrastructure must be carefully managed. Initially, these systems are likely to emerge within the city centre, associated with high-profile developments. For optimal results, centralized system operators should partner with developers to strategically place new decentralized projects, ensuring that they complement the existing infrastructure. This could involve incentivizing these systems on the city's outskirts to reduce strain on long-distance water pumping or prioritizing these concepts in densely populated areas where conventional supplies are stressed by increased demand.

In the early phases (for example, <5% of overall water use), the impact of decentralized systems on the centralized utility will probably be minimal. However, over time, two key concerns arise: (1) changes in water movement through the centralized system (affecting demand, wastewater characteristics and so on) and (2) potential shifts in revenue due to a changing customer base. Fortunately, the gradual pace of urban change in most wealthy cities affords institutions ample time to plan for these transitions and adapt their business models accordingly[7].

A shift to a hybrid urban water system will require support from utilities, real estate developers, government officials and members of the public. As the needed changes may require institutional reforms and may result in higher costs for water services during the initial phase of implementation, it will be necessary to describe the broader value proposition beyond immediate benefits to users of the water system. Hybrid water systems potentially provide benefits to the entire community by enhancing the resilience and sustainability of water, food and energy. The adoption of hybrid water systems will also require a vision for system financing, design and operation that convinces decision-makers that the transition will take place in a manner that is economically efficient, reliable and protective of public health and the environment.

The first step in building support for hybrid systems involves the creation of a unified narrative that places distributed water systems at the centre of a strategy for enhancing food security, economic development, health and wellbeing. The appeal of integrating distributed water systems lies in their strong alignment with broader societal goals of resource circularity and climate change adaptation, as these concepts excel in promoting local water treatment and reuse, minimizing waste and reducing strain on centralized systems. While new technologies sometimes face public scepticism, achieving legitimacy can considerably bolster their adoption[137–139]. Legitimacy often hinges on three factors: (1) a user's belief that the technology offers personal benefits, (2) familiarity with how the technology works and (3) trust in the institutions managing it.

Importantly, the degree of public familiarity with water reuse varies globally. In many places, the public is accustomed to using treated wastewater or grey water for non-potable applications such as landscape irrigation and toilet flushing. In these communities, efforts should centre on building legitimacy and trust in technologies such as urine source separation and the use of treated wastewater for growing fruits and vegetables. Demonstration projects, which are often conducted at the pilot scale, help build familiarity with these applications, suggesting that the critical area for emphasis may be trust building.

To cultivate strong trust, transparent management and regulation of these projects are essential. Involving trusted independent oversight groups, similar to the role of expert panels in the United States, could provide an additional layer of public reassurance and scrutiny. This approach underscores the responsible implementation of these concepts, demonstrating that public health, safety and environmental safeguards are prioritized alongside innovation. Building support and legitimizing the practices associated with hybrid urban water systems are key prerequisites for the diffusion of this new approach. However, a successful transition to a hybrid system also faces barriers associated with the system of permitting and monitoring system performance. Regulatory aspects often act as barriers to the broader adoption of innovative technologies in the water sector owing to concerns about the ramifications of failure (for example, public health impacts and inefficient use of public expenditures). Successful transitions require the adaptation of institutional arrangements and new regulatory frameworks[131,140–143]. Collaborative policies at local and national levels, driven by the efforts of utility and government leaders, will be crucial for the creation of a supportive regulatory framework. The policy innovations needed to facilitate change must be adaptable to unexpected challenges that may arise as hybrid systems develop and thus will require dedicated advocates for change.

High costs could serve as another barrier to the adoption of hybrid urban water systems, especially in the early stage of the transition. In the initial stage of the transitions, when costs for equipment needed to operate distributed treatment system are high and regulatory issues are likely to result in delays and added costs (for example, delayed permits, requirements for on-site operators and requirements to analyse large numbers of samples to validate system performance), well-designed subsidies can relieve financial pressure and incentivize adoption[144,145]. Research shows that such government support reduces uncertainty for green technology companies, encouraging them to bring solutions to market[144–146].

While simply offering financial incentives for decentralized system adoption is unlikely to guarantee widespread success[130,147], targeted subsidy approaches can be powerful tools in facilitating acceptance and implementation[148,149]. One valuable example is the green building certification process. Certifications such as the Leadership in Energy and Environmental Design provide financial support and market recognition for projects integrating sustainability features, including water-efficient technologies. A similar approach could be applied to source separation adoption, encouraging developers and homeowners to embrace these systems. The Battery Park City project in New York demonstrates another effective subsidy strategy[120,150]. Here, government grants aimed at reducing combined sewer overflows defrayed a substantial portion of the project's costs. These concepts often have the potential to mitigate similar water management challenges, making them viable candidates for targeted government funding. Similarly, one of the most crucial and straightforward subsidies lies in the connection fees of hybrid systems to water and sewer systems. Currently, the pricing structures of many utilities are not designed to accommodate hybrid approaches. Adjusting these connection fees could meaningfully incentivize the adoption. However, it is essential to acknowledge that utility revenue models vary widely and developing equitable subsidy structures may require location-specific strategies.

While green building certifications represent a powerful tool to promote sustainability, they currently do not have an explicit focus on decentralized water systems. Incorporating these systems into certification criteria would considerably boost their adoption. By rewarding water-efficient and innovative water management technologies, certifications would create a market incentive for developers to embrace the concept. The proven willingness of renters and buyers to pay a premium for green buildings provides a key advantage, making the integration of decentralized systems an attractive value proposition for developers and building owners.

For example, certifications could award points for systems that reduce reliance on potable water for non-potable needs, such as irrigation or toilet flushing. After these initial projects are implemented, it will be essential to re-evaluate the associated benefits and costs. This ongoing assessment, coupled with the expected improvements in the cost, performance and reliability of approaches over time (the experience curve), will help policymakers and building professionals fine-tune subsidies and incentives to achieve the desired societal outcomes. Importantly, this evolution is likely to unfold over several decades, allowing for gradual adjustments, a long-term perspective on the integration of distributed systems and benefits from the learning gained from the first, more expensive and riskier projects.

Summary and conclusions

This study presents a techno-economic and environmental assessment of a decentralized water and wastewater management system that employs source separation and the recovery of energy, water and nutrients in wastewater. It encompasses vertical farming and solar photovoltaics—two synergistic approaches that enhance sustainability, reduce costs and promote circular economies. The paper delves into the strategic interplay within the water–energy–food nexus to fortify resilience, diminish reliance on centralized systems and foster sustainability.

Key observations from this study are as follows:

- The decentralized source separation-based paradigm maximizes resource recovery and enhances resilience and sustainability while reducing costs. When the same functionality is considered (that is, providing drinking-quality water without developing new forms of traditional supplies), the overall treatment cost could be about half that of conventional treatment.
- Higher resource recovery efficiencies and the ability to easily process food waste in the decentralized approach can lead to the recovery of 40–50% more energy compared with existing centralized energy recovery approaches. The decentralized system also uses 85% less water from the utility. It exhibits an approximately 50% increase in nitrogen recovery and a 90% increase in phosphorus recovery, with less than one-third of the environmental impacts (for example, global warming and eutrophication).
- The implementation of the decentralized approach would necessitate an approximate additional investment of 4 ± 0.5% relative to the construction of new residential blocks to incorporate the required pipes, treatment devices and monitoring equipment. Nevertheless, the decentralized source separation system can benefit from synergistic strategies (that is, vertical farming, photovoltaics and potable reuse capabilities) that can lead to payback mechanisms to offset investment costs in periods as short as 10–15 years.
- The synergy with a vertical farm could provide residents with the equivalent of daily, nutrient-rich salad that, if valued at market prices, would offset the vertical farm investment costs within 10–12 years. Selling the surplus crops could offset the system's operating costs. While the initial investment in vertical farming increases slightly (3.2%), it supports the financial sustainability of the entire system over the long term.
- Adding a photovoltaic system requires a slight increase in initial investment (%). However, after a payback period of 5–10 years (depending on location), the ongoing energy cost savings will help offset investments in both the vertical farm and the decentralized water system.
- The decentralized source separation would take up to 7–9% of the basement space for the city block-scale development. Coupling the system with vertical farming using automated modular containers would require an additional 10–15% of basement floor space.
- The wastewater produced by decentralized systems conforms to current quality regulations. Although in this study the treated water is reused within the block for non-drinking applications,

it could be an alternative of costly direct or indirect potable reuse approaches. The efficiency in treating grey water provides a cost-effective method of recycling 85% of the water demand, thereby alleviating the burden on traditional water sources.

- The recovered plant-essential nutrients can be used for on-site vertical farming, landscaping or other purposes, depending upon opportunities and community values. Vertical farming can enhance food resilience while offsetting some costs associated with water treatment and resource recovery.
- Proactive engagement with stakeholders (regulators, utilities, developers and the public) is crucial to addressing potential barriers, building legitimacy for unfamiliar technologies, reforming institutions to accommodate hybrid water systems and creating targeted incentives, especially during the early phases of adoption.

Methods

Scenario overview

In a preliminary analysis[11], we investigated the economic performance and environmental impacts of implementing a decentralized source-separation approach in seven types of residential and urban developments. These developments included single-family homes, low-rise dwellings, low/medium-rise, medium-rise, medium/high-rise and high-rise buildings (Supplementary Table 2.1). Our cost calculations and results of a previous analysis of energy use and environmental impacts revealed that economies of scale make larger buildings, accommodating over 300 people, the most cost-effective options among residential developments [11]. While this approach intends to reflect the potential cost variations that would arise when scaling up the decentralized system to serve larger populations, a full economic analysis of scaling impacts remains an area for future research. It is important to consider that scaling up centralized systems benefits from economies of scale, potentially reducing capital costs per unit. Conversely, decentralized systems might experience less substantial cost reductions with scaling, but their operational costs are likely to remain lower than those of a centralized system, even in a larger context. Nevertheless, it is important to note that the main advantage of decentralized systems lies in their potential for resource recovery, which can generate additional revenue and offset costs. Further research is needed to determine the point at which the cost advantages of each approach intersect, offering insights into the most economically viable solutions for different population sizes and service requirements.

Building upon those initial findings, we focussed on a typical city block designed to accommodate 2,000 population equivalents, consisting of eight high-rise buildings, each with 12 stories and 250 population equivalents, following the typical occupancy rate found in Europe (that is, 2.3 inhabitants per dwelling) and an average apartment floor space of 30 m^2 per capita (Fig. 6). We estimated the per storey area, including common areas, using equation (1), where A_s represents the area per storey, A_{hh} is the area per household, γ is a constant (equal to 1.15) and N_{hh} is the number of households in the building (Supplementary Table 2.2). An additional 30 m^2 per storey was allocated for common spaces.

$$A_s = \gamma \times A_{hh} \times N_{hh} + 30 \tag{1}$$

The total area available for rainwater collection per building, or rainwater catchment surface, was calculated to be 670 m^2. These buildings were arranged around a central rectangular space and shared a common basement with a standard floor height of 3 m for the storage of technology, resulting in a total rainwater collection area of 5,360 m^2 (Supplementary Table 2.1).

This study includes the investigation of the potential of decentralized rainwater harvesting and solar energy generation to support critical urban infrastructure across geographically diverse cities (Supplementary Table 3.1). To examine varying climates, we selected five cities representing a range of Köppen–Geiger classifications: Miami (North America, equatorial), Santiago de Chile (South America, arid), Barcelona (Europe, Mediterranean), Hong Kong (Asia, warm with dry winters) and Toronto (North America, temperate). We analysed average monthly precipitation and solar irradiance data to estimate rainwater supply potential and solar energy generation capacity (Supplementary Tables 3.2–3.7). While we acknowledge that climate change impacts precipitation patterns, this study used historical averages. Future studies should consider more recent climate projections to assess extreme variability, potential shorter and more intense storms and explore rainwater storage.

Model overview

We developed a series of models adopting the source-separation concept to investigate the feasibility of implementing decentralized water and wastewater treatment systems (Supplementary Discussions 19 and 23). The models were built following the recommendations of the International Water Association (IWA) Guidelines for Using Activated Sludge Models[151] using the advanced modelling platform SIMBA# (v4.2). All the models were designed with an energy-producing anaerobic co-digestion process as the main biological treatment with the influent flows derived from a source separation approach (that is, organic waste and brown, yellow and grey water) instead of using energy-intensive conventional aeration-based treatment (that is, activated sludge), which do not follow a source separation approach. The developed models for the mainstream process were built on an adapted biokinetic model based on the Anaerobic Digestion Model 1 of the International Water Association[29]. The adapted models were specifically built to allow the consideration of adding additional substrates (for example, food waste) to the brown and black water streams. The model was modified to consider pH changes by using a specific algebraic equation solver.

The corresponding aeration system for the grey water flow and the biofilm-based nitrogen removal subsystem is used in the inCTRL-adapted activated sludge model (CTRL-ASM) biokinetic model developed by the Institut für Automation und Kommunikation[152]. To construct the layout of the aeration system, we included blowers, pipes, fittings, valves and diffusers mechanistic models for each actuator. The piping system was modelled using the Darcy–Weisbach equation, with the friction factor calculated using the Swamee and Jain (1976) equation[153]. The pressure rise across blowers and pressure drops across valves and diffusers were calculated using polynomial functions based on airflow rate, which were calibrated using manufacturer data. Aeration control was operated as ammonia-based aeration control with optimal solid retention time (SRT) control[154] and accounted for by means of continuous feedback using proportional–integral or proportional–integral–derivative (PID) control algorithms. To model the behaviour of the automatic valves, a control algorithm was implemented that fixes the valve position of the lane with the highest oxygen requirement, thereby allowing the other valve to vary to adjust the required airflow.

The subsystem for the nitrogen removal of the effluent generated by the anaerobic co-digestion mainstream process was modelled with an in-house inCTRL-ASM biofilm-based biokinetic model, which includes two-step nitrification and the growth of anammox bacteria, in addition to hydrolysis, adsorption, fermentation and the growth of ordinary heterotrophic organisms, phosphorus accumulating organisms and methylotrophs. The anammox biokinetic submodel was based on the model of Koch et al.[115]. Simulation results were cross-checked with an Excel-based model exclusively built for this project. The Excel-based model was used to calculate under steady-state conditions the size, cost, performance and main technical details of all necessary equipment units and correlate, through engineering-based equations, using data from peer-reviewed literature, manufacturers and

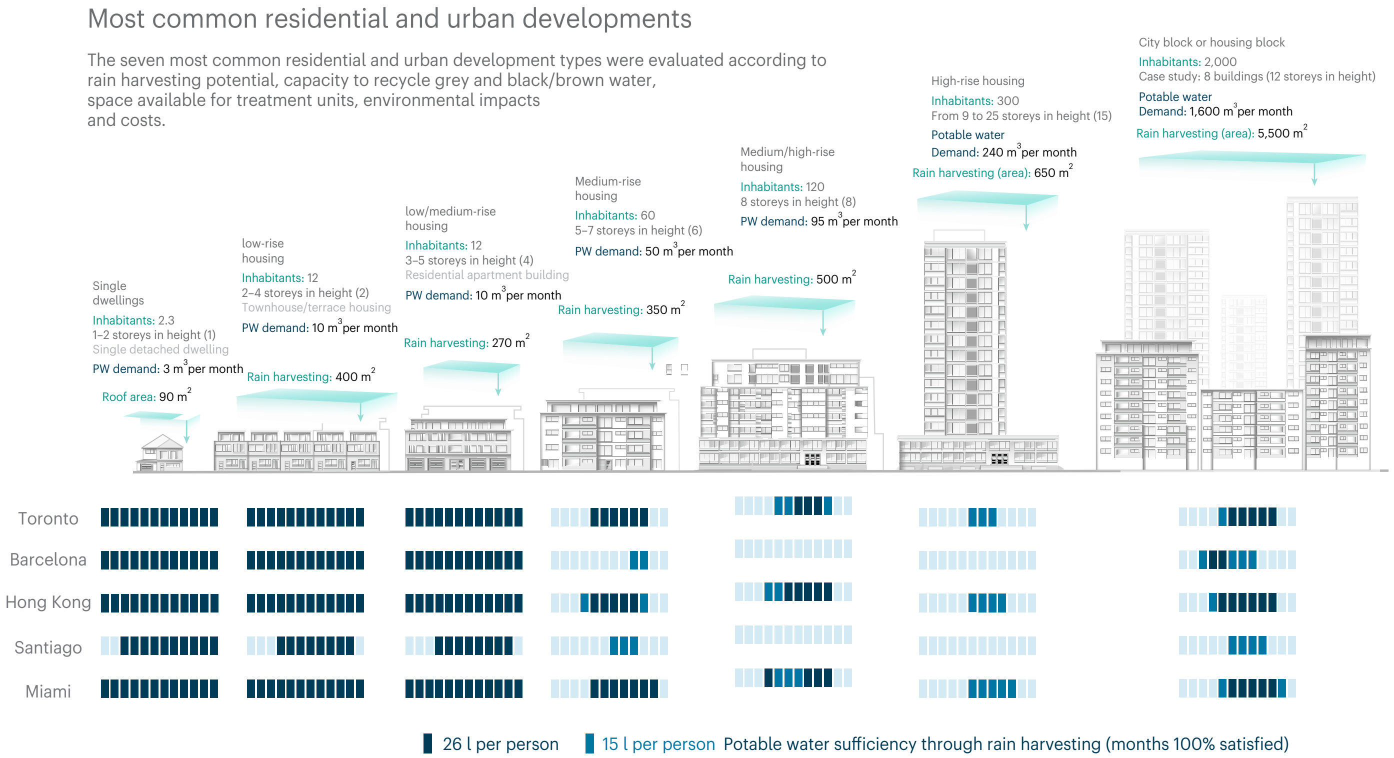


Fig. 6 | Characterization of the most common urban developments and their corresponding rain harvesting potential. Characterization of the most common residential and urban developments according to their number of inhabitants (using an average of 2.3 habitants per household), number of stories and total potable water demand (estimating 26 l per person per day); available roof area that could be used for rain harvesting (90% of available roof area); and total space (as volume) of a typical basement or underground floor for each type of development. Rainwater collection potential per type of building is depicted using coloured bars where each fraction represents a month of the year (from January to December) when demand can either be satisfied or not, depending on the location and total monthly rainfall. PW, potable water.

specialized software (for example, Capdetworks for cost estimation). The simulation results and piping design were further cross-checked with complementary software specialized in source separation modelling[66,155,156] and software to provide detailed mass and energy flow analysis[67] (Supplementary Tables 21.1–21.6).

To comprehensively assess a conventional treatment scenario, we employed two centralized models for robust comparison: (1) conventional activated sludge (CAS) with MLE configuration: the MLE process serves as a cornerstone of biological nutrient removal. For both centralized-based models and the decentralized model, we ensured an identical influent (though drawn from different streams within the overall system), a shared co-digestion approach, identical aeration setup and control parameters (ammonia-based aeration control, airflow/valve-opening logic, blower settings and so on), plus matched environmental conditions. This carefully standardized approach enables the most direct comparison for a variety of treatment performance aspects and (2) MBR as CAS: recognizing the inherent advantage of having built already the decentralized model's MBR for grey water treatment, we repurposed this modular unit within a second centralized model. For this adaptation, the MBR receives a combined brown water, food waste and grey water feed that simulates centralized sewage composition. Notably, this repurposed design retains the original MBR block, characterization, aeration and control strategies, providing a truly apples-to-apples comparison with the decentralized system.

In certain instances, unit processes or scenarios were scaled up or down to account for factors such as mass transfer limitations, efficiency variations and model constraints while remaining consistent with established modelling practices. This was particularly relevant for small-volume systems, where scaling was necessary to accurately represent key parameters such as mass transfer and residence times. The adjustments were noted in figure captions within the supplementary information.

Decentralized source separation layout overview

We compared five treatment configurations involving the use of traditional, vacuum and urine-diverting toilets (Supplementary Table 1.1). The five treatment configurations had anaerobic co-digestion as a main treatment, but some scenarios considered the treatment of black water, where no urine diversion (UD) was employed, while other scenarios considered a urine-diverting approach, where the black water stream was further divided into the yellow and brown streams and the source-separated yellow stream was treated independently under the corresponding configuration. The latter scenario of adopting urine-diverting toilets was selected for this study (city block) owing to its highest potential in economic and environmental aspects (Supplementary Table 1.3). The selected model had two main treatment trains installed in series for brown and grey water, while urine was directed towards additional equipment designed to harvest N-based and P-based fertilizers from the flow.

Once treated, the recovered water will be utilized for applications typically associated with grey water sources that are not meant for drinking purposes (for example, cleaning, gardening and showers), even if quality standards for drinking water were met. Potable water was supplied either by the conventional and centralized water supply system or by the collection and treatment of rainwater by RO, UV filtration and remineralization (for example, water-drop filter, 2021).

The incorporation of kitchen food waste (KFW) into the brown water flow was employed in some scenarios to achieve higher loads of organic matter and consequently increased biogas production in the

UASB reactor. For these scenarios, a dedicated KFW collection system should be in place, involving separate bins, under-sink disposals or other collection methods suited to the building or community context. An organic loading rate of 10 g m^{-3} was targeted for co-digestion because it offers the optimum methane conversion rate of around 62% (ref. 157). The installed reactor was expected to operate at an organic loading rate of 10.4 g m^{-3}, a temperature of 35 °C and a short hydraulic retention time of 2.6 days[157–163]. The described operation allowed the reactor to cover 55% of its energy consumption through biogas.

A single-stage oxygen-limited autotrophic nitrification-denitrification (OLAND) process was considered for the treatment of the UASB reactor effluent to remove nitrogen from the brown water stream. The biofilm surface was sized according to the influent nitrogen load. Phosphorus as struvite was recovered simultaneously in the UASB and obtained by implementing a crystallizer and a decanter where supersaturation is achieved through the maintenance of reactor pH at 8 by the addition of $Mg(OH)_2$. Calculations of effluent nutrient concentrations, struvite production, consumption of $Mg(OH)_2$, electricity demand and reactor and decanter volume are included in Supplementary Information.

After nutrient removal treatment, brown and grey water are mixed, and aerobic treatment is performed in a side-stream membrane bioreactor coupling an aerated biological treatment tank and a cross-flow, multi-tube membrane loop. A hydraulic retention time of 16.2 h and a reactor volume of 164 m^3 were used. Even if the incorporation of an MBR in the treatment layout substantially increases operational costs, the inclusion of an aerobic stage ensures adequate effluent quality. The challenge of meeting phosphorus concentration guidelines for wastewater reuse was solved by incorporating a final stage composed of a flat sheet RO membrane followed by a UV lamp. This also provides additional pathogen removal.

Urine is collected separately and stabilized in an electrochemical cell coupled with a crystallizer[164–166] without the need for added chemicals. Precipitation of around 30% of the phosphates in the wastewater, mainly calcium phosphate, is expected in the cell. The resulting stream is directed to an MABR for nitrification. The recovered concentrate from the urine treatment train is used in the vertical farm in conjunction with the rest of the harvested fertilizers (Supplementary Tables 11.7 and 11.8).

Urine-holding containers are distributed among the buildings to ensure proper collection[167]. Sludge from the UASB reactor and the MBR, as well as RO concentrate, are valorized through use in vertical farming. Costs of sludge management, including laboratory testing of soil and water, transport, application to the field and additional expenses, are included in the economic analysis[148]. KWF is pre-treated before its mixing with brown water in an agitated tank (for example, Tanks West and Fisher Scientific) by grinding and homogenization[161,168,169]. The preparation of the brown water and KFW mix is operated in batches. Holding tanks for source and treated water equalization are installed and sized according to available literature[170]. Adequate flow equalization helps optimize sizing and ensure effective treatment, as well as homogenize water quality[171].

Installation, maintenance and monitoring in new buildings are included in the costs (Supplementary Tables 18.6 and 22.9). The cost of replacement parts within the installation's studied lifespan is accounted for by considering the life expectancy of system parts[172].

Sewer infrastructure

Pipe lengths, types and costs were calculated using the Urban Water Infrastructure Model for sewers (Supplementary Tables 15.5 and 15.6). Lengths were calculated based on housing density and area, the latter of which was adapted to the floor space of each building. Pipes were assumed to originate at the centre of every housing ground floor storey. A model parameter (f_2) representing the housing shape factor was estimated for each scenario[45]. Cost scenarios for the decentralized treatment systems considered both the possibility of using existing pipelines as grey water sewers and the need to retrofit or install new infrastructure. Costs of installation for brown, yellow and rainwater sewers and of connecting the housing block to municipal water are included in all cases. High-density polyethylene (HDPE) pipes ($\o$ = 70 mm and 32 mm, respectively) were used for brown and yellow water. In the scenarios including new grey water sewers, un-reinforced concrete pipes of 110 mm in diameter were used. Rainwater is collected with HDPE pipes, and gutter and downpipes are considered to be already included in the building design[173]. Pumping to return water to households and to avoid obstructions is included for all flows, with pipes operating by gravity where appropriate. Lengths are calculated independently for each building in the block with a shape factor (model parameter f_2) of 1.44 and the corresponding housing density.

Brown and yellow streams considered existing commercially available piping concepts that allow the separation of the different wastewater streams within the existing infrastructure (Supplementary Discussion 15.4). The alternatives can split the drained streams without affecting the structural fabric of existing buildings, as new pipelines could be installed inside the existing ones following a tube-in-tube approach (or replaced with pipelines with such characteristics). A tube-in-tube approach or the so-called double inliner system would be feasible for retrofitting source separation systems into existing pipes without extensive constructive intervention[174–177].

Grey water and rainwater pipes were assumed for gravity water collection. Black water pipes were assumed to be operated also by gravity; nevertheless, preliminary studies evaluated the advantages and disadvantages of different toilet types, including conventional and vacuum toilets. The choice of toilet type markedly impacts sewer design, pumping requirements, sizing and materials. While this study focusses on urine-diverting toilets owing to their superior nutrient recovery efficiency, sewer-related details on the preliminary studies with other toilet types can be found in Supplementary Table 15.3.

Drinking water demand pipes were evaluated using the same methodology, and scenarios involving dual piping for a portion of the drinking water demand were evaluated. While a dual piping scenario could be implemented to address potential public concerns about consuming reclaimed water, this approach is not the primary focus of this study. The system is designed to produce drinking water quality for all household uses, and focussing on the dual piping scenario would not fully showcase the system's potential to efficiently reclaim and purify wastewater for all purposes. Further details regarding the piping configurations, considerations and associated costs for this scenario can be found in Supplementary Section 15.5.

Sewer methodology and calculation are detailed in Supplementary Section 2.

Cost estimation

Information from technology manufacturers and specialized costing software (that is, CapdetWorks) were used to calculate the CapEx and OpEx costs of the water and wastewater treatment systems for all scenarios (Supplementary Tables 18.5 and 18.6). Values obtained from CapdetWorks were employed for the assessment of the UASB reactor and CAS. Benefits from the recovery of nutrients and biogas were estimated and included in the economic analysis[178–181].

$$\mathrm{OpEx} = \sum_{t=1}^{T} \frac{\mathrm{OpEx}_t}{(1+r)^t} \tag{2}$$

$$I = \sum_{t=1}^{T} \frac{I_t}{(1+r)^t} \tag{3}$$

$$\mathrm{TC} = \sum_{t=1}^{T} \frac{\mathrm{OpEx}_t}{(1+r)^t} + \mathrm{CApEx} \tag{4}$$

OpEx and incomes (I) were calculated considering an interest rate (r) of 5% and a time horizon (T) of 30 years[182]. Equations 2 and 3 yield the total discounted lifetime OpEx and I, where OpEx$_t$ and I_t are the costs and incomes, respectively, at the time t. Total costs (TC) were calculated according to equation (4) integrating both OpEx and CApEx.

To evaluate the economic performance (CapEx and OpEX) of the treatment alternatives, three cost scenarios were considered for each alternative, each representing different levels of investment and operational expenses. For the presented scenario—UD—all three cost scenarios assume the collection of brown, yellow and grey water separately and all treat the flows under the same process flow diagram (Supplementary Table 1.3). The lower-cost scenario is focused on meeting regulatory permits with the basic maintenance and remote and in situ monitoring costs, and the existing piping in buildings is expected to be repurposed for the grey water stream, as it represents 80% of the total conventional household flow[183]. Moreover, the lower-cost scenario considers a highly efficient granular-based process (Nereda technology) for the grey water[184]. On the other hand, for the average-cost scenario, a MBR is used instead of the granular-based Nereda system because it is a well-established approach with high reliability, ease of operation, small space footprint and extensive data available for accurate cost quantification. Regarding the highest cost scenario, it assumes the installation of new grey water piping, state-of-the-art UD toilets from Laufen (Switzerland)[185], enhanced remote monitoring, extended laboratory capabilities, increased labour hours instead of some remote monitoring and proactive maintenance measures.

To account for the influence of electricity prices and electricity grid mix on operational costs, we considered these factors across a range of scenarios in our analysis. These scenarios incorporated different cost ranges per kWh, reflecting current averages and highs within the United States kWh (ref. 186) and Europe[187] (US \$0.14 kWh^{-1}, US \$0.24 kWh^{-1} and US \$0.34 kWh^{-1}, respectively).

Composition of flows

Per capita wastewater production was assumed to be 108 l day^{-1}, 15 l day^{-1} and 1.5 l day^{-1} for grey, black and yellow water, respectively, considering the use of urine-diverting toilets capable of recovering 70% of urine[10,24,158]. Non-recovered urine is assumed to end up in the brown water sewer. The daily average of organic food waste is 150 g People Equivalent^{-1} (Supplementary Table 4.3).

While the possibility of deviations due to specific events is acknowledged, an average composition of wastewater in the system is assumed, as presented in Table 1. Concentrations are calculated from daily constituent load per capita and are in concordance with previous studies[25,168,188–192]. Food waste composition allows calculating the final composition of the treatment trained influent[157,193,194].

The effluent composition presented in Table 2 is based on removal efficiencies and model results from SIMBA#[152]. The composition of the effluent from all simulated systems meets the guidelines established by the United States Environmental Protection Agency (US EPA) (EPA/600/R-12/618), WHO (GDWQ, 2011 and 2006) and the European Union (regulation 2020/741) for reuse in urban and bathing applications.

Vertical farming

We integrated a vertical farm with hydroponic culture methods into the water reuse infrastructure, allowing for the application of the fertilizers collected from the system to produce vegetables. Hydroponic systems use less water compared with open-field agriculture (Supplementary Discussion 26.1). They also exhibit lower supply chain-related emissions and facilitate cultivation in all environments[38,77,86,195–199]. The proposed vertical farm is based on a closed-loop concept where water and nutrients are recycled, allowing for further reduction in input requirements by employing a nutrient film technique[195,199,200].

Table 1 | Composition of black water, undiluted fresh urine considering urea hydrolysis, grey water, organic food waste and the mixture of brown water, non-recovered urine and food waste

In mg l^{-1}	BW	YW	GW	FW[a]	BrW	BrW+nrYW+FW
COD	10,500	10,400	472	286	2,490	5,437
BOD	3,560	3,870	175	218	800	2,987
TN	2,000	8,800	8.00	6.00	80.0	335
NH_4-N	1,800	463	3.00	0.8	72.0	88.5
TP	260	800	5.00	3.2	34.0	82.4
TSS	8,360	0.0	175	190	2,790	4,560
VSS	6,690	0.0	64.0	180	2,230	3,925

[a] mg g^{-1} wet basis. BW, black water; YW, yellow water; GW, grey water; FW, food waste; BrW, brown water; nrYW, non-recovered yellow water.

Table 2 | Composition of treated brown water and grey water effluent for reuse

Parameter	Effluent composition (mg l^{-1})
COD	1.24
BOD	0.65
TN	1.56
NH_4-N	0.10
N-NO_3	0.76
TP	0.04
TSS	0.02
VSS	0.01

COD, Chemical Oxygen Demand (mg l^{-1}); BOD, Biochemical Oxygen Demand (mg l^{-1}); TN, Total Nitrogen (mg l^{-1}); NH_4-N, Ammonium Nitrogen (mg l^{-1}); N-NO_3, Nitrate Nitrogen (mg l^{-1}); TP, Total Phosphorus (mg l^{-1}); TSS, Total Suspended Solids (mg l^{-1}); VSS, Volatile Suspended Solids (mg l^{-1}).

The estimated production area per crop was obtained from an optimization model that considers capital and operational costs, marketable weight per plant and harvest cycle for each crop, consumer price and per capita consumption[84–87,201]. The total cultivation area in the housing block was estimated to be 913 m^2 distributed across containerized units or by external facades. For the facades alternative, the harvest was distributed considering two facades of the block in a greenhouse-like structure and divided into four areas, each with an independent recirculation loop to facilitate pumping and nutrient uptake. The positioning of the vertical farm is subject to the local sun path in each location (for example, in Barcelona, the two facades of the block were assumed to be oriented north-east to south-west). The closed-loop system solution based on RO-demineralized water utilizes treated effluent from the reuse system. To account for evaporation and minor losses inherent in the process, make-up water is to be replaced every 10 days (ref. 202) and is pumped at a flow rate of 1.5 l min^{-1} from supply tanks located within the shared basement together with wastewater treatment and germination area. The estimated water use for vertical farming is expected to be less than 2% of the decentralized treatment capacity.

Capital and operational costs are calculated on the basis of literature and supplier data, and further details can be found in Supplementary Section 26.2.

Photovoltaic panels

The installation of solar panels was investigated in a set of cities representing the different Köppen–Geiger climates (Supplementary Table 3.1): Barcelona and Santiago de Chile (Mediterranean climate), Amsterdam (oceanic or maritime climate), Hong Kong and Miami (tropical rainforest climate), and Seoul and Toronto (humid continental climate). The photovoltaic installation was composed of direct current monocrystalline 425 W panels (SunPower) with a 20% efficiency distributed across 75% of the block roof surface. Calculations for yearly electricity output from solar installation were based on average available sun hours in the specific location and solar panel performance[203–208]. Domestic demands were estimated according to electric load sizing and verified by comparison to the country's per capita electricity consumption[186]. The size of the solar system was 900 kW and the occupied area on the roof was around 4,000 m^2. Lithium batteries (Dragonfly Energy) were assumed and sizing accounted for 1.5 backup days. The facility's power demand and sizing of direct current to alternating current inverters were dependent on the maximum expected load size considering coincidence factors per household and between all dwellings in the housing development.

Risk assessment and treatment

We employed a comprehensive risk assessment approach to guide the design of our decentralized water system (Supplementary Table 25.2). We evaluated potential hazards across various water sources (rainwater, grey water, biosolids and so on) using a detailed risk matrix and adopted validated approaches to ensure consistently high-quality water that meets recommended virus removal targets and withstand some of the challenges of small system operations[20,64]. This analysis considered microbial contamination, chemical pollutants and emerging contaminants. On the basis of this risk assessment, we tailored treatment processes (for example, advanced monitoring, high-total solids processes and confined gases management) to match the specific needs of each water source and reuse application. This approach ensures responsible resource recovery while prioritizing environmental sustainability and public health.

We understand the importance of advanced monitoring to minimize risk and build public trust. Our system incorporates a robust monitoring programme that would satisfy the most stringent water quality requirements, even if the reused water is not for direct potable consumption. While this conservative approach may increase initial costs, we believe it is crucial for public acceptance. We have conducted a detailed cost analysis of our selected monitoring approach, considering laboratory tests, sensors (CapEx and OpEx) and real-time remote monitoring (Supplementary Tables 24.1–24.5).

For further context, please note that our risk assessment and mitigation strategies are outlined in detail in the paper's Supplementary Information. We have incorporated internationally recognized guidelines (for example, the WHO and US EPA) and existing successful cases[20,64], and may consider using quantitative microbial risk assessment tools in the future. While our initial monitoring plan is designed for maximum safety, costs could potentially be reduced over time with in situ analyses, optimization based on performance data and technological advancements in sensors and control systems (Supplementary Discussion 25).

Data availability

Output data produced by our analysis are deposited in a public database available at https://figshare.com/s/8aafb87d3e2cfccacd97.

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Author contributions

M.G.-B., D.L.S. and M.P. conceived the presented idea. M.G.-B., I.B. and M.M.-S. designed the methodology, with input from M.P. and M.V., and D.R. M.G.-B., I.B. and O.S. built and ran the corresponding models, compiled all required data for their validation and carried out the corresponding analysis. M.G.-B. and D.L.S. led the writing of the manuscript, with contributions from all authors. All authors discussed the results and contributed to the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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