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From wastewater treatment plants to decentralized resource factories

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Current wastewater management practices underutilize wastewater as a valuable source of water, energy, and essential plant nutrients. A new paradigm shift is needed, one that integrates the water-energy-food nexus into wastewater management. Decentralized wastewater management has the power to redefine not only the urban water cycle but also reshape society towards a more economic and environmentally sustainable future.

Under recovery of valuable resources from managing wastewater as a silo from other relevant city functions

For over a century, centralized wastewater treatment has dominated urban sanitation. This approach relies on sewer systems to transport wastewater from cities to large, linear wastewater treatment plants (WWTPs) that prioritize pollutant removal over resource recovery. This has inherent limitations. To this day, only 11% of treated wastewater is recycled[1], and very little of its energy potential is captured[2]. The main technology, activated sludge, is an extremely energy-hungry process designed to destroy valuable nutrients instead of recovering them[3]. This process not only consumes about 1–3% of the United States of America global electricity and is a major source of greenhouse gas emissions (0.18 to 0.98 kg CO_2e per cubic meter of wastewater treated)[4], but also removes nitrogen (rather than being recovered as fertilizer) while 90% of phosphorus gets trapped in biosolids[5]. Even if the large amount of produced biosolids that need to be costly treated can eventually be used as fertilizer, they represent a fraction of recoverable nutrients, requiring complex transportation and retaining about 90% of all the microplastics captured in the sewer (up to 1% by weight)[6], so the widespread practice of using biosolids as fertilizers can contaminate soil and our daily crops with microplastics[7].

This awareness is fueling a shift toward viewing wastewater as a potential source of water, energy, and nutrients. To maximize recovery, we need to separate waste streams, stopping the practice of merging greywater and blackwater which hinders efficient recovery. We should favor anaerobic treatment (energy-producing) over energy-intensive aerobic processes and embrace a circular economy approach that integrates wastewater treatment with water reuse and resource recovery[8]. A radical change in wastewater management is needed for long-term sustainability. This "new paradigm" seeks to move away from traditional linear models and leverages systems thinking and technological advancements to contribute to restoring global carbon and nutrient cycles[9]. Extreme decentralization, treating wastewater at the building scale, holds transformative potential[8].

While the potential benefits of extreme decentralization are clear and real implementations in developed countries are starting to be a reality[10,11], practical widespread adoption remains limited[12]. This reluctance stems partly from technological inertia, a preference for familiar, albeit inefficient, infrastructure. Additional concerns include the need for dual plumbing systems, limited experience with building-scale water recycling, and potential public perception issues. While these challenges seem addressable, a more significant obstacle exists: technology lock-in. The current activated sludge process implemented in developed countries had an early lead as the most innovative technology over a century ago. Since then, it has received a constant flow of investments through the years that helped establish dominance while hindering the advancement of competing technologies. This dominance legacy is difficult to overcome due to the sunk costs of past investments and the resistance of institutions that benefit from the status quo. A similar example happened with solar power[13]. For solar power to progress to a state in which it is regarded as a standard of green energy and sustainability, it took more than four decades. Thus, as it has happened before, extreme decentralization will have to break this lock-in situation and unlock the full potential of decentralization by demonstrating the wide societal, economic, and environmental benefits.

Water-energy-food nexus approach for wastewater management & treatment

By demonstrating the broader benefits of this approach, a more sustainable and efficient future in wastewater management can be envisioned. Traditional wastewater management often approaches sanitation solely from a pollution control perspective, overlooking the critical water-energy-food nexus within urban contexts. Extreme wastewater decentralization, integrated with vertical farming and on-site renewable energy systems, positions urban areas as water, energy, and nutrient production centers – enhancing urban resilience. To fully realize and quantify these benefits, decentralized wastewater systems must be planned, designed, and evaluated holistically alongside nutrient usage and renewable energy. This approach is essential to fully understand and quantify the benefits (tangible and non-tangible) of implementing decentralized systems for wastewater management. In this context, recognizing and quantifying externalities of decentralized systems in terms of decarbonization and circular economy in urban settings is crucial for a deeper understanding of the economics of shifting from wastewater treatment to water, nutrient, and energy factories.

Climate change and its impact on water availability are a major concern, with an estimated 2.06 billion urban residents projected to face water scarcity by 2050[14]. Traditional wastewater infrastructure planning often fails to adequately consider these impacts, potentially hindering effective long-term urban planning. To address this challenge, sustainability evaluations of urban water systems must integrate several crucial factors. These include the uncertainties caused by climate change, such as shifts in precipitation and temperature patterns that directly impact water availability. Additionally, the effects of aging infrastructure on water supply and associated costs need to be carefully considered, alongside the potential for fluctuating water prices driven by both climate change-induced scarcity and the maintenance or replacement of outdated infrastructure. Transitioning to "resource factories" – facilities that recover nutrients, water, and energy from wastewater – could further impact the cost of water and wastewater services. Therefore, having a thorough socio-economic understanding of these potential price changes is vital to ensure affordability and create a just paradigm shift in wastewater management that benefits all stakeholders.

While extreme decentralization may initially gain traction in high-income countries, it holds long-term promise for various communities worldwide. Centralized water services could play a significant supporting role by providing access to tap water and sewer systems. This creates a hybrid approach where investments in decentralized solutions reduce the need for new centralized water projects, address the decreasing reliability of imported water supplies, or expand the capacity of existing sewage treatment plants[14]. A shift to hybrid urban water systems will require strong support and involvement from utilities, real estate developers, government officials, and the public. As these changes may necessitate institutional reforms and potential short-term increases in water service costs, it is crucial to highlight the broader value proposition beyond immediate benefits to users. Emphasizing the resilience, sustainability, and resource circularity aspects that hybrid water systems promote can be a key factor in garnering support. In doing so, several approaches can be adopted. Nevertheless, the first step is to create a unified narrative that positions distributed water systems as central to enhancing food security, economic development, health, and well-being. To build strong trust, transparent management and regulation of these projects are essential. Involving trusted independent oversight groups can provide additional public reassurance and scrutiny. During the initial phase of the transition, when the costs of equipment for distributed treatment systems are high and regulatory issues may cause delays and additional expenses, well-designed subsidies can alleviate financial pressure and encourage adoption. In conclusion, our current approach to wastewater management is unsustainable. Centralized treatment plants cannot afford anymore failing to utilize the valuable resources present in wastewater. A paradigm shift is necessary, we need a systemic approach that views urban areas as "resource factories" producing water, energy, and nutrients, all grounded in the water-energy-food nexus. Decentralized wastewater management offers promise, but current approaches lack a holistic perspective. To bridge this gap, hybrid systems can be initially implemented and should complement existing infrastructure. While a successful implementation will require collaboration across various entities and a commitment to reimagining our relationship with resources, this journey could unlock a future where urban centers become engines of sustainability, resilience, and innovation.

Data availability

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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M.M.S.: conceptualization; writing original draft. M.P.: conceptualization; supervision. D.R.: conceptualization; supervision. M.G.B.: conceptualization; writing original draft.

Competing interests

The authors declare no competing interests.

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