Turning Waste into Value

Digital Twin-Driven Circular Systems in Industry 5.0

What if waste wasn't waste? Here we propose embedding digital twins into circular waste systems under the Industry 5.0 paradigm, to autonomously convert discarded streams into usable value. By bridging real and virtual models, these systems can autonomously monitor, route, and regenerate materials.

The era of Industry 5.0, where human-machine collaboration meets sustainability is opening new possibilities for infrastructure. Central to this transformation are digital twins, virtual replicas that continuously mirror and predict physical systems (Ali et al., 2025). In wastewater treatment, much potential is lost, discarded streams, varying contaminant loads, and rigid controls limit flexibility (Wang et al., 2024). Among pollutants, PFAS ("forever chemicals") typify the challenge. Found in effluents from ~17 to 11,800 ng/L, they resist degradation and accumulate in sludge (Tang, 2023; Arvantiti et al., 2024). Conventional treatment technologies struggle to remove PFAS effectively, making smarter, adaptive systems essential (Amen et al., 2023). In this Perspective, we outline how embedding digital twin-driven circular systems into wastewater infrastructure can reimagine waste as a resource, optimise PFAS management dynamically, and steer infrastructures toward greater sustainability and resilience.

Industry 5.0 & Circular Economy

Industry 5.0 marks a new stage of industrial transformation, emphasising sustainability, resilience and human machine collaboration beyond the automation focus of industry 4.0. It envisions intelligent systems that complement, rather than replace, human insight, forming the foundation for environmentally restorative production models (Campana et al., 2025). Within this paradigm, the circular economy offers a pathway to reconcile industrial growth with ecological stability by maintaining materials in continuous loops and eliminating the concept of waste. This model redefines discarded by-products as inputs for new process, creating feedback-driven value chains. As recent studies highlight, digitalisation acts as the enabling layer for this transition, linking sensors, analytics, and modelling tools into adaptive control systems (Wang et al., 2024). The convergence of Industry 5.0 and circularity provides fertile ground for digital twin technologies, which can optimise circular principles through real time monitoring and predictive optimisation. (Ali et al., 2025)

What Are Digital Twins?

A digital twin is a dynamic, data-driven virtual representation of a physical system that continuously updates in real time through sensor feedback. Unlike traditional simulation models, which are static and isolated, digital twins evolve alongside their physical counterparts, mirroring changes, predicting performance, and enabling proactive control (Wang et al., 2024). Each twin integrates layers of information: sensor data, mathematical models, and AI analytics, forming a closed feedback loop where insights from the virtual model inform actions in the physical system. This interconnectivity allows operators to test scenarios digitally before implementing them, reducing risk and resource waste. In environmental engineering, digital twins have already been applied to wastewater treatment plants, where they optimise aeration, energy use, and contaminant removal in real time (Campana et al., 2025). When embedded within circular frameworks, these systems extend beyond efficiency, supporting adaptive infrastructure capable of learning, self-correcting, and aligning operational decisions with broader sustainability goals. (Ali et al., 2025)

The Global Waste Challenge

Modern waste systems are reaching their breaking point. Across the world, growing urban populations and industrial expansion have driven a surge in waste generation that existing infrastructure can no longer keep pace with (UNEP, 2022). Vast quantities of valuable materials end up buried, burned, or flushed away, symptoms of a system designed for disposal rather than recovery. Nowhere is this more evident than in the treatment of wastewater, where energy-intensive processes struggle to cope with fluctuating inflows and emerging contaminants (Wang et al., 2024). The result is inefficiency, pollution, and a dangerous complacency toward invisible threats that accumulate silently over time. Among these, PFAS compounds have become a symbol of modern waste failure: persistent, toxic, and virtually indestructible under conventional treatment (Tang, 2023). Their presence exposes the fragility of systems built for another era. Unless our infrastructure evolves to adapt and learn, today's waste challenge will become tomorrow's environmental crisis.

PFAS: A Persistent Threat

Among the many pollutants that slip through modern treatment systems, per- and polyfluoroalkyl substances (PFAS) stand apart for their persistence and invisibility These "forever chemicals" have become woven into our daily life, from non-stick cookware to waterproof fabrics and cosmetics, yet their durability in products mirrors their refusal to break down in nature. Once released into wastewater, PFAS resist conventional biological and chemical treatments, surviving every filtration stage as shown in Figure 1 (Tang, 2023). Instead, they accumulate in sewage sludge and re-enter the environment through land application or leachate (Arvantiti et al., 2024)). Traces have now been found in rivers, soil, wildlife, and even human blood, linking prolonged exposure to hormonal disruption, immune suppression, and certain cancers (Ehsan et al., 2023). Their microscopic presence creates a false sense of safety. Current

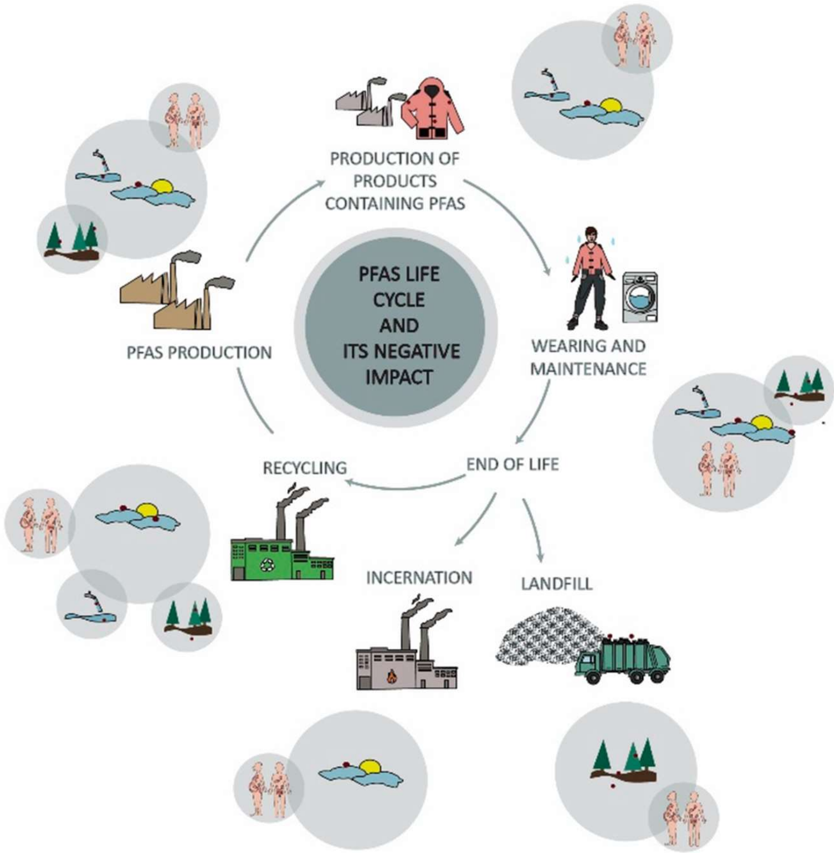

Figure 1 Lifecycle of PFAS, illustrating the circulation through production, consumer use, and end of life stages (Jeric et al, 2025)

remediation technologies remain limited, often transferring PFAS between media rather than destroying them (Amen et al., 2023). This enduring contamination exposes not only a technological failure but a moral one.

How Digital Twins Can Help

Digital twins bring into view a world where our infrastructure can listen, learn, and respond to changing conditions. In wastewater systems, a twin can continuously integrate sensor data on flow rates, pollutant concentrations, and hydraulic states to build a live, evolving model of the plant (Wang et al., 2024). That model becomes a decision engine simulating different treatment pathways, predicting PFAS hotspots, and suggesting when to switch strategies or reroute flows. A pilot study showed that pairing soft sensors with machine learning calibration let the digital twin react faster to changing influent conditions. (Force and Barillo, 2024). In a PFAS-sensitive context, the twin might simulate adsorption regeneration schedules or membrane cleaning intervals, optimising them to avoid PFAS breakthrough. Overtime, the twin refines itself having learnt from real outcomes to improve future predictions. By closing the feedback loop, digital twins make wastewater plants proactive rather than reactive, turning blind spots into actionable insights and giving us a fighting chance to manage persistent chemicals.

Mechanics of a Digital Twin Circular Economy

At the heart of a circular economy is the ability to see value where we once saw waste and digital twins make that vision possible. They mirror the physical world through data, models, and feedback: sensors capture change, simulations interpret it, and algorithms act. In wastewater plants, this means tracking contaminants, energy, and dosing while optimising recovery. When scaled across networks, twins share data on resource flows and reuse, forming digital ecosystems that make circularity tangible (Ali et al., 2025). AI integration strengthens this loop, revealing inefficiencies and new reuse pathways (Campana et al., 2025). The result is infrastructure that adapts and regenerates value with every cycle.

Case Study: Digital Twin Innovation in the Netherlands

In North Holland, the water company PWN and the regional authority HHNK partnered to protect Lake IJsselmeer from micropollutant contamination. At their Wervershoof wastewater plant, they built an advanced ozonation system supported by a digital twin developed with AM-Team's AMOZONE platform (AM-TEAM, 2023). The virtual model mirrored real operations, allowing engineering to simulate pollutant removal and optimise ozone dosage before start-up. Once online, the twin became a "digital coach", letting operators test what-if scenarios and refine treatment safely offline. The next step was real time integration, and this will enable the twin to predict pollutant levels and automatically adjust controls to balance efficiency and by-product formation. Although focused on pharmaceuticals, the project demonstrates how digital twins can manage persistent pollutants like PFAS by providing predictive control system-wide visibility. As HHNK's technologist noted, "When real-time coupling is made, we can really talk about a smart treatment plant."

Barriers and Challenges

For all their promise, digital twins are not a silver bullet. Building one requires vast amounts of high-quality data, yet in wastewater systems, sensor networks remain limited and prone to noise or calibration drift, especially for trace contaminants like PFAS (Wang et al., 2024). There's also the issue of cost and expertise. Creating a dynamic digital replica demands skilled data scientists and process engineers which are resources that many utilities lack (Core, 2024). Beyond the technical hurdles lie cultural ones, operators may be hesitant to trust algorithmic decisions over human judgement. Cybersecurity adds another layer of concern, as linking critical water infrastructure to cloud-based models introduces vulnerabilities (Campana et al., 2025). These obstacles don't diminish the potential of digital twins; rather they remind us that innovation and infrastructure evolve hand in hand. Progress will depend on investment, transparency, and a shared belief that smart systems can serve both people and the planet.

Roadmap & Future Directions

The path forward lies in uniting technology, policy, and people. For digital twins to truly transform waste and water management, investment must focus on open data infrastructure and real time sensing, particularly for emerging contaminants such as PFAS (Su et al., 2025). Advances in low-cost electrochemical and optical PFAS sensors are already showing promise for continuous monitoring, which could soon feed directly into adaptive twin systems (Wang et al., 2024). Collaboration will also be key. Partnerships between utilities, universities, and tech firms can accelerate learning and reduce cost barriers (AM-Team, 2023). The long-term goal is a federated network of digital twins, where local systems share insights globally, creating collective intelligence for pollution prevention (Campana et al., 2025). It's an ambitious vision, but one rooted in necessity. The necessity to build not just smarter systems, but wiser ones where data, engineering, and human intent align for the planet's wellbeing.

Conclusion

Digital twins are more than tools. They represent a shift in how we care for our environment. When paired with the circular economy, they turn waste into wisdom, offering a path to confront "forever chemicals" like PFAS with foresight and accountability (Su et al ., 2025; Wang et al., 2024). Their promise is simple yet profound. A future where technology can restore balance.

Key points

- *Digital twins make wastewater systems adaptive, enabling real-time decisions from live data.*
- *PFAS exposes the limits of conventional treatment and the fragility of outdated systems.*
- *Coupling digital twins with circular economy design turns waste into value through dynamic optimisation.*
- *Projects like AMZONE prove digital twins' viability in contaminant control.*
- *A global twin network could share intelligence for pollution prevention and resilient infrastructure.*

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