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Integrating silica sand recovery into wastewater treatment: Circular economy applications in GRP pipe manufacturing

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ABSTRACT

The growing global sand crisis emphasises the urgent need to identify alternative sources of silica sand. Construction-grade sand, in particular, is the most extracted solid material worldwide after water, with annual consumption reaching record levels due to rapid urbanisation and infrastructure expansion. Sand extraction is directly linked to riverbed degradation, coastal erosion, and habitat destruction, leading to severe environmental damage. In accordance with circular economy objectives, valorising quartz-rich waste through industrial symbiosis reduces both disposal costs and the demand for virgin raw materials. In addition to these environmental and economic incentives, silica's intrinsic properties also contribute to its value. In many industrial sectors, including composites and construction materials, silica (SiO_2) is valued for its mechanical strength, thermal stability, and chemical resistance. These characteristics allow it to act as a performance-enhancing material rather than a simple filler. This review presents a detailed examination of the evolving processes within wastewater treatment plants (WWTPs) that enable the recovery of silica sand in support of the circular economy. It systematically explores the origins and movement of silica sand within wastewater, the technologies used for its recovery and purification, characterisation techniques, applications in GRP pipe production, policy mechanisms that support circular flows, and areas for future research. By synthesising current scientific knowledge and presenting practical examples, this article aims to promote broader adoption of silica sand recovery and contribute to the creation of sustainable urban material systems.

Keywords: circular economy, silica sand recovery, glass fibre reinforced plastic, wastewater treatment plants, resource recovery, urban mining

INTRODUCTION

The circular economy has evolved from a theoretical idea to a practical requirement due to the rising demand for raw materials and the increasing urgency to address environmental deterioration (Geissdoerfer et al., 2017). Wastewater treatment plants (WWTPs), historically viewed primarily as public health infrastructure designed to prevent pollution, have become the vanguard of this change. A circular economy paradigm reimagines WWTPs as Water Resource Recovery Facilities (WRRFs) instead, where they recover valuable resources from wastewater in addition to treating it (Capodaglio, 2023; Neczaj & Grosser, 2018). Silica sand is one of the many materials found in wastewater that possesses a promising yet untapped potential. This material, which is frequently found in the grit collected at WWTPs, is traditionally thought of as a contaminant that needs to be eliminated in order to safeguard treatment equipment, but can in fact serve as a secondary raw material for several industries (Faragò et al., 2021; Kostrzewa et al., 2023). One creative way to incorporate material recovery procedures into sustainable manufacturing is through the creation of glass fibre reinforced plastic (GRP) pipes using recovered silica sand.

According to a study by (Tabak, 2025), grit waste recovered from WWTPs exhibited appropriate gradation and mechanical stability for use as fine aggregates in construction applications, highlighting the potential of wastewater-derived mineral fractions beyond simple landfill disposal. Their findings indicated that properly cleaned and graded grit has the potential to meet quality standards comparable to natural sand, supporting its reuse in low-load-bearing structures and non-structural concrete. The increasing interest in repurposing inorganic wastes from wastewater streams to close material loops within urban infrastructure systems is consistent with this observation.

The growing worldwide sand crisis emphasises how urgent it is to identify substitute supplies of silica sand. This type of material, especially construction-grade sand, is the most extracted solid material globally after water, with annual consumption reaching unprecedented levels due to rapid urbanisation and infrastructure expansion (United States Geological Survey, 2021). The extraction of sand is directly linked to riverbed degradation, coastal erosion, and habitat destruction, causing extensive environmental damage. Moreover, several studies have shown that sand scarcity has already begun to trigger social conflicts and illegal mining activities, a trend expected to worsen as demand continues to outstrip supply (Bendixen et al., 2021; Smigaj et al., 2025; Torres et al., 2017). Recovering silica sand from WWTPs has two advantages in this regard: it lessens dependency on unsustainable sand mining methods and generates value from a waste stream, which increases resource efficiency (Cornejo et al., 2019). The strategic use of wastewater-recovered sand in construction materials offers a dual benefit: reducing reliance on virgin sand and diverting waste toward sustainable applications (Kostrzewa et al., 2023; Tabak, 2025). While existing case studies focus on specific applications such as concrete and brick production, they collectively highlight the broader potential of recovered silica streams within a circular economy framework.

In line with the objectives of the circular economy, valorising wastes rich in quartz through industrial symbiosis lowers the cost of disposal and raw material acquisition. (Kehrein et al., 2020) reported that industrial symbiosis strategies can generate economic and environmental benefits, supporting the viability of integrating recovered resources such as silica sand into production cycles.

Beyond these environmental and economic motivations, silica's inherent material qualities also contribute to its value. In many industrial applications, including composites and building materials, silica (SiO_2) is valued for its mechanical strength, high thermal stability, and chemical inertness. These material qualities position silica as a functional contributor to product performance rather than a mere filler.

The aim of this review is to present a comprehensive examination of the transitioning processes within WWTPs that make it possible to collect silica sand for the advancement of the circular economy. This analysis systematically explores the origins and pathways of silica sand within wastewater streams, recovery and purification technologies, characterisation methods, applications in GRP pipe production, policy frameworks facilitating circular resource flows, and prospective research directions. By synthesising the existing scientific literature and highlighting practical case studies, this article seeks to support the broader adoption of silica sand recovery practices and contribute to the development of truly circular urban material systems.

WASTEWATER TREATMENT PLANTS AND THE CIRCULAR ECONOMY

Conceptual shift: from WWTPs to WRRFs

The connection between waste management, consumption, and manufacturing is reinterpreted by the circular economy. Rather than viewing waste as an endpoint, the circular economy envisions waste streams as repositories of valuable resources that can be recaptured and reintroduced into production cycles. (Capodaglio, 2023; Kaza et al., 2018) emphasised that the recovery of municipal wastewater streams can lessen the environmental impact of raw material extraction while promoting circularity. These streams are unexploited sources of rich minerals and commodities. Their findings highlight how WWTPs can operate as urban mines, generating new secondary resource supply chains while advancing sustainability goals (Neczaj & Grosser, 2018; Stahel, 2016).

Figure 1 illustrates the transformation of conventional WWTPs into WRRFs, contrasting the unsustainable linear model of extraction

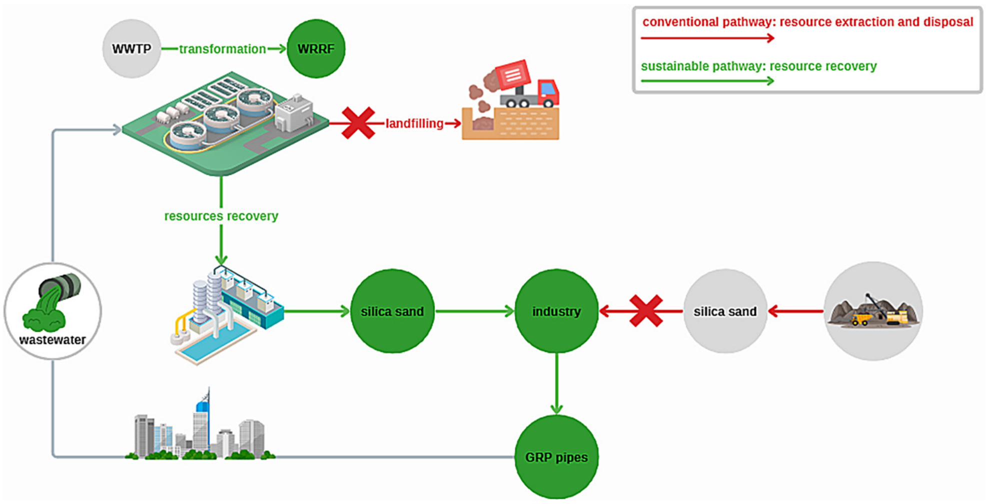

Figure 1. Circular economy pathways: sustainable resource recovery vs. conventional extraction and disposa

and disposal with a circular economy pathway based on resource recovery. This transformation encompasses the recovery of clean water, energy (as biogas), nutrients such as nitrogen and phosphorus, and various secondary materials like silica sand (Capodaglio, 2023). This integrated approach enables facilities to contribute to sustainable urban development by offsetting virgin material demand, reducing waste disposal, and generating value from materials previously considered pollutants (Neczaj & Grosser, 2018).1

Silica sand recovery as urban mining

Silica sand recovery specifically aligns with several circular economy initiatives. In order to lessen the negative environmental effects of extracting virgin resources, the process reflects the principles of urban mining, which uses anthropogenic material flows as alternative resource pools (Bendixen et al., 2021; Torres et al., 2017; United Nations Environment Programme, 2019). By recovering sand from wastewater streams, municipalities can establish local supply chains for construction materials, which decreases transportation emissions and lowers the environmental footprint of infrastructure projects (Bendixen et al., 2021; Torres et al., 2017; United Nations Environment Programme, 2019).

By lowering dependency on virgin sand extraction and incorporating recovered resources into construction, composite manufacturing, and other industries, this process enhances larger sustainability initiatives and demonstrates how material recovery and circular urban economies are intertwined (Kehrein et al., 2020).

Industrial symbiosis and sustainable development goals

The recovered sand can support industrial symbiosis strategies by linking wastewater management operations with downstream manufacturing sectors, such as GRP composite production (Kehrein et al., 2020). This interconnection amplifies the environmental and economic benefits of circular resource management and fosters resilience within urban infrastructure systems.

Moreover, the recovery of silica sand also directly supports several United Nations Sustainable Development Goals (SDGs). Silica sand recovery contributes to SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production) by promoting sustainable water management and responsible material use (Ram & Bracci, 2024). Additionally, by lowering the carbon emissions linked to the mining and transportation of virgin sand, it also has implications for SDG 13 (Climate Action) (Torres et al., 2017).

Policy frameworks enabling material recovery

Policy developments at the international level further reinforce the relevance of material recovery strategies in WWTPs (Ghisellini et al., 2016). Increased material recovery from waste streams and the development of secondary raw material markets are a crucial component of the European Union's Circular Economy Action Plan (Ellen MacArthur Foundation, 2013; European Commission, 2020). Within this framework, initiatives such as the End-of-Waste Criteria allow materials recovered from waste, once meeting defined quality standards, to re-enter the market as products rather than being classified as waste (Neczaj & Grosser, 2018). Applying such regulatory frameworks to recovered silica sand could significantly boost its marketability and promote broader implementation by industry stakeholders.

Challenges to implementation

Significant challenges remain in embedding silica sand recovery processes within existing WWTP operations (Kirchherr et al., 2017). Technical obstacles related to sand purity, process scalability, and incorporation into current treatment workflows must be overcome (Kehrein et al., 2020). Moreover, it is necessary to carefully navigate regulatory restrictions, especially those regarding material categorisation as well as health and safety regulations. Economic feasibility studies are also essential to demonstrate the cost-effectiveness of recovery operations relative to virgin material sourcing. Public perception and acceptance of "waste-derived" materials must also be actively managed through transparent communication and certification systems (Osmani, 2013). Additionally, environmental factors such as soil pH can influence the long-term mechanical integrity of GRP pipes. (Ancas & Profire, 2018) found that exposure to highly acidic or alkaline soils can reduce the mechanical performance of GRP materials, which emphasises the importance of environmental compatibility when deploying GRP pipes, including those potentially incorporating recovered silica sand.

SOURCES AND PATHWAYS OF SILICA SAND WITHIN WASTEWATER TREATMENT PLANTS

(Capodaglio, 2023) identified multiple ways mineral particles can enter wastewater streams, such as runoff from urban construction sites and industrial discharges from manufacturing facilities using sand-intensive processes. According to their research, urban development and industrial activities significantly contribute to mineral loads in municipal wastewater, shaping the composition of grit collected in treatment plants. Designing efficient recovery systems and anticipating changes in material quality requires a good understanding of these pathways.

Urban and industrial origins of silica sand

One prominent source of silica sand in wastewater systems is urban runoff. During rainfall, surface water collects dust, soil particles, and construction debris from streets, sidewalks, and unpaved areas. These sediments, which are abundant in quartz minerals, end up washed into stormwater systems or combined sewers. The contribution of silica-rich dust and other fine mineral particles is predominantly noticeable in cities undergoing increased construction activity (Bendixen et al., 2021). Industrial activities, such as manufacturing processes involving sandblasting, glass production, or ceramics, also contribute to silica sand loads in wastewater streams when residual particulates are discharged into municipal sewers. Though smaller in volume, domestic sources transported through household drains include soil leftovers carried by household drains, fine mineral particles washed off from cleaning products and deteriorated building materials.

Sand trajectories within WWTP processes

The configuration and operating procedures of the treatment facility dictate the precise paths that silica sand takes after it enters the WWTP. In preliminary treatment stages, grit chambers play a vital role in capturing heavy, inorganic solids such as sand, gravel, and small stones. Grit chambers are typically designed to maintain a flow velocity that allows heavy particles to settle while suspending lighter organic solids. Horizontal flow grit chambers, aerated grit tanks, and vortex-type grit separators are among the standard technologies used for this purpose (Judd et al., 2017). Hydrocyclone-enhanced systems further improve grit separation efficiency by utilising centrifugal forces to segregate particles based on density differences, enabling the capture of even finer sand fractions (Huang et al., 2021). Properly functioning grit chambers remove the majority of silica sand at this early stage. However, inefficiencies in grit removal can result in sand bypassing these systems and progressing into primary sedimentation tanks, biological reactors, or secondary clarifiers. Accumulations of mineral grit in these units can interfere with treatment efficiency, reduce active volumes, and necessitate costly maintenance procedures. In particular, significant grit deposition can occur over time in anaerobic digesters, creating thick inert layers that must be periodically removed to preserve process stability (Huang et al., 2021).

Role of filtration systems and spent filter media

Apart from grit chambers, silica sand is accumulated in filter beds at WWTPs that use tertiary treatment techniques such as multimedia filtration or fast sand filtration. To eliminate any remaining suspended particles and pathogens, clean water is run through layers of fine sand and other media in these systems. The sand filter media gradually become clogged with trapped particles, biofilms, and chemical precipitates, necessitating periodic backwashing and eventual replacement. Although more thorough cleaning methods are usually needed before reuse, spent filter media provide another possible use of silica sand for recovery (Jaeel & Abdulkathum, 2018).

Sand from sewer and drainage maintenance

Significant amounts of sand-laden debris are also produced by sewer system maintenance procedures like vacuuming sanitary sewers and stormwater drains. Though often mixed with organic residues and debris, sand collected during sewer cleaning can represent an additional stream of recoverable material if conveyed to WWTPs and processed appropriately (Tabak, 2025).

Specialised fine particle separation systems

In addition to standard grit removal processes, some wastewater treatment facilities employ advanced separation technologies to collect fine mineral particles that escape conventional systems. These approaches include enhanced sedimentation techniques and high-efficiency grit removal units designed to capture smaller, denser particulates. Although they make up a small portion of the total recovered sand fraction, they are a valuable addition to primary grit chambers because they increase overall mineral recovery rates and lessen the loads of abrasive materials on downstream machinery (Capodaglio, 2023; Judd et al., 2017).

CHARACTERISATION OF RECOVERED SILICA SAND

(Kostrzewa et al., 2023) reported that recovered sand from WWTP grit chambers exhibited chemical and physical properties compatible with use in non-structural concrete and mortar fillers, based on characterisation data. Their findings demonstrated that with adequate pre-treatment, grit waste could transition from a problematic residue to a viable secondary raw material, highlighting the significance of comprehensive characterisation protocols in validating material reuse.

Mineralogical composition

Mineralogical analysis, typically performed using X-ray diffraction (XRD) techniques, confirms the crystalline phases present within the recovered material. The mineralogical composition of thoroughly cleaned grit from WWTPs is dominated by quartz (SiO_2), with trace amounts of feldspar, calcite, and other silicate minerals, as studies by (Diniz Melo et al., 2011; Tabak, 2025) demonstrate. This composition is highly desirable for industrial applications, particularly where chemical inertness and mechanical stability are required.

To contextualise these findings, Table 1 summarises the silica content and notable impurities across different sand sources relevant to reuse applications. The comparison highlights how recovered sands differ from virgin industrial silica and other alternative materials in both purity and

Table 1. Typical silica content and impurities in different sand sources, compiled from Kostrzewa et al. (2023), Vijayan et al. (2023), Welz (2024)

Material	SiO_2 content	Notable impurities and characteristics
Virgin industrial silica sand	95–99%	Minor clay, heavy minerals if present
WWTP grit sand (unwashed)	50–70%	20–40% organics, Al, Fe, VOCs, RSCs
WWTP grit sand (washed)	80–95%	Residual silts, clays, trace metals, organics <2%
Spent filter media	>90%	Fe/Mn oxide coatings, increased porosity
Semiconductor waste silica	approx. 99%	Ultrafine colloidal particles in slurry

Note: *VOCs = volatile organic compounds; RSCs = reduced sulphur compounds.

contaminant profiles. This overview reinforces the importance of characterising chemical and impurity properties before selecting recovered sand for specific uses.

This mineralogical consistency is in line with the compositions reported for commercially produced GRP pipes, which list silica sand as a key filler component (International Climate Intelligence System, 2025).

Particle size distribution

Particle size distribution is another significant element. Effective size analysis, conducted through laser granulometry or traditional sieve analysis, determines whether the recovered sand falls within the target size ranges for specific applications. A particle size distribution mainly between 0.2 mm and 1.0 mm is thought to be ideal for the manufacturing of GRP composites (Diniz Melo et al., 2011). Recovered sand must therefore undergo appropriate screening to eliminate excessively fine or coarse fractions.

Organic matter content

Organic matter content is a significant quality determinant, as residual organics can compromise the performance of sand in composite matrices. The organic fraction is commonly measured via loss on ignition (LOI) tests at about 550°C. Target thresholds generally require LOI values below 5% by weight for construction applications, with even stricter criteria for composite filler use (Mazzoli & Moriconi, 2014). Advanced washing and thermal drying techniques are used to meet these requirements (Liu et al., 2017; Oliveux et al., 2015).

Environmental safety and leachability

Environmental safety assessments focus on the potential leachability of heavy metals and other contaminants. To evaluate this risk, the Toxicity Characteristic Leaching Procedure (TCLP), established by the U.S. Environmental Protection Agency (EPA), is widely applied as the standard method to evaluate the potential release of hazardous substances. Empirical studies indicate that properly cleaned grit sands from WWTPs typically exhibit heavy metal concentrations well below regulatory limits, rendering them safe for reuse (Diniz Melo et al., 2011; Oliveux et al., 2012).

Microbiological quality

Lastly, it is necessary to evaluate the presence of pathogens, particularly when considering applications where human contact with the material is possible. Thermal drying at temperatures exceeding 105°C effectively eliminates bacterial and viral contaminants, ensuring the hygienic safety of recovered sand for industrial applications (Jaeel & Abdulkathum, 2018).

RECOVERY AND PURIFICATION TECHNOLOGIES FOR SILICA SAND

Oliveux et al. (2015) highlighted the role of combined mechanical and thermal treatments in composite recycling, offering insights transferable to sand recovery processes. The review evaluated a variety of washing, screening, and drying techniques for sand reuse. Their findings emphasise the importance of combining mechanical and thermal treatments to meet industrial specifications, particularly for applications requiring low contaminant levels.

Successful recovery of silica sand from wastewater streams depends on the effective integration of a sequence of mechanical, physical, and, where necessary, chemical processes. These technologies must guarantee that the finished product meets industrial specifications while continuing to be both environmentally friendly and economically feasible. Careful integration of recovery systems into existing WWTP workflows is critical to minimise operational disruptions and maximise material yields (Kehrein et al., 2020). While the integration of material recovery presents unique challenges for municipal WWTPs, case studies from industrial sectors demonstrate the feasibility of closed-loop water and material recycling. For instance, Xu et al. (2024) discussed silica removal challenges and control strategies in reverse osmosis processes, highlighting principles that can inform circular economy approaches in industrial water treatment.

Mechanical separation techniques

As the first critical step, sand must be mechanically separated from the incoming wastewater stream. This occurs primarily in grit chambers, where flow velocities are controlled to allow dense, coarse particles to settle out. In horizontal-flow grit chambers, a combination of flow reduction and sedimentation is used to remove sands. In contrast, aerated grit tanks enhance separation by creating spiral flow patterns that encourage grit deposition. By creating centrifugal forces that separate dense particles from lighter organic matter, vortex-type grit separators increase the effectiveness of grit removal (Judd et al., 2017).

Washing and classification processes

In recent years, hydrocyclone-based grit separation systems have gained attention due to their ability to capture finer sand fractions that traditional systems may fail to gather. Strong rotational flow produced by hydrocyclones pushes dense particles outward toward the sides of a conical tank, where they spiral downward into a grit collection chamber (Huang et al., 2021). Hydrocyclones are particularly beneficial in facilities seeking to recover as many finer silica particles as possible for industrial reuse.

Once collected, the grit undergoes mechanical washing to remove organic pollutants, fine silt, and light debris. By agitating the material within a flow of clean water, spiral classifiers or grit washers separate heavier mineral particles from lighter organic matter according to density differences. Vibratory screens or oscillating sieves are then used to further sort the material by particle size, removing oversized debris and fine particles that fall outside target specifications for reuse (Liu et al., 2017; Pickering, 2006). The recovery of sand within WWTPs depends strongly on the efficiency of each treatment stage. Table 2 provides an overview of the typical removal efficiencies and particle size ranges captured at key stages of treatment. This information is critical for understanding how each process contributes to the overall yield and quality of recovered sand.

Density and magnetic separation enhancements

Float-sink tanks and other density separation methods are occasionally employed to enhance the removal of remaining organic fractions. Magnetic separation units may also be incorporated where ferrous contaminants, originating from corroded pipes or industrial discharges, are present. These processes collectively refine the sand to a composition closely resembling natural aggregates used in construction (Oliveux et al., 2015).

Thermal drying and sterilisation

Recovered sand from WWTP sludge is typically subjected to thermal drying and chemical washing to reduce organic content and improve material quality prior to reuse. Such conditioning processes help reduce moisture and contaminant levels, ensuring compliance with leaching limits (Tabak, 2025). Moisture reduction is particularly important when the sand is intended for use as a filler in resin-based composites, where excessive water can interfere with resin curing, weaken interfacial bonding, and compromise the mechanical performance of the final product (Yang et al., 2012).

Modern WRRFs often incorporate combined heat and power (CHP) systems to enhance energy recovery, and the resulting waste heat can be repurposed for auxiliary processes such as sludge or sand drying (Capodaglio, 2023).

Chemical treatment for high-purity applications

For uses such as the production of optical glass or electronic components that require exceptionally high silica purity, chemical treatments, including acid washing with diluted hydrochloric or

Table 2. Efficiency of sand recovery at different WWTP treatment stages, compiled from Huang et al. (2021), Judd et al. (2017), Liu et al. (2017).

Stage/Equipment	Particle size removed	Removal efficiency (benchmarked at the smallest particle size)
Screening (bars/screens)	>5 mm	Not applicable (protective function)
Grit chamber (gravity/vortex)	>200 μm	Approx. 95% at 200 μm
Grit chamber (fine sand 100–150 μm)	100–150 μm	Approx. 70–80% at 100 μm
Hydrocyclone	50–100 μm	Approx. 70% at 50 μm
Sand washer/classifier	organic removal	Organic content reduced to <2%
Tertiary filtration	ultrafine suspended solids (<50 μm)	Approx. 99% TSS* removal at <50 μm

Note: *TSS = total suspended solids.

sulfuric acid solutions, may be used. However, for applications like GRP pipe production, mechanical and thermal purification processes are generally sufficient to meet quality standards, provided that proper operational protocols are followed (Diniz Melo et al., 2011). Additionally, membrane-based systems combining ultrafiltration and bipolar membrane electrodialysis have been explored for recovering high-purity silica and fluoride from industrial wastewater, offering potential for advanced applications (Vijayan et al., 2023).

APPLICATIONS OF RECOVERED SILICA SAND

Construction uses

Kostrzewa et al. (2023) reported that the physical and chemical properties of washed WWTP grit sands align with standard specifications for fine aggregates in non-structural concrete and mortar fillers, suggesting potential suitability. Beyond concrete and mortar, recovered silica materials have demonstrated potential in other construction applications. Tabak (2025) evaluated the incorporation of wet silica sludge into clay brick manufacturing, achieving favourable compressive strength, porosity, and water absorption at up to 50% replacement levels. Those findings suggest that silica-rich by-products from wastewater treatment may serve as supplementary materials in fired ceramic products, and potentially inspire related strategies for other construction materials.

Similarly Job (2013), Oliveux et al. (2015) and Pickering (2006) highlighted opportunities to integrate recycled fillers into cementitious matrices, supporting their valorisation in diverse building materials. Additionally, Smigaj et al. (2025) noted that recovered sand from municipal waste streams is well suited for uses such as road sub-base layers and trench backfilling, provided it meets standard performance criteria through basic assessment.

Filtration applications

Recovered silica sand has shown promise as a filtration medium in the field of industrial water treatment. Reclaimed sand can be utilised again in multimedia filtering systems and quick sand filters following the proper reconditioning process, which includes cleaning and thermal sterilisation. Recovered sand retained high hydraulic conductivity and particle retention capacities, making it appropriate for continued service in tertiary treatment and industrial process water recycling systems (Jaeel & Abdulkathum, 2018; Welz, 2024). Moreover, Huang et al. (2021) observed that grit fractions recovered from wastewater treatment maintained effective filtration performance when adequately washed and graded.

GRP pipe production

Recovered silica sand offers significant potential for integration into composite material manufacturing, particularly for the production of GRP pipes, where silica sand is widely used as a standard filler material (Ancas et al., 2021; Diniz Melo et al., 2011; International Climate Intelligence System, 2025).

GRP pipes are typically produced using either filament winding or centrifugal casting techniques. While thermal and mechanical treatments guarantee low organic content and minimal moisture, which are essential for achieving good resin-sand bonding and uniform dispersion within the composite matrix, mineralogical analyses validate the dominance of inert quartz phases (Diniz Melo et al., 2011).

Although Tabak (2025) focused on incorporating wet silica sludge into clay brick manufacturing rather than polymer composites, their findings of favourable mechanical performance support the broader feasibility of valorising recovered silica in construction materials.

A complementary example is provided by Osmani (2013), who investigated the reuse of ground GRP waste in composite and concrete applications. Their findings, alongside those of Yang et al. (2012), showed that recycled composite fillers could be reintegrated with acceptable mechanical performance for specific applications. While these studies focused on recycling composite waste rather than external silica sources, they reinforce confidence in the broader feasibility of substituting recovered silica sand for virgin sand in GRP pipe manufacturing.

Environmental and economic benefits

Substituting recovered sand for virgin sand in GRP production has substantial environmental benefits. Manufacturers can lessen the carbon footprint of their raw materials, decrease the ecological damage caused by sand mining, and help create more sustainable supply chains by lowering their dependency on recently extracted sand, aligning with broader resource recovery and sustainability goals (Cornejo et al., 2019; Torres et al., 2017). In addition, the usage of urban-mined materials enhances material security and reduces vulnerabilities associated with fluctuating worldwide sand markets (Bendixen et al., 2021; Torres et al., 2017).

ECONOMIC AND OPERATIONAL PERSPECTIVES ON FULL-SCALE SILICA SAND RECOVERY

Economic feasibility of resource recovery

Techno-economic analysis (TEA) is a fundamental tool for assessing the feasibility of integrating resource recovery technologies into wastewater treatment plants (WWTPs). According to Clack et al. (2024), TEA bridges engineering performance with financial viability by quantifying capital investment, operational costs, and potential revenue streams. As explained by Udugama et al. (2017), applying TEA in WWTPs allows stakeholders to identify high-value recovery opportunities embedded in waste streams, promoting efficient system upgrades that align with circular economy goals.

While many recovery technologies demonstrate promising environmental benefits, they frequently struggle to achieve financial viability. For example, Calicioglu et al. (2021) showed that wastewater-derived duckweed biorefineries reduced eutrophication potential but remained economically unfeasible due to high capital and operational costs. Wong et al. (2023) similarly reported that nutrient recovery systems in sub-Saharan Africa offer agronomic benefits yet face market and infrastructure barriers that hinder adoption. These cases reveal a critical insight: strong environmental performance does not automatically translate into viable investment, reinforcing the importance of TEA to identify and address economic bottlenecks early in development. In the context of silica sand recovery, these same principles apply, where economic viability must be demonstrated through clear metrics and localised assessments before implementation at scale.

To quantify profitability, TEA employs key indicators such as net present value (NPV), internal rate of return (IRR), and payback period. Al-Sayed et al. (2023) reported a payback time of nearly eight years for a membrane bioreactor system designed for water reuse, illustrating the long-term financial planning required for such investments. As noted by Kehrein et al. (2020), market incentives and policy frameworks can significantly influence outcomes by improving returns or reducing reliance on conventional energy. Taken together, these metrics help determine not only whether a technology is viable, but also how sensitive it is to real-world conditions, enabling informed and scalable decision-making.

Insights from circular bioeconomy technologies

Technologies developed under the circular bioeconomy provide valuable guidance for designing and implementing inorganic resource recovery systems in wastewater treatment plants (WWTPs), including the recovery of silica sand. Approaches such as nutrient recovery, cellulose extraction, and biochar production illustrate how waste can be reimagined as a resource through integrated processes that optimise environmental and economic outcomes. These technologies, as demonstrated by Barragán-Ocaña et al. (2023), show transferable methodologies for silicate recovery, especially in how they enhance input efficiency, minimise waste, and embed recovery within existing WWTP operations.

Biorefineries offer a model for such integration by transforming organic waste into fuels and high-value products. Barragán-Ocaña et al. (2023) emphasise the role of biorefineries in shifting industrial processes toward complete valorisation of inputs. Comparable strategies can be applied to WWTPs by adapting these recovery logics to inorganic streams such as sand and grit. For instance, Ruiz et al. (2020) describe how hydrothermal pretreatment, typically used for biomass fractionation, could be repurposed to process silicate-rich sludge without relying on aggressive chemicals. Székács (2017) adds that such adaptations align with circular principles by maintaining material purity while reducing environmental impact.

The economic frameworks behind biorefinery development further strengthen the relevance of this comparison. Ou et al. (2021) state that techno-economic analysis of biomass recovery systems helps identify the conditions under which resource recovery becomes financially viable. The same analytical rigour is needed for silica sand recovery, where costs must be weighed against revenue from secondary raw materials. Krassnitzer et al. (2023) point out that advanced recovery technologies can reposition WWTPs as hubs for material generation rather than waste disposal. By following this example, silica recovery can become both technically feasible and economically justified.

Barriers and drivers in real-world integration

The integration of silica sand recovery systems into wastewater treatment plants (WWTPs) is shaped by a complex mix of financial, regulatory, and technical factors. According to Kehrein et al. (2020), high capital costs remain one of the most significant barriers, as installing new recovery infrastructure requires substantial investment that smaller municipalities often cannot afford. You et al. (2023) note that market fluctuations for recovered materials, such as nutrients or construction-grade sand, add uncertainty to the return on investment, making plant operators hesitant to commit. Regulatory barriers can be equally limiting. As explained by Neczaj & Grosser (2018), unclear rules surrounding recovered material quality or conflicting effluent discharge requirements can delay or even block adoption. Technical issues further complicate matters, since wastewater composition varies between locations and no single recovery method is universally effective, particularly when scaling up from pilot to full-scale systems (Chen et al., 2023; Mannina et al., 2022).

Examples from other recovery technologies demonstrate that these challenges are not insurmountable. Van der Hoek et al. (2018) describe the Energy and Raw Materials Factory in the Netherlands, where cellulose, bioplastics, and other materials are recovered through modular system upgrades. A similar staged approach could reduce financial risk for silica sand recovery, allowing operators to validate performance before full deployment. Innovations such as bioelectrochemical systems (Cerrillo et al., 2023), mobile nutrient recovery units (Kyllönen et al., 2021), and microalgae-based processes for nutrient removal (Goh et al., 2022) show how technology can address both operational and economic bottlenecks. These cases also highlight the importance of stakeholder engagement, as regulatory alignment and market positioning are more easily achieved when industry partners, policymakers, and the public are actively involved.

Key drivers for adoption include environmental co-benefits, scalability, and revenue potential. Mannina et al. (2021) emphasise that recovering multiple resources in parallel, such as treated water, nutrients, and silica, improves environmental outcomes while generating new income streams. Modularity, as discussed by Neczaj & Grosser (2018), allows plants to expand capacity incrementally in line with market demand and available funding. Supportive regulations, funding programmes, and tax incentives can further lower investment risks (Mannina et al., 2021). Wang et al. (2015) point out that advances in filtration materials and process integration reduce operational costs while boosting recovery efficiency. Finally, by positioning WWTPs as resource hubs connected to industries like construction, where high-purity sand is in demand, recovery projects can secure stable markets, reinforcing both their economic and environmental value (Tongur & Atmaca, 2024).

Evaluation tools for feasibility and optimisation

Multi-criteria decision analysis (MCDA) is a key method for assessing the feasibility of resource recovery systems in wastewater treatment plants (WWTPs), as it integrates environmental, technical, and socio-economic factors into a structured evaluation. According to Omran et al. (2021), defining criteria such as contaminant removal efficiency, emissions reduction, cost-effectiveness, and operational performance allows stakeholders to balance conflicting priorities. Saghafi et al. (2019) note that MCDA is particularly valuable when comparing treatment technologies with different recovery potentials. Methods such as the analytic hierarchy process (AHP) and preference ranking organisation method for enrichment evaluations (PROMETHEE) provide adaptable frameworks that can be refined to reflect local socio-economic and environmental contexts (Vivas et al., 2019; Ziemba, 2022).

Cost-benefit analysis (CBA) and life cycle assessment (LCA) complement MCDA by focusing on financial and environmental performance, respectively. CBA quantifies capital and operational costs alongside revenues from recovered resources, as illustrated by Santos et al. (2021) in wastewater company performance analysis. LCA evaluates impacts such as greenhouse gas emissions, energy use, and biodiversity effects throughout a technology's life cycle Davis et al.

(2019). Bryant & Coats (2021) showed that phosphorus recovery can remain strategically important despite increased emissions, while Cornejo et al. (2016) demonstrated how scaling can improve both cost-efficiency and sustainability. Together, CBA and LCA reveal trade-offs that might be overlooked if economic and environmental assessments are conducted separately.

These tools are increasingly applied to inorganic material recovery, including sand and grit. Nagy et al. (2023) demonstrated how MCDA can rank recovery configurations based on rates, costs, and environmental impacts, while Furness et al. (2023) combined LCA with MCDA to assess sustainability in wastewater management. Kamble et al. (2017) also integrated fuzzy multi-criteria decision-making into LCA to evaluate municipal wastewater treatment technologies relevant to grit recovery. Scenario-based MCDA has been used to incorporate sand and grit recovery into urban wastewater planning (Zheng et al., 2016). As Omran et al. (2021) emphasise, combining MCDA, CBA, and LCA offers a robust decision-support framework for ensuring that inorganic recovery strategies are both economically viable and environmentally sustainable.

Policy, funding, and institutional support

Transforming WWTPs into WRRFs depends on policies that frame wastewater as a resource, not just waste (Duque et al., 2021). Instruments like the EU Circular Economy Action Plan set recovery targets and support adoption through funding and technical assistance, while India's National Draft Water Reuse Norms 2024 highlight similar priorities (Salmina et al., 2023). Such measures work best when combined with governance models linking municipalities, industry, and communities, but they must also fit local infrastructure capacities, a gap noted by Neczaj & Grosser (2018).

Financing is central to feasibility. Grants under the European Green Deal lower capital risk for recovery projects and can improve utilities' financial positions (Santos et al., 2021; Smol et al., 2025). Public–private partnerships combine municipal mandates with private investment, enabling faster deployment (Kehrein et al., 2020). Locally, performance-based funding and eco-taxes can reward high recovery rates (Cerrillo et al., 2023), while international development finance has funded grit and sand recovery upgrades in lower-income regions (Chen et al., 2023).

Institutional backing also requires pilot projects, training, and public engagement. Demonstrations help bridge policy goals with operational practice (Qtaishat et al., 2022), and public awareness campaigns can increase acceptance of products from recovered materials (Salmina et al., 2023). Clear rules, targeted funding, and coordinated institutions together reduce adoption barriers, allowing sand and grit recovery to deliver economic and environmental benefits (Montwedi et al., 2021).

Case studies and pilot projects

Case studies and pilot projects showcase the technical and economic feasibility of diverse resource recovery processes in wastewater treatment plants, providing valuable insights applicable to grit and sand recovery. According to Mannina et al. (2021), a pilot plant optimised multi-resource extraction by integrating operational and financial considerations to inform full-scale adoption. In industrial runoff trials, Blondeel et al. (2015) showed that combining sand–anthracite filtration with coagulation and flocculation can achieve high removal efficiencies, providing a basis for scalable grit recovery. Studies of particle behaviour also matter: Judd et al. (2017) found that mixed organic and inorganic particles alter settling properties, which pushes designs toward tailored configurations, and operational analyses of grit chambers confirm this need for configuration-specific optimisation (He et al., 2022).

Building on these findings, analogous resource recovery efforts demonstrate strategies and design principles that can be directly adapted for silica sand recovery. Patziger (2021) applied computational fluid dynamics to guide design improvements that raise grit separation efficiency, and Ansari et al. (2017) identified forward osmosis as an additional recovery pathway from municipal wastewater. Reuse routes are already practical: Borges et al. (2015) found that washed grit-chamber sand can serve as a sustainable construction aggregate with high fixed solids content, reducing disposal needs and creating a saleable product.

Techno-economic assessments from pilot and full-scale projects reinforce the financial and operational viability of resource recovery. Mannina et al. (2022) demonstrated that optimising anaerobic digestion in water resource recovery facilities reduced energy costs and improved overall efficiency. Bouzas et al. (2019) reported that struvite crystallisation achieved about 90% recovery efficiency with a payback period of roughly three years, providing a strong return on investment. High-rate algal pond systems, described by Craggs et al. (2014), removed up to 95% of nitrogen while lowering operational expenditure, and anaerobic membrane bioreactors demonstrated similar benefits by increasing energy yields and reducing running costs in separate studies by Ugwuanyi et al. (2024) and Robles et al. (2021).

FUTURE RESEARCH DIRECTIONS AND TECHNOLOGICAL DEVELOPMENTS

According to (Kehrein et al., 2020), public-private partnerships could accelerate the integration of recovered sand in industrial supply chains by lowering investment risks and encouraging innovation. Their analysis stressed the importance of multi-stakeholder collaboration in overcoming financial, regulatory, and technical hindrances, especially in emerging markets where circular material practices are still developing. Co-investment in recovery infrastructure, cost-sharing arrangements, and joint ventures between downstream companies and wastewater utilities could all be made possible by such partnerships.

A promising but still emerging field of practice is the recovery and repurposing of silica sand from WWTPs for industrial uses, especially in GRP pipe production. For widespread adoption as well as integration into existing industrial and municipal frameworks, several fields require targeted research, technological innovation, and policy development (Kehrein et al., 2020; Oliveux et al., 2015).

Scaling up recovery systems

The scaling up of recovery processes from pilot or demonstration projects to full-scale operational models is a top research objective. While numerous studies have validated the technical feasibility of recovering and reusing WWTP-derived sand at laboratory and small-plant scales (Kehrein et al., 2020; Oliveux et al., 2015), full industrial integration remains limited. Therefore, the goal of future research should be to create scalable, modular sand recovery units that can be installed into existing WWTP infrastructures without seriously interfering with primary treatment procedures. In addition, long-term operational studies are required to estimate the durability, maintenance requirements, and lifecycle costs associated with integrated sand recovery systems.

Environmental and economic assessments

Another crucial topic is the thorough evaluation of the financial and environmental advantages of silica sand recovery. Life cycle assessments (LCA) that compare recovered and virgin sand across indicators, including embodied energy, greenhouse gas emissions, and ecosystem impacts, are crucial to build a strong environmental case for adoption. Similarly, techno-economic analyses (TEA) that include capital expenditure, operational costs, savings from reduced virgin material procurement, and potential revenue from sand sales will be necessary to convince municipal decision-makers and private investors of the viability of such systems (Capodaglio, 2023; Cornejo et al., 2019).

Technological innovations

Technological innovation can further improve recovery efficiencies and broaden application potentials. Advanced real-time monitoring systems employing machine learning algorithms could optimise grit chamber operations for maximal mineral capture under varying influent conditions. Low-energy drying technologies, including solar-assisted or waste heat-powered drying systems, offer promising avenues to reduce operational costs and carbon emissions associated with material preparation (Vijayan et al., 2023).

Policy and standardisation needs

There is an immediate need for clear criteria and certification programs for recovered sand on the regulatory front. In addition to facilitating market adoption, quality standards that outline permissible levels for pollutants, particle size distributions, and mechanical properties will serve to enhance market acceptance and reduce perceived risks among end-users. Additionally, establishing clear pathways for granting end-of-waste status to recovered sands will eliminate legal ambiguities that currently prevent innovation and investment in this field (Kehrein et al., 2020; Neczaj & Grosser, 2018).

Public perception and acceptance

As a final point, proactive measures are in order to improve public perception. Even with technical validation, materials derived from waste streams often face societal scepticism. Educational initiatives, transparency in material testing and certification, and prominent flagship projects showcasing successful applications of recovered sand in well-known infrastructure or industrial projects can help foster acceptance or even enthusiasm towards circular material solutions (Kehrein et al., 2020; Osmani, 2013).

CONCLUSIONS

The conversion of WWTPs into WRRFs presents an unmatched chance to integrate municipal infrastructure with the principles of the circular economy. Silica sand recovery represents a particularly compelling facet of this transformation, providing a pathway to reduce dependence on unsustainable virgin sand extraction, mitigate environmental degradation, and valorise a waste stream historically viewed as a nuisance.

Scientific evidence demonstrates that silica sand recovered from wastewater treatment processes meets the physical, chemical, and environmental criteria necessary for integration into high-value industrial applications, notably in the production of GRP pipes. The technologies required for sand recovery, including grit separation, mechanical washing, particle sizing, and thermal drying, are mature, readily adaptable to existing WWTPs, and capable of producing materials of industrial-grade quality.

The potential of recovered sand is further supported by analogies drawn from other recycling fields, such as the reuse of ground GRP waste in new composites, and by cross-sector examples like the valorisation of wet silica sludge in brick production. These examples reinforce the position that recovered silica can effectively replace virgin sand in composite production procedures without sacrificing the quality of the final product.

There are still obstacles to overcome in the areas of public acceptance, economic viability, legal frameworks, and scaling up. Nonetheless, targeted research, supportive policy development, and pilot-scale implementation projects can accelerate the widespread adoption of recovered silica sand, thereby integrating circular economy principles into industrial manufacturing and wastewater management.

Building on these findings, the expanded analysis of economic and operational perspectives highlights specific pathways to address the remaining barriers to silica sand recovery. Robust techno-economic analysis, combined with market alignment and targeted institutional support, can transform initial feasibility into long-term viability. Insights from circular bioeconomy technologies show that modular and staged integration into WWTP operations reduces capital risk and facilitates progressive scaling. Evaluation tools such as multi-criteria decision analysis, cost–benefit analysis, and life cycle assessment enable optimisation and informed trade-off decisions, while case studies demonstrate that operational efficiency and market readiness can be achieved under real-world conditions. Together, these strategies position silica sand recovery as both an environmentally beneficial and economically sound component of circular urban infrastructure.

By embracing silica sand recovery, cities can move closer to achieving sustainable resource management, improving material security, and building resilient, circular urban ecosystems. In addition to addressing current environmental and economic issues, this transition creates the framework for long-term changes that will lead to a regenerative urban future.

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