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Sewage sludge valorisation and resource recovery: Emerging technologies, contaminant fate, and future perspectives

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ABSTRACT

The increasing generation of sewage sludge and the demand for more sustainable waste management have shifted attention from conventional disposal towards resource recovery and sludge valorisation. Sewage sludge contains substantial amounts of organic matter, nutrients and mineral components that can be recovered as energy, fertilizers and value-added materials. However, the presence of heavy metals, pharmaceuticals, per- and polyfluoroalkyl substances (PFAS), microplastics and other contaminants may constrain the safe application of recovered products and influence the overall environmental performance of valorisation processes. This critical review evaluates current and emerging pathways for sewage sludge valorisation, focusing on energy recovery, nutrient recovery, carbon-based products, mineral and material recovery, and integrated sludge biorefinery concepts. The pathways are assessed in terms of resource recovery potential, product characteristics, energy and chemical requirements, contaminant fate, residual streams and technological maturity. Particular attention is given to the distinction between contaminant removal and destruction and to the potential transfer, transformation or concentration of contaminants during sludge processing. The analysis indicates that no single valorisation pathway can be considered universally sustainable, as its environmental performance depends on sludge characteristics, process conditions, target products and residua stream management. Integrated approaches combining energy, nutrient and material recovery may provide greater resource efficiency, provided that contaminant fate and product quality are adequately controlled. Future development should therefore prioritize simultaneous assessment of resource recovery efficiency, product quality, contaminant behaviour and overall environmental performance rather than focusing on recovery yields alone.

Keywords: environmental risk assessment, resource recovery, circular economy, contaminant fate, environmental sustainability.

INTRODUCTION

The expanding deployment of wastewater treatment technologies has resulted in increasing sewage sludge generation, making sludge management an important environmental and resource challenge. Rather than being considered solely a residual material requiring disposal, sewage sludge contains organic matter, nutrients and mineral components that can potentially be recovered and converted into energy, secondary raw materials and value-added products. Consequently, sludge management has progressively shifted from conventional disposal towards resource recovery and valorisation, particularly within circular economy (Figure 1) and circular bioeconomy frameworks. Current valorisation pathways include energy and organic carbon recovery, nutrient recovery, production of carbonaceous materials, and recovery of mineral and construction-related resources. The potential of these pathways, however, depends on sludge composition, resource characteristics, process configuration, energy and chemical requirements, and the management of residual streams (Cecconet and Capodaglio, 2022).

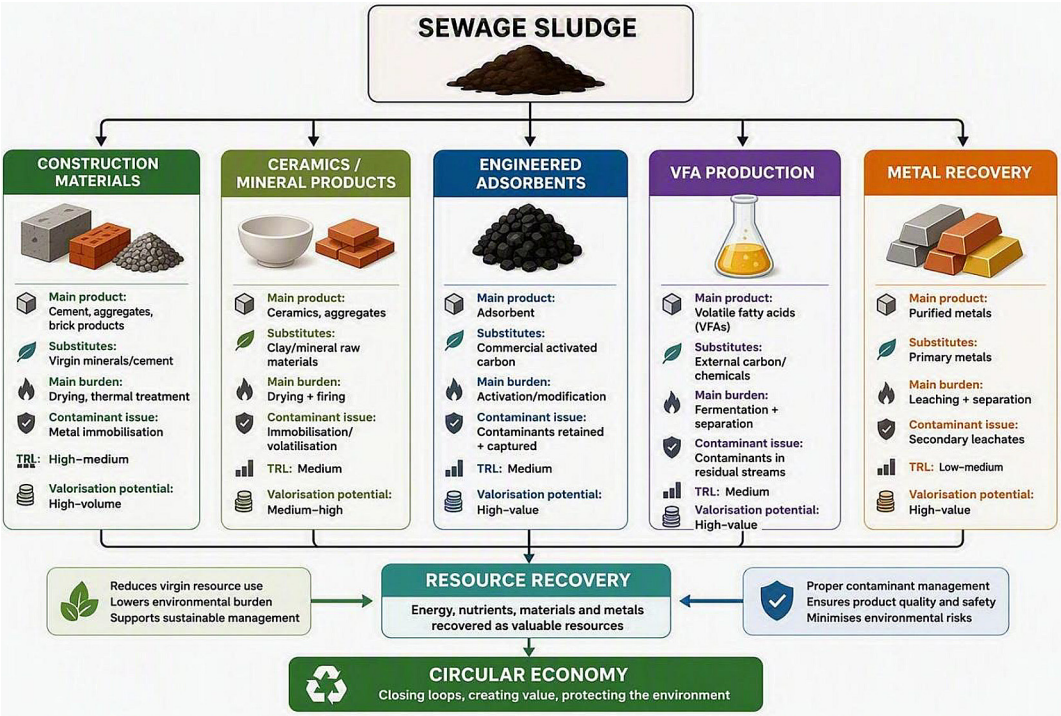

Figure 1. Sewage sludge recovery products in the circular economy (prepared with the assistance of an AI graphical tool)

Among the resources present in sewage sludge, organic matter and phosphorus have received particular attention. Organic matter can be converted into biogas or other energy carriers through biological and thermochemical processes, or used as a precursor for carbonaceous products such as biochar and hydrochar. Phosphorus is of particular interest because its recovery can contribute to the production of secondary phosphorus resources and reduce dependence on primary mineral sources. However, the recoverability and quality of phosphorus-containing products depend on its chemical speciation and association with mineral phases, particularly iron, aluminium and calcium (Yu et al., 2021a, Yu et al., 2021b). The development of integrated sludge biorefineries has further expanded this concept by combining several recovery pathways within a single process chain. Such integration may increase resource utilization, but it may also increase process complexity, energy and chemical requirements, and the number of residual streams requiring management.

A major challenge for sludge valorisation arises from the simultaneous presence of valuable constituents and contaminants. Sewage sludge may contain heavy metals, pharmaceuticals, per- and polyfluoroalkyl substances (PFAS), microplastics, pathogens and other contaminants of emerging concern. Their presence is particularly relevant when sludge-derived products are intended for agricultural or environmental applications. Previous studies have shown that contaminants may persist through conventional stabilization processes and may be retained, transformed or redistributed during subsequent treatment (Sánchez et al., 2022, Casella et al., 2023, Saliu and Sauvé, 2024). Consequently, contaminant behaviour must be considered alongside resource recovery when assessing the environmental performance of sludge valorisation pathways.

An important distinction in this context is that contaminant removal from the original sludge matrix does not necessarily represent contaminant destruction. Depending on the contaminant and process conditions, processing may result in degradation, transformation, immobilization, volatilization, transfer to another phase or concentration in a recovered product or residual fraction. This distinction is particularly relevant for thermochemical and hydrothermal processes, where contaminants may exhibit different patterns of redistribution among solid, liquid and gaseous streams (Nahar et al., 2024). Similarly, the environmental suitability of sludge-derived carbonaceous products depends not only on their material properties

but also on the concentration, chemical form and environmental availability of residual contaminants (Zhao et al., 2023). Thus, high recovery efficiency for a target resource does not necessarily indicate an overall environmental benefit.

The assessment of sludge valorisation therefore requires consideration of several interconnected factors, including resource recovery, product quality, contaminant fate, energy and chemical requirements, residual-stream management and the intended end use of recovered products. This is particularly important because different pathways may involve distinct trade-offs. For example, thermal treatment may facilitate energy or carbon recovery while concentrating inorganic contaminants in solid products, whereas nutrient recovery may produce more defined secondary raw materials but require chemical inputs and generate secondary liquid or solid streams. Similarly, agricultural reuse may return nutrients and organic matter to soils while creating potential pathways for environmental exposure to residual contaminants. These trade-offs make direct comparison among valorisation pathways difficult, particularly because studies frequently apply different system boundaries, performance indicators and definitions of recovery efficiency.

Although numerous studies and reviews have examined individual aspects of sewage sludge valorisation, including phosphorus recovery, sludge-derived carbonaceous materials, thermochemical treatment, agricultural applications and sludge biorefineries (Yu et al., 2021a, Zhao et al., 2023, Cecconet and Capodaglio, 2022, Nahar et al., 2024), an integrated comparison linking resource recovery with product quality, contaminant fate and residual-stream management remains necessary. In particular, the sustainability of integrated sludge biorefineries should not be assumed solely from the number or efficiency of recovered products, because additional process stages may alter contaminant partitioning and increase energy, chemical and residual-management requirements. Accordingly, this review critically evaluates current and emerging pathways for

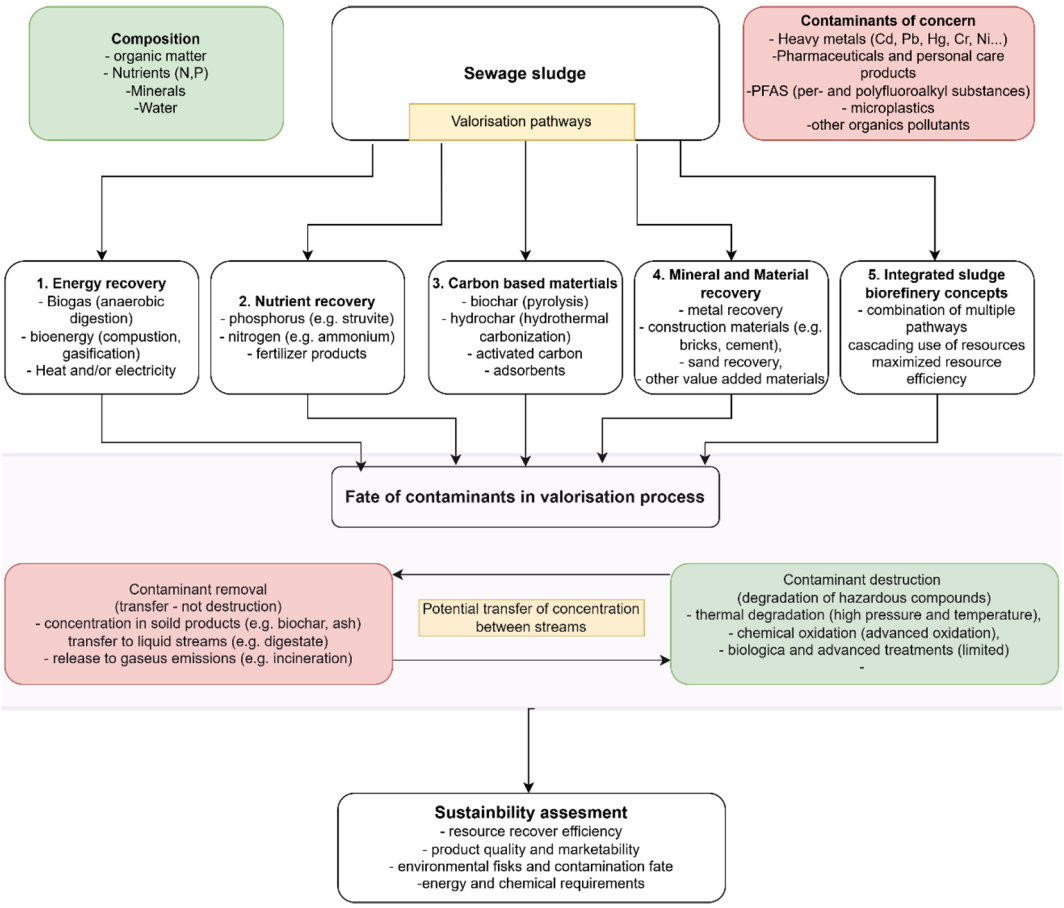

Figure 2. Conceptual framework for sewage sludge valorisation, integrating resource recovery, product quality, contaminant fate and residual-stream management

sewage sludge valorisation, including energy and nutrient recovery, carbon-based products, mineral and material recovery, and integrated sludge biorefinery concepts. The pathways are compared using a common framework that considers resource recovery potential, product characteristics, energy and chemical requirements, contaminant fate, residual streams and environmental implications, with particular attention to the distinction between contaminant removal and destruction and to the transfer, transformation and concentration of contaminants during sludge processing.

REVIEW SCOPE AND CONCEPTUAL FRAMEWORK

This study was conducted as a critical literature review of established and emerging approaches for sewage sludge valorisation, with particular emphasis on resource recovery, product quality, contaminant fate, process requirements and environmental implications. The review was designed to compare different valorisation pathways using a common analytical framework rather than to establish a universal ranking of technologies based on a single performance indicator.

In this review, sewage sludge valorisation is defined as an overarching concept encompassing the recovery of energy, nutrients, organic carbon, and mineral or material resources from sewage sludge and its processed fractions. The conceptual framework used in the review is presented in Figure 1. It considers valorisation as a sequence in which resources are recovered while contaminants may be degraded, transformed, immobilised, transferred between process streams or concentrated in recovered products or residual fractions.

LITERATURE SEARCH

The literature search was conducted using the Scopus, Web of Science, ScienceDirect and Google Scholar databases and covered publications published between 2010 and 2026. The search focused on scientific literature addressing sewage sludge resource recovery, sludge valorisation, sludge biorefineries and contaminant fate during sludge treatment and valorisation. Particular attention was given to studies

Table 1. Search categories, keywords and main focus of the literature search

No.	Search category	Keywords / related terms	Main focus of the search
1	Sewage sludge valorisation and resource recovery	“sewage sludge”; “wastewater sludge”; “sludge valorisation”; “sludge valorisation”; “resource recovery”; “sludge biorefinery”; “circular economy”; “circular bioeconomy”	Identification of studies addressing the general concepts, potential resources and development of sewage sludge valorisation and resource recovery
2	Energy and organic carbon recovery	“anaerobic digestion”; “biogas”; “methane”; “volatile fatty acids”; “organic carbon recovery”	Identification of biological pathways for energy and biochemical recovery from sludge-derived organic matter
3	Nutrient recovery	“phosphorus recovery”; “phosphate recovery”; “nitrogen recovery”; “nutrient recovery”; “struvite”; “phosphate precipitation”	Identification of pathways for recovery of phosphorus, nitrogen and other nutrients and production of reusable nutrient products
4	Thermochemical and hydrothermal conversion	“pyrolysis”; “gasification”; “hydrothermal treatment”; “hydrothermal carbonisation”; “hydrothermal carbonization”; “hydrothermal liquefaction”	Identification of thermal and hydrothermal pathways for energy, carbon and material recovery
5	Carbon-based products	“biochar”; “hydrochar”; “sludge-derived biochar”; “sludge-derived hydrochar”; “carbonaceous materials”	Identification of carbonaceous products, their properties and potential applications
6	Mineral and material recovery	“mineral recovery”; “ash recovery”; “sewage sludge ash”; “construction materials”; “secondary raw materials”	Identification of pathways for recovery and reuse of mineral fractions and sludge-derived materials
7	Contaminants and contaminant fate	“heavy metals”; “pharmaceuticals”; “personal care products”; “PFAS”; “microplastics”; “pathogens”; “antibiotic resistance”; “contaminant fate”; “contaminant degradation”; “contaminant transformation”	Assessment of contaminant occurrence, persistence, degradation, transformation, immobilisation, phase transfer and concentration during sludge treatment and valorisation
8	Integrated sludge biorefinery	“sludge biorefinery”; “integrated sludge treatment”; “integrated resource recovery”; “cascading recovery”; “sequential recovery”	Identification of integrated and sequential approaches combining energy, nutrient, carbon and/or mineral recovery

addressing energy and organic carbon recovery, nutrient and phosphorus recovery, carbon-based products, mineral and material recovery, and integrated treatment systems. Additional searches were conducted for contaminant groups relevant to sludge valorisation, including heavy metals, pharmaceuticals and personal care products, per- and polyfluoroalkyl substances (PFAS), microplastics, pathogens and antibiotic resistance determinants. Relevant publications were identified using combinations of keywords and related terms covering the main valorisation pathways and contaminant groups (Table 1). The search strategy was designed to capture both established technologies and emerging approaches, while also identifying studies addressing contaminant behaviour and redistribution during sludge processing.

LITERATURE SELECTION

The review primarily considered peer-reviewed research articles and review papers published between 2008 and 2026. Publications were selected based on their relevance to the scope of the review and their contribution to understanding resource recovery pathways, recovered product characteristics, contaminant fate, process requirements or residual-stream management.

Review articles were used to identify major technological pathways, concepts and research trends, whereas original research studies were used particularly for quantitative information on process performance, product characteristics and contaminant behaviour. Foundational publications published before 2010 were also considered when they provided important information on fundamental mechanisms, established technological principles or the development of specific valorisation approaches. Because this study was designed as a critical literature review, the literature was selected qualitatively rather than through a formal systematic screening procedure. Particular emphasis was placed on studies providing relevant experimental evidence, representative performance data, mechanistic information or broader assessments of environmental implications. The selected literature was not assumed to be directly comparable across all studies because reported results may differ substantially in terms of feedstock characteristics, process conditions, system boundaries and performance indicators.

ANALYTICAL FRAMEWORK

The selected literature was analysed using a common framework comprising seven main dimensions:

1) sludge characteristics and recoverable resources,
2) valorisation pathway and underlying process principle,
3) recovered products and their relevant properties and potential applications,
4) energy and chemical requirements,
5) contaminant fate and redistribution,
6) residual-stream generation and management, and
7) potential environmental implications and resource substitution.

Resource recovery was assessed according to the type and characteristics of the recovered resource rather than recovery efficiency alone. Energy recovery pathways were considered in terms of their ability to convert organic matter into usable energy carriers, whereas nutrient recovery pathways were evaluated according to their potential to produce concentrated and reusable nutrient products. Carbon and material recovery pathways were assessed with respect to the properties, stability and potential applications of the resulting materials, including biochar, hydrochar, ash-derived products and construction-related materials.

Product quality was considered an essential component of the assessment because recovery of a target constituent does not necessarily result in a technically or environmentally suitable product. Where information was available, the analysis considered contaminant concentrations, chemical form, mobility or environmental availability in recovered products, together with their intended applications. Particular attention was given to applications involving direct or indirect environmental exposure, such as agricultural use.

Contaminant fate was assessed separately from contaminant removal. Where information was available, the analysis considered whether contaminants were degraded or destroyed, transformed into other chemical forms, immobilised, transferred between solid, liquid and gaseous phases, or concentrated in recovered products or residual fractions. This distinction was particularly important for contaminants that cannot be destroyed, such as heavy metals, and for persistent organic contaminants for which disappearance from the original sludge matrix may result from transformation or phase transfer rather than complete destruction.

Residual stream management was also considered as an integral part of each valorisation pathway. Relevant streams included digestates, process liquors, ashes, char fractions, concentrated contaminant streams and other secondary solids or liquids. Transfer of contaminants from the original sludge to another process stream was therefore not considered equivalent to their elimination, particularly where the resulting stream requires further treatment, reuse or disposal.

Finally, the potential integration of complementary processes within a sewage sludge biorefinery was considered qualitatively. Examples included anaerobic digestion followed by nutrient recovery and subsequent treatment of residual solids, as well as combinations of biological and thermochemical processes. The analysis focused on whether process integration could increase overall resource utilization while maintaining acceptable product quality and contaminant management, without disproportionate increases in energy demand, chemical consumption or residual-stream generation. The resulting framework was used to synthesize the literature across different valorisation pathways and to identify the principal trade-offs between resource recovery, product quality, contaminant fate, process requirements, residual-stream management and potential environmental benefits.

SEWAGE SLUDGE VALORISATION AS A MULTIDIMENSIONAL RESOURCE RECOVERY PROBLEM

The literature reviewed in this study demonstrates that sewage sludge valorisation should be understood as a multidimensional resource recovery problem rather than as a simple conversion of waste into a single useful product. Sewage sludge contains several potentially recoverable fractions, including organic carbon, phosphorus, nitrogen and mineral components, but these resources are embedded within a heterogeneous matrix that also contains contaminants. Consequently, the suitability of a given valorisation pathway depends not only on the concentration of a target resource, but also on its chemical form, interactions with other sludge components, the characteristics of the recovered product, the resources required for processing, and the fate of contaminants throughout the treatment chain. This perspective is particularly important when different valorisation pathways are compared. High recovery of a target resource does not necessarily translate into high environmental value if substantial energy or chemical inputs are required, if the recovered product has limited end-use potential, or if contaminants are transferred or concentrated into the product or residual streams. Accordingly, resource recovery should be evaluated together with product quality, contaminant fate, energy and chemical requirements, residual-stream generation and the potential substitution of conventional resources.

ENERGY AND ORGANIC CARBON RECOVERY

Organic matter represents one of the most readily exploitable fractions of sewage sludge. Anaerobic digestion can convert biodegradable organic matter into biogas while simultaneously contributing to sludge stabilisation and volume reduction. From a circular-economy perspective, this pathway is attractive because part of the organic fraction is converted into an energy carrier that can potentially substitute for externally supplied energy. However, the amount of recoverable energy depends strongly on sludge biodegradability, organic matter content, pretreatment requirements, digestion conditions and the efficiency of biogas utilisation. Consequently, methane production or volatile-solids reduction alone does not fully characterise the environmental value of anaerobic digestion.

An additional limitation is the fate of contaminants. Anaerobic digestion does not eliminate all contaminants present in sewage sludge. Some organic micropollutants may undergo partial degradation, whereas others may persist or be transferred to the digestate. Thus, energy recovery may be achieved without eliminating the contaminant burden of the original sludge, making subsequent management or valorisation of the digestate an important part of the overall process chain.

Fermentative pathways provide another possibility for recovering organic carbon in the form of volatile fatty acids (VFAs) and other soluble intermediates. These products may serve as chemical feedstocks or substrates for subsequent biological processes. However, such pathways require control of hydrolysis and acidogenesis and may compete with direct energy recovery through anaerobic digestion. The choice between energy production and recovery of higher-value carbon intermediates should therefore consider the

intended product, local energy demand, downstream infrastructure and the potential value of the recovered carbon.

Thermochemical technologies provide an alternative route for converting the organic fraction, particularly when sludge has been sufficiently dewatered or when residual solids remain after biological treatment. Pyrolysis can generate a carbon-rich solid together with gaseous and liquid fractions, whereas gasification is primarily directed towards the production of combustible synthesis gas. Hydrothermal processes are particularly relevant for wet sludge because they can process feedstocks with substantially higher moisture contents than conventional dry thermochemical systems. This can reduce the need for energy-intensive drying and improve the suitability of thermal conversion where sludge dewatering represents an important energy constraint.

However, thermochemical conversion should not automatically be interpreted as contaminant destruction. The behaviour of contaminants depends on their physicochemical properties and on operating conditions. Organic contaminants may undergo degradation or transformation, whereas inorganic contaminants such as metals cannot be destroyed and may become concentrated in the remaining solid or ash fraction. Hydrothermal processing may additionally redistribute contaminants between solid and aqueous phases. Consequently, the composition and treatment requirements of all process fractions should be considered when evaluating the environmental implications of thermochemical technologies (Nahar et al., 2024).

Overall, the comparison of biological, fermentative and thermochemical pathways indicates that their differences extend beyond the amount of organic matter converted. They produce different forms of recovered carbon, require different process inputs and generate different residual streams. The relevant question is therefore not simply how much carbon is recovered, but in what form it is recovered, what further processing is required, and how the associated contaminants are distributed among the resulting fractions.

The values reported in Table 2 illustrate the diversity of performance indicators used in studies of sewage sludge valorisation. Product yield, elemental recovery, conversion efficiency and other study-specific metrics describe different aspects of process performance and should therefore not be interpreted as directly comparable efficiencies. This heterogeneity also demonstrates why recovery performance needs to be considered together with product characteristics, process inputs and residual-stream management.

COMPOSTING AND AEROBIC BIOSTABILISATION OF SEWAGE SLUDGE

Composting is an effective biological treatment method for sewage sludge, enabling the stabilisation of organic matter, partial pathogen inactivation, and the production of a nutrient-rich material that may be used as a soil amendment, provided that applicable quality and safety requirements are met (Bożym and Siemiątkowski, 2018). Co-composting sewage sludge with municipal solid waste (MSW), green waste, or other biodegradable materials can improve the carbon-to-nitrogen ratio, aeration, and structural properties of the composting mixture (Malinowski et al., 2019). Aerobic bio stabilisation similarly promotes the microbial degradation of biodegradable organic matter, reducing biological activity and the potential for odour generation (Cárdenas-Talero et al., 2022). These processes can contribute to the recovery of organic matter and nutrients, particularly nitrogen and phosphorus, while reducing the volume of readily biodegradable material. However, their efficiency depends on process conditions, including moisture content, oxygen supply, temperature, and the composition of the feedstock. Although thermophilic conditions can reduce pathogen levels, heavy metals are not destroyed during biological treatment and may become concentrated in the final product as organic matter decomposes (Bożym and Siemiątkowski, 2018). Composting can also reduce the concentrations of certain organic contaminants through biodegradation, although persistent pollutants may remain in the compost or become associated with its organic fraction (Lü et al., 2021). Furthermore, emissions of ammonia and greenhouse gases, nutrient losses, and the generation of contaminated leachate should be considered when evaluating the environmental performance of these processes. Therefore, the agricultural or environmental use of the final product requires assessment of its stability, maturity, nutrient content, pathogen levels, and contaminant concentrations to ensure safe and sustainable application.

Table 2. Representative resource recovery performance of sewage sludge valorisation pathways reported in the literature

Resource / pathway	Feedstock / process	Main recovered product	Reported result	Indicator type	Main limitation	Reference
Organic carbon → biogas	Anaerobic digestion	Biogas / CH_4	Performance strongly dependent on sludge biodegradability and VS content	Methane production / VS destruction	Persistent contaminants may remain in digestate	Cecconet & Capodaglio (2022)
Organic carbon → VFAs	Thermal-alkaline pretreatment + alkaline fermentation	VFAs / SCFAs	Hydrolysis rate 68.7%; VFA production 261.32 mg COD g^{-1} VSS; VS reduction 54.19%	Hydrolysis / VFA production / VS reduction	Chemical demand and process control	Liu et al. (2018)
P → soluble P	Anaerobic-based processes	Soluble phosphate	P release depends strongly on P speciation and sludge composition	P release to liquid phase	Fe/Al binding and EPS can inhibit release	Yu et al. (2021)
P → phosphate product	Sludge ash + wet chemical extraction	P-rich phosphate product	Up to 90% P separation reported under selected conditions	P separation / recovery	Chemical consumption; impurity removal	Franz (2008)
P → recovered P	Incineration → SSA → P extraction	Recovered phosphate	High P recovery reported for selected SSA-processing configurations	P recovery	Metal association and downstream purification	Xu et al. (2023)
Carbon → biochar	Pyrolysis	Biochar	38.2–47.8 wt.% under investigated conditions	Solid-product yield	High ash content; possible contaminant concentration	Cedrone et al. (2024)
Carbon → biochar	Pyrolysis of biological sludge	Biochar	40–73 wt.%	Solid-product yield	Yield depends on operating conditions	Tarelho et al. (2020)
Carbon → bio-oil	Fast pyrolysis	Bio-oil	Maximum organic oil yield of 41 wt.% daf	Bio-oil yield / energy recovery	Product quality and contaminant transfer	Trinh et al. (2013)
Carbon → bio-oil	Fast pyrolysis	Bio-oil	44.8–48.5 wt.% wet basis; 71.3–77.1 wt.% daf	Bio-oil yield	Strong feedstock dependence	Alvarez et al. (2016)
Carbon → hydrochar	HTC	Hydrochar	Approximately 62–80 wt.%	Hydrochar yield	High ash content; product quality varies	Huezo et al. (2021)
Carbon → hydrochar	HTC	Hydrochar	62.0–64.1 wt.%	Solid-product yield	Nutrient and contaminant redistribution	Liu et al. (2024)
Carbon + nutrients → hydrochar/ liquid	Co-HTC of sludge and whey	Hydrochar + liquid fraction	Hydrochar yield increased from 57.10 to 64.14 wt.%	Hydrochar yield / C and nutrient enrichment	Additional substrate required; liquid requires treatment	Petrović et al. (2023)

Note: reported values are technology and feedstock specific and should not be interpreted as directly comparable percentages. Depending on the study, the reported metric may represent product mass yield, recovery of a target element, conversion of an organic fraction, or another study-specific performance indicator. Values should therefore be interpreted within the system boundaries and calculation methodology of the individual study.

NUTRIENT RECOVERY AND PHOSPHORUS VALORISATION

Phosphorus recovery is one of the most important arguments for considering sewage sludge as a secondary resource. Sewage sludge can contain substantial quantities of phosphorus, but its recoverability is strongly affected by its chemical speciation and association with iron, aluminium, calcium and organic matter. Therefore, total phosphorus concentration alone is insufficient to characterise phosphorus recovery potential (Yu et al., 2021a, Yu et al., 2021b). The distinction between total phosphorus content, phosphorus released into a recoverable phase and phosphorus incorporated into a usable product is particularly important

when comparing different recovery pathways. Biological and chemical treatment processes can alter phosphorus speciation and improve its availability for subsequent recovery. Anaerobic processes may increase the soluble phosphorus fraction under appropriate conditions, creating opportunities for recovery from the liquid phase. Chemical extraction can also mobilise phosphorus from sludge or ash, after which precipitation or crystallisation can be used to produce more concentrated phosphorus-containing products. However, chemical recovery may require substantial quantities of acids, bases or precipitating agents. The environmental value of phosphorus recovery should therefore be considered in relation to chemical consumption, energy demand and the treatment requirements of the resulting residual streams. Thermal treatment followed by ash processing represents another important route. Incineration substantially reduces the organic fraction and concentrates phosphorus in the resulting ash, potentially facilitating subsequent phosphorus extraction. However, phosphorus may remain associated with mineral phases or metals, increasing the complexity of downstream separation. In addition, thermal treatment does not remove inorganic contaminants. Instead, some metals may become concentrated in the ash or in the recovered mineral fraction. Consequently, phosphorus recovery from sewage sludge ash should be coupled with contaminant characterisation and appropriate control of the final product. These observations indicate that phosphorus recovery should not be assessed solely on the basis of phosphorus concentration or extraction efficiency. A phosphorus-rich fraction has greater practical value when the phosphorus is sufficiently available for the intended application, the product meets relevant quality requirements and the additional chemical and energy requirements are proportionate to the environmental benefit achieved.

CARBONACEOUS PRODUCTS AND MINERAL/MATERIAL RECOVERY

The conversion of sewage sludge into biochar or hydrochar has attracted considerable interest because these materials may combine resource recovery with carbon management and potential environmental applications. Sludge-derived biochar can possess a porous structure and surface functionalities that make it potentially useful as an adsorbent or soil amendment. However, its properties depend strongly on feedstock composition and process conditions, while the presence of metals and other contaminants may limit certain applications (Mian et al., 2023, Zhao et al., 2023).

An important distinction must therefore be made between producing a carbonaceous material and producing a safe, marketable product. During thermal treatment, decomposition of organic matter can increase the relative concentration of inorganic elements in the remaining solid fraction. A biochar with favourable surface properties may consequently contain elevated concentrations of metals. Its environmental suitability depends not only on total contaminant concentrations, but also on their chemical forms, mobility and bioavailability. This distinction is particularly important when sludge-derived biochar is intended for agricultural or other environmentally exposed applications.

Hydrothermal carbonisation offers a related approach with the advantage of being suitable for relatively wet feedstocks. Hydrochar yield and properties depend on feedstock composition and operating conditions, while the process may redistribute nutrients and contaminants between the hydrochar and aqueous phase (Basri et al. 2025). Consequently, the production of a high-yield solid product does not by itself demonstrate that the overall process has achieved beneficial resource recovery. Material recovery from sewage sludge ash provides an additional route for valorisation. Mineral components can potentially be incorporated into construction materials or used as secondary raw materials. Such applications may reduce the demand for virgin mineral resources and provide an outlet for fractions that are difficult to valorise biologically. However, leaching behaviour and the long-term stability of contaminants must be considered before recovered mineral products are used in construction or environmental applications. Incorporation of contaminants into a stable matrix may reduce their immediate mobility, but immobilisation should not be equated with destruction. Overall, carbonaceous and mineral products illustrate the importance of distinguishing product generation from product quality. A high product yield may be accompanied by concentration of inorganic contaminants, while a material with favourable physicochemical properties may still require additional treatment before a particular end use is acceptable. Product quality should therefore be evaluated against the requirements of the intended application rather than against yield alone.

CONTAMINANT FATE ACROSS VALORISATION PATHWAYS

One of the most important findings emerging from the reviewed literature is that contaminant fate should be evaluated together with resource recovery. Wastewater treatment promotes the transfer of many particle-associated and hydrophobic contaminants from the aqueous phase to sludge, making sludge a relevant sink for a range of contaminant classes. Valorisation processes can subsequently redistribute these contaminants among recovered products and secondary process streams. The environmental significance of a treatment step therefore depends not only on the reduction of contaminant concentrations in the original sludge, but also on the destination and form of the contaminants after processing. Heavy metals illustrate this issue particularly clearly. Unlike organic contaminants, metals cannot be destroyed by conventional treatment. They can, however, change chemical form, partition between process fractions or become incorporated into mineral phases. Thermal processes can reduce the organic mass of sludge and consequently increase the relative concentration of metals in the remaining solid fraction. From a mass-balance perspective, an apparent reduction in metal concentration in the original material or transfer away from the initial sludge matrix may therefore reflect redistribution or concentration rather than destruction. Immobilisation can reduce contaminant mobility under particular conditions, but it does not eliminate the contaminant mass. Organic micropollutants such as pharmaceuticals and personal care products exhibit more variable behaviour. Their degradation depends on molecular structure, treatment conditions and the specific process applied. Anaerobic treatment can result in partial degradation of some compounds, whereas others may persist or form transformation products (Wang et al., 2024). Consequently, measurement of the parent compound alone may provide an incomplete picture of contaminant fate and potential environmental relevance.

PFAS represent an additional challenge because the strong carbon–fluorine bond contributes to the chemical stability of many compounds. Their presence in biosolids is particularly relevant when recovered sludge-derived products are intended for environmental applications (Saliu and Sauvé, 2024, Zhou et al., 2024). A reduction in the concentration of an individual PFAS in sludge should therefore not automatically be interpreted as complete destruction. Depending on the compound and process conditions, transformation, phase transfer or concentration in residual products may also contribute to the observed decrease. Microplastics constitute another important constraint. Wastewater treatment systems can retain substantial proportions of microplastics, resulting in their accumulation in sludge (Casella et al., 2023). Conventional biological treatment does not necessarily eliminate these particles, while subsequent processing may alter their size, morphology or polymer characteristics rather than completely mineralising them. Consequently, reductions in particle abundance or changes in particle characteristics should be distinguished from actual destruction, and the environmental significance of transformation products or residual particles requires further investigation. These examples demonstrate that contaminant assessment should move from a concentration-based approach towards a mass-balance and fate-based approach. For each contaminant group, the relevant question is not simply how much remains in the original sludge, but where the contaminant goes, in what chemical or physical form, and what is the environmental relevance of the resulting fraction.

The examples summarised in Table 3 also demonstrate why the term “removal” should be used cautiously. Depending on the contaminant and process, an observed decrease may represent degradation, transformation, immobilisation, phase transfer or concentration elsewhere in the system. These processes have substantially different implications for environmental performance and should therefore be distinguished when reporting the results of valorisation studies.

INTEGRATED SLUDGE BIOREFINERY

The concept of an integrated sewage sludge biorefinery provides an opportunity to overcome some of the limitations associated with single-purpose treatment. Rather than targeting a single end product, a biorefinery approach can enable the sequential recovery of multiple resource fractions from the same feedstock. For example, organic matter can initially be converted into biogas or VFAs, nutrients can subsequently be recovered from liquid fractions, and residual solids can then be subjected to thermal treatment or used

Table 3. Representative contaminant fate during sewage sludge valorisation

Contaminant group	Valorisation pathway	Observed fate	Reported indicator	Main implication
Heavy metals	Thermal treatment / HTC	Retention, concentration or redistribution	Mass distribution between fractions	Removal from sludge does not imply destruction
Pharmaceuticals/PPCPs	Anaerobic digestion / advanced treatment	Partial degradation, persistence or transformation	Parent-compound removal/degradation	Transformation products may remain relevant
PFAS	Hydrothermal treatment	Compound-specific degradation/ transformation	Degradation of individual PFAS	Parent-compound loss does not necessarily indicate complete defluorination
Microplastics	Biological / thermal treatment	Retention, fragmentation or transformation	Particle abundance/size/ polymer characteristics	Physical reduction does not necessarily equal mineralisation

for material recovery. Such integration may increase the utilisation of organic and mineral fractions and reduce the amount of residual material requiring final disposal (Cecconet & Capodaglio, 2022). However, integration also introduces additional complexity. Each treatment step requires energy, chemicals, infrastructure and process control. More importantly, one process may transfer contaminants into a stream that subsequently becomes the feedstock for another process. For example, contaminant-containing digestate or process water generated during an initial recovery step may require additional treatment before nutrient or carbon recovery can be performed. Similarly, thermal processing of residual solids may concentrate inorganic contaminants in ash or carbonaceous products. The biorefinery concept should therefore be understood as a sequence of coupled material and contaminant flows rather than simply as a combination of multiple recovery technologies.

A system may achieve high individual recovery efficiencies at several stages while simultaneously increasing the concentration of contaminants in a downstream product or residual stream. Consequently, the performance of an integrated system cannot be inferred by adding the individual recovery efficiencies of its component processes. The objective of integration should instead be optimisation of the complete process chain. Recovered products should have sufficient quality and potential value to substitute conventional products, while contaminant-containing residual streams should be safely managed. Life-cycle assessment and techno-economic assessment can provide useful tools for evaluating these trade-offs, particularly when alternative combinations of biological, chemical and thermochemical processes are compared.

CROSS-PATHWAY TRADE-OFFS AND ENVIRONMENTAL IMPLICATIONS

A central issue identified in this review is the potential divergence between resource recovery efficiency and overall environmental performance. A process may achieve high phosphorus recovery while requiring substantial quantities of chemicals. A thermal process may produce a useful carbonaceous material while concentrating metals in the solid fraction. Anaerobic digestion may generate renewable energy while leaving persistent contaminants in the digestate. These examples demonstrate that recovery efficiency represents only one dimension of the performance of a valorisation pathway.

A more comprehensive assessment should therefore consider at least seven interconnected dimensions: resource recovery, product quality, contaminant fate, energy demand, chemical consumption, residual-stream management and the potential substitution of conventional resources. These dimensions are interdependent rather than independent performance indicators. Improving one may increase or decrease the performance of another. For example, intensified extraction may increase phosphorus recovery while increasing chemical consumption, whereas more severe thermal treatment may alter contaminant destruction or redistribution while also changing product yield and quality.

Product quality is particularly important because the environmental benefit of recovery ultimately depends on whether the recovered material can be used as a substitute for a conventional product. A material suitable for controlled industrial use may not be appropriate for direct agricultural application. Similarly, a phosphorus product with low contaminant content may

have greater practical value than a phosphorus-rich material containing elevated concentrations of potentially mobile metals. Product quality should therefore be assessed against the requirements of the final application rather than against recovery yield alone. The same principle applies to residual streams. A technology that produces a valuable product but generates a difficult-to-manage liquid, gas or solid residue may simply shift the environmental burden to another part of the process chain. Consequently, environmental performance should be considered at the level of the complete system rather than at the level of an individual recovery step. The comparison also highlights the importance of resource substitution. Recovery of a material has greater environmental value when the recovered product can effectively replace a virgin resource or conventional energy carrier without generating disproportionate additional environmental burdens. Thus, the practical value of a recovery pathway depends not only on how much material is recovered, but also on what the recovered material replaces and what additional processing is required to make that substitution possible.

FUTURE PERSPECTIVES

First, more studies are needed to establish complete contaminant mass balances across integrated sludge treatment systems. Research frequently reports contaminant removal from the original sludge without quantifying the corresponding distribution among gas, liquid, solid and recovered-product fractions. Such information is essential for distinguishing genuine destruction from phase transfer, redistribution or concentration. Second, greater attention should be given to transformation products and the environmental availability of contaminants. Measuring only parent compounds may underestimate potential environmental relevance, particularly for pharmaceuticals and PFAS. Future studies should therefore combine chemical analysis with assessments of toxicity, mobility and bioavailability where appropriate. Third, standardised indicators are needed to facilitate comparison between valorisation pathways. Recovery efficiency should be reported together with product purity and quality, contaminant concentration and fate, energy consumption, chemical demand and residual generation. Clear definitions of recovery, yield, conversion, retention and contaminant removal would further reduce ambiguity when comparing results from different studies. Fourth, future research should increasingly focus on integrated systems rather than individual technologies. Biological, chemical and thermochemical processes may be combined according to the characteristics of the local sludge and the demand for recovered products. However, integration should be based on process compatibility and whole-system environmental performance rather than on maximisation of the number of recovered products. Finally, greater attention should be given to validation of recovered products under realistic end-use conditions. Laboratory-scale production of a resource-rich material does not necessarily demonstrate that the material can replace a conventional product at the required technical, environmental or regulatory quality. Long-term stability, contaminant mobility, product performance and realistic substitution potential should therefore be incorporated into future assessments.

OVERALL SYNTHESIS

Overall, the reviewed literature indicates that sewage sludge has significant potential as a source of energy, nutrients, carbonaceous materials and mineral resources. However, the environmental and economic value of valorisation cannot be determined from resource recovery efficiency alone. It also depends on whether recovered resources meet the quality requirements of their intended applications, contaminants are adequately controlled, process inputs are minimised, and problematic residual streams are avoided or appropriately managed. The concept of a sludge biorefinery is therefore most useful when it is considered as a whole-system framework rather than simply as a strategy for maximising the number of recovered products. Effective valorisation requires simultaneous consideration of resource recovery, product quality, contaminant fate, process inputs, residual streams and resource substitution. In this context, the distinction between contaminant removal and actual destruction is fundamental: a reduction in contaminant concentration in the original sludge does not necessarily represent an environmental benefit if the contaminant has been transferred, transformed or concentrated elsewhere in the system. A practical framework for comparing sewage sludge valorisation pathways should combine life

cycle assessment (LCA) with techno-economic analysis (TEA). LCA enables the evaluation of environmental impacts across the entire system, including energy and chemical consumption, contaminant fate, residual-stream management, and the potential benefits of substituting conventional resources with recovered products. TEA complements this assessment by evaluating capital and operating costs, process performance, potential revenues, and economic feasibility. Both approaches should account for the quality and intended application of recovered products, since high resource recovery efficiency does not necessarily translate into environmental benefits or commercial viability. Meaningful comparisons also require consistent system boundaries, functional units, and performance indicators. Integrating LCA and TEA can therefore support the identification of valorisation pathways that balance resource recovery, environmental protection, and economic performance.

CONCLUSIONS

Sewage sludge should be considered a heterogeneous secondary resource containing recoverable organic matter, nutrients, carbon, minerals, and potentially valuable elements.. Existing valorisation pathways enable the recovery of these constituents in forms such as biogas, volatile fatty acids, phosphorus- and nitrogen-based products, carbonaceous materials, construction materials, and mineral resources. However, the practical value of these pathways depends not only on resource recovery efficiency but also on product quality, safety, functionality, and the potential to substitute conventional resources. The findings of this review indicate that no single valorisation pathway is universally optimal. Anaerobic digestion and fermentation are suitable for organic carbon conversion and energy recovery, nutrient-recovery technologies enable the production of targeted fertilizer products, and thermal and mineral-processing routes facilitate the recovery of carbon, phosphorus, and other valuable materials from residual solids and ash. Combining these technologies may increase overall resource recovery, but successful integration requires careful management of process interactions, energy and chemical consumption, and the distribution of contaminants among products and residual streams. Contaminant management remains a major challenge for sustainable sewage sludge valorisation. Heavy metals, organic micropollutants, per- and polyfluoroalkyl substances, microplastics, pathogens, and antibiotic resistance determinants may persist, undergo transformation, or become concentrated in particular process streams. A reduction in contaminant concentration does not necessarily indicate contaminant destruction or a corresponding reduction in environmental risk. Future research should therefore prioritise the long-term fate and transformation of contaminants, the assessment of their bioavailability and potential transfer into recovered products, and the development of reliable monitoring methods and quality criteria for their safe use. Several technological and implementation challenges also require further investigation, including high energy and chemical requirements, variable sludge composition, process integration, economic feasibility, and the management of secondary residues. In particular, more pilot- and full-scale studies are needed to validate integrated valorisation pathways under realistic operating conditions. Consistent life cycle assessment and techno-economic analysis, based on transparent system boundaries and comparable performance indicators, are essential for identifying configurations that provide genuine environmental and economic benefits. Further research should also evaluate the long-term stability, safety, and market acceptance of recovered products and establish reliable approaches for substituting conventional raw materials. Overall, the transition towards a sewage sludge biorefinery requires a shift from single-purpose treatment to integrated recovery of multiple resource fractions. The most appropriate valorisation strategy should be selected through a whole-system assessment that balances resource recovery, product quality and usability, contaminant control, environmental impacts, economic feasibility, and residual-stream management. Addressing the identified research gaps and technological barriers will be essential to translate promising laboratory and pilot-scale processes into safe, economically viable, and environmentally sustainable solutions.

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