

Review

Beyond Stand-Alone Technologies: Integrated Pathways for Energy, Nutrient and Carbon Recovery from Sewage Sludge

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Abstract

Sewage sludge (SS) management is progressively shifting from waste disposal toward resource recovery and circular bioeconomy approaches. While conventional technologies such as anaerobic digestion (AD), incineration, and land application remain widely adopted, increasing attention is directed toward processes capable of simultaneously recovering energy, nutrients, and carbon-based products. Most existing reviews evaluate biochemical, thermochemical, and electrochemical technologies as stand-alone options, whereas their integration within sludge biorefineries remains comparatively underexplored. This critical review examines how conventional and emerging technologies, including hydrothermal carbonization (HTC), pyrolysis, and bioelectrochemical systems (BES), can be combined to improve resource recovery. The literature was selected based on topical relevance and publication date, prioritizing recent studies on resource recovery and integrated treatment configurations. Particular attention is given to AD-HTC, AD-pyrolysis, and AD-BES. The comparison indicates that AD-HTC is particularly relevant for wet digestate because it avoids complete drying and offers opportunities for process-water recycling and nutrient recovery, whereas AD-pyrolysis provides energy-rich products and carbonaceous solids but requires greater attention to drying and heat integration. AD-BES can enhance methane or nutrient recovery, although energy performance depends strongly on external electrical input and operating conditions.

Keywords: anaerobic digestion; bioelectrochemical systems; hydrothermal carbonization; nutrient recovery; process integration; sewage sludge; sludge biorefinery; water resource recovery facility



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1. Introduction

Global sewage sludge (SS) production has been estimated at approximately 53 million tonnes per year on a dry-solids basis, based on regional data and 2022 United Nations population statistics [1]. Sludge generation is expected to increase further with population growth, urbanization, and the expansion of wastewater treatment, making its management a major environmental and logistical challenge in terms of treatment, disposal, and valorization [2]. Its composition depends on wastewater characteristics, or treatment configuration and operational conditions, but it generally includes a high fraction of organic matter,

elevated moisture content, nutrients such as nitrogen and phosphorus, and a wide range of contaminants, including heavy metals, pathogens, and emerging pollutants [3–9].

Traditionally, SS has been managed through disposal-oriented or waste-to-energy-focused routes, such as landfilling, land application, incineration, and anaerobic digestion (AD). However, landfilling and direct land application are increasingly restricted by more stringent regulations dictated by concerns related to greenhouse gas emissions, soil contamination, and public acceptance. Incineration and co-combustion allow effective volume reduction and pathogen destruction but are often limited by high energy demand for sludge drying, limited efficiency in converting the enthalpic content of SS into heat and/or electrical energy, air emission control requirements, and residual ash management. Biochemical treatment through anaerobic digestion remains the most widely applied biological process for SS stabilization and energy recovery, producing biogas for heat and power generation. Nevertheless, AD is frequently constrained by the slow degradation of recalcitrant organic fractions and by the need for further treatment or management of the residual digestate [10–12].

Emerging thermochemical and bioelectrochemical technologies provide complementary or alternative routes to conventional treatments. Thermochemical processes such as hydrothermal carbonization (HTC), pyrolysis, and gasification enable the conversion of SS into energy-dense products, including hydrochar, biochar, bio-oil, and syngas, while reducing sludge volume and modifying the partitioning of contaminants among product and residual streams [4,13,14]. Bioelectrochemical systems (BES), including microbial fuel cells (MFCs) and microbial electrolysis cells (MECs), offer innovative pathways for energy recovery through electricity or hydrogen generation under relatively mild operating conditions, with MFCs producing electricity and MECs requiring external voltage to support hydrogen production or other cathodic recovery reactions [15–17].

Although most studies have investigated these technologies individually, their stand-alone application often presents technical, economic, or environmental limitations. For this reason, research is currently focusing on the integration of biochemical, thermochemical, and bioelectrochemical processes in hybrid configurations. Process integration may improve overall energy efficiency, reduce residual waste streams, and enable the simultaneous recovery of multiple products. However, the realization and magnitude of these benefits depend on the configuration and performance of the complete treatment train, auxiliary energy demand, process scale, and the management of intermediate streams. Examples include the coupling of AD with HTC or pyrolysis for digestate valorization, as well as the integration of AD with BES to enhance bioenergy production and nutrient recovery [18,19].

Beyond energy recovery, integrated treatment schemes also open new opportunities for the extraction of value-added compounds such as volatile fatty acids (VFAs), phosphorus, and nitrogen, supporting the development of sewage-sludge-based biorefinery concepts [20,21]. In this review, nutrient recovery is reserved for cases where nitrogen or phosphorus is extracted, precipitated, or captured as a defined, reusable product or stream, whereas nutrients merely accumulated in ash, biochar or char, hydrochar, digestate, or process water are treated as recovery potential unless suitability for nutrient reuse is demonstrated. Energy recovery refers to usable energy outputs, carbon recovery to sludge-derived carbon retained or converted into reusable products or streams, and resource efficiency to increasing useful outputs while reducing waste and input requirements. Valorization describes the conversion of SS or intermediate streams into useful products, while sludge biorefinery refers to an integrated platform for recovering multiple resources from SS. Policies for the valorization of residual streams increasingly promote the recovery of materials, possibly with high added value, alongside energy recovery [22,23]. From this perspective, the relative emphasis on material and energy recovery may vary, but

individual technologies should be evaluated according to their contribution within an integrated system aimed at maximizing overall resource recovery. When effectively integrated, these technologies may reduce the net energy demand of WWTPs and, under favourable plant-specific conditions, contribute to energy-neutral or net-positive operation [23–25].

Recent reviews have extensively addressed individual sewage sludge treatment and valorization technologies, whereas comparatively less attention has been given to their integration and to the associated trade-offs among energy, nutrient, and carbon recovery. These three dimensions were selected because they represent major resource streams from sewage sludge whose distribution and recovery are directly influenced by the choice and integration of treatment technologies.

The objective of this review is to provide an integration-centred assessment of conventional, emerging, and hybrid technologies for sewage sludge (SS) valorization within a circular economy framework. Rather than focusing on individual processes, this work critically analyzes how anaerobic digestion, thermochemical conversion, and bioelectrochemical systems can be strategically combined and optimized to enhance overall energy recovery while closing carbon and nutrient cycles and reducing environmental burdens. Several established routes, such as anaerobic digestion, incineration, and co-combustion, and emerging technologies, including hydrothermal carbonization, pyrolysis, gasification, and bioelectrochemical systems, are examined with particular emphasis on hybrid configurations enabling simultaneous energy and material recovery. The review therefore adopts an integrated and multi-dimensional perspective, linking energy generation, nutrient recovery, and carbon valorization within sludge-based biorefinery configurations. By synthesizing recent technological advances, identifying key synergies and trade-offs, and highlighting relevant technical and research gaps, this review aims to support the development of more resource-efficient and circular sewage sludge management strategies.

2. Literature Search and Review Approach

This work was developed as a critical review. An integrative approach was adopted to synthesize evidence from different study types and to examine technological complementarities, process integration, and resource-recovery trade-offs. Literature selection was mainly based on topical relevance and publication date, with priority given to recent studies on sewage sludge treatment, valorization and resource recovery. Studies were considered relevant when they directly addressed sewage sludge treatment, valorization, resource recovery, or process integration and reported information on process configuration, operating conditions, treatment streams, recovery outcomes, or integration constraints. Potential overlap was assessed by comparing authorship, feedstock, reactor configuration, operating conditions, and reported datasets; related publications were retained only when they provided distinct information or outcomes. Overall, 129 of the 168 scientific references included in this calculation (76.8%) were published between 2020 and 2026, with a median publication year of 2022. Primary legal documents, policy reports, standards, and statistical sources were excluded. The literature search was last updated in July 2026. Earlier publications were also considered when they provided fundamental information on established processes, relevant experimental or full-scale evidence, or information not adequately covered by more recent studies. The literature search was performed using mainly Scopus and Web of Science and was based on combinations of “sewage sludge” with technology-related terms, including “anaerobic digestion”, “incineration”, “co-combustion”, “hydrothermal carbonization”, “pyrolysis”, “gasification”, “bioelectrochemical systems”, “microbial fuel cell”, and “microbial electrolysis cell”. Additional terms, including “energy recovery”, “nutrient recovery”, “phosphorus recovery”, “carbon recovery”, “resource recovery”, “process integration”, “biorefinery”, and “Water Resource Recovery Facility”, were used according

to the specific topic investigated. Experimental, pilot- and full-scale studies, modelling studies, and techno-economic or life-cycle assessments were considered when relevant to the objectives of the review. Particular attention was given to studies directly investigating integrated treatment configurations. However, since the available literature specifically addressing process integration in sewage sludge valorization is still limited, studies on individual processes were also considered to identify possible technological complementarities, synergies and limitations. Accordingly, the integrated pathways discussed in this review include both configurations supported by direct experimental or modelling evidence and prospective configurations derived from the critical analysis of individual technologies. This distinction is explicitly considered in the discussion of integrated approaches.

3. Regulatory Frameworks as Drivers for Technology Selection

The management of sewage sludge (SS) is strongly influenced by regulatory frameworks, which define acceptable disposal routes, emission limits, and quality requirements for sludge-derived products. These requirements can therefore influence the feasibility of different management and valorization routes. Although regulatory approaches differ among regions, common trends can be identified in the progressive restriction of landfilling, increasing control of land application, and growing interest in energy and resource recovery. However, regulatory requirements should be distinguished from policy orientations: while regulations establish mandatory conditions for sludge management, policy strategies may favour resource recovery and circularity without directly prescribing specific treatment technologies.

In the European Union, sewage sludge management is regulated through a combination of waste, environmental, and sector-specific legislation. The use of SS in agriculture has traditionally been governed by Directive 86/278/EEC [R1], which establishes limit values for heavy metals in sludge and soils to protect human health and the environment. The Directive establishes EU-wide limit values, while Member States may adopt more stringent requirements. Consequently, conditions for agricultural use can differ considerably among countries. These limits, together with additional national restrictions on organic pollutants and pathogens, have progressively reduced the acceptability of direct land application in several Member States. At the same time, the Landfill Directive (1999/31/EC) [R2] and its subsequent amendments have strongly limited the landfilling of biodegradable waste, including sewage sludge, by imposing strict pre-treatment requirements and landfill acceptance criteria. As a result, landfilling of untreated or minimally treated SS has been largely phased out in many EU countries. Incineration and co-combustion are regulated under the Industrial Emissions Directive (2010/75/EU) [R3], which sets emission limit values for pollutants such as NO_x, SO₂, particulate matter, and heavy metals, increasing the cost and complexity of thermal treatment. More recently, the EU Circular Economy Action Plan and the revised Waste Framework Directive (EU) 2018/851 [R4] have reinforced the policy shift toward waste valorization, energy recovery, and nutrient recycling. These policy developments strengthen the broader policy context for resource recovery and circularity.

In the United States, sewage sludge management is mainly regulated at the federal level through the U.S. Environmental Protection Agency (EPA) framework. The direct use or disposal of sewage sludge, commonly referred to as biosolids, is governed by the 40 CFR Part 503 Rule [R5], which establishes pollutant concentration limits, pathogen reduction requirements, and vector attraction reduction criteria. This regulation defines the conditions under which sewage sludge can be land-applied, landfilled, or incinerated. In addition, biosolids are classified as Class A or Class B based on pathogen reduction performance. Class A biosolids, typically obtained through advanced stabilization or thermal treatment, can be applied to land without site restrictions, whereas Class B biosolids are

subject to controlled land application conditions. Although land application remains an important management route in several regions of the United States, its acceptance is increasingly influenced by public concerns, state-level restrictions, and limitations on suitable agricultural land. At the same time, landfilling of sewage sludge is discouraged due to rising disposal costs and methane emission concerns. Thermal treatment options, including incineration and co-combustion, are regulated under the Clean Air Act through specific emission standards for sewage sludge incinerators, imposing strict limits on pollutants such as particulate matter, mercury, nitrogen oxides, and sulfur oxides. Therefore, the federal framework establishes minimum conditions for sludge use and disposal, while additional state requirements and local conditions can further influence the practical selection of management routes.

As for China, which represents one of the fastest-growing contexts in terms of sewage sludge production driven by rapid urbanization and the expansion of wastewater treatment infrastructure, national regulations have progressively tightened to address environmental risks associated with sludge disposal. Land application of untreated sludge is strongly restricted, while landfilling is increasingly discouraged due to land scarcity and environmental concerns. As a result, incineration has rapidly emerged as a dominant sludge treatment option in large urban areas, supported by national policies promoting volume reduction and centralized treatment. However, high energy demand and air emission concerns have raised questions about the long-term sustainability of incineration-only strategies. Recent policy documents increasingly emphasize energy recovery, resource efficiency, and circular economy principles, supporting the development of resource-recovery and integrated treatment approaches. Table 1 provides a summary of the main regulatory frameworks and policy drivers for sewage sludge management practices in the EU, USA, and China. The reported values are not directly comparable regulatory thresholds. They refer to different regulatory categories and conditions of use in the three jurisdictions and are reported on a dry-matter basis according to the respective regulatory framework. EU legislation establishes common requirements that may be complemented by stricter national provisions.

Table 1. Comparison of main regulatory frameworks and policy drivers for sewage sludge management in the EU, United States, and China.

Aspect	European Union (EU)	United States (USA)	China
Main regulatory reference	Directive 86/278/EEC (land application) [R1]; Directive 1999/31/EC (landfill) [R2]; IED * 2010/75/EU (incineration) [R3]	EPA 40 CFR * Part 503 (Biosolids Rule) [R5]; Clean Air Act (SSI * standards) [R6]	GB 4284-2018 (agricultural use) [R7]; GB 18918-2002 (pollutant discharge standard) [R8]
Land application status	Allowed under EU requirements, with additional and potentially stricter national provisions	Allowed under federal standards (Class A/Class B biosolids), with additional state-level requirements possible	Strongly restricted; limited to treated and compliant sludge
Cadmium limit (Cd)	20–40 mg kg ^{−1} d.m.	85 mg kg ^{−1} d.m.	<3 mg kg ^{−1} d.m. (Grade A)
Lead limit (Pb)	750–1200 mg kg ^{−1} d.m.	840 mg kg ^{−1} d.m.	<300 mg kg ^{−1} d.m. (Grade A)
Copper limit (Cu)	1000–1750 mg kg ^{−1} d.m.	4300 mg kg ^{−1} d.m.	<500 mg kg ^{−1} d.m. (Grade A)

Table 1. Cont.

Aspect	European Union (EU)	United States (USA)	China
Zinc limit (Zn)	2500–4000 mg kg ^{−1} d.m.	7500 mg kg ^{−1} d.m.	<1200 mg kg ^{−1} d.m. (Grade A)
Pathogen requirements	Requirements complemented by national provisions	Explicit Class A/Class B criteria	Mandatory stabilization and hygienization
Landfilling	Strongly restricted (pre-treatment required)	Allowed but discouraged by cost and policy	Discouraged; limited by land availability
Incineration regulation	IED: strict limits on NO _x , SO ₂ , PM, metals, dioxins	Clean Air Act: NSPS */Emission Guidelines for sewage sludge incineration units	National emission standards; incineration/co-incineration increasingly used under land constraints
Phosphorus recovery	Supported by EU circular-economy and resource-recovery policies; specific requirements depend on the applicable framework	Not mandatory, site-dependent	Increasing interest, not yet mandatory
Policy orientation	Circular economy, resource recovery, decarbonization	Risk-based management, GHG mitigation	Volume reduction, energy recovery, circular economy
Main implications for sludge management	Increasing constraints on disposal and land application, together with policy support for circularity and resource recovery	Management route depends on compliance with federal and state requirements and local conditions	Strong emphasis on stabilization and volume reduction, with increasing attention to resource recovery

* CFR—Code of Federal Regulations; IED—Industrial Emission Directive; NSPS—New Source Performance Standards; SSI—Sewage Sludge Incineration/Incinerators. Note: Numerical limits are reported on a dry-matter basis and are derived from the regulatory sources indicated in the “Main regulatory reference” row for each jurisdiction. The EU values represent the ranges specified in Annex I B of Council Directive 86/278/EEC [R1]. The US values are the ceiling concentrations specified in Table 1 to 40 CFR 503.13 [R5]. The Chinese values are the Grade A sludge-product limits specified in Table 1 of GB 4284-2018 [R7].

Regulatory List

- R1. Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture.
- R2. Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste.
- R3. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control).
- R4. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste
- R5. U.S. Environmental Protection Agency. Standards for the Use or Disposal of Sewage Sludge. Code of Federal Regulations, Title 40, Part 503.
- R6. U.S. Environmental Protection Agency. Standards of Performance for New Stationary Sources and Emission Guidelines for Existing Sources: Sewage Sludge Incineration Units. Code of Federal Regulations, Title 40, Part 60, Subparts LLLL and MMMM.
- R7. GB 4284-2018. Control standards of pollutants in sludge for agricultural use. China.
- R8. GB 18918-2002. Discharge standard of pollutants for municipal wastewater treatment plant. China.

Overall, regulatory frameworks shape the feasibility of sludge-management and valorization routes through requirements related to use, treatment, emissions, product quality, and waste or product status. Land application is primarily constrained by sludge quality, contaminant levels, and pathogen requirements, whereas thermal treatment is strongly affected by emission limits and residual-solid management. Nutrient recovery depends on

both the efficiency of the recovery process and the requirements applicable to the intended use of the recovered material. Similarly, the commercialization of sludge-derived products, including hydrochar and biochar, depends on their quality, contaminant content, intended application, and applicable waste or product status. These regulatory factors may therefore favour or constrain specific valorization routes, but their influence remains dependent on the characteristics of the recovered streams and the regulatory context in which they are used. Beyond the parameters currently addressed by the main sludge regulations, it must be considered that the fate of emerging contaminants, including per- and polyfluoroalkyl substances (PFAS), microplastics, and pharmaceutical residues, depends on the treatment pathway and remains incompletely characterized, limiting conclusions regarding the safe reuse of hydrochar, biochar, ash, digestate, and recovered nutrient products. Within these regulatory and technical constraints, wastewater treatment plants may progressively evolve into Water Resource Recovery Facilities (WRRFs), where biological, thermochemical, and electrochemical processes operate synergistically to maximize the recovery of valuable resources from sewage sludge. This integration-centred perspective provides the framework for the technologies discussed in the following sections.

4. Conventional Technologies for Energy Recovery from SS

Sewage sludge contains a significant fraction of organic matter, largely biodegradable, which makes it a suitable feedstock for energy recovery. Conventional energy recovery technologies mainly include thermal processes, such as incineration and co-combustion, aimed at exploiting the total content of organic matter, and biochemical processes, such as anaerobic digestion (AD), aimed at the biogasification of the biodegradable share. These technologies are technically mature and widely implemented in municipal WWTPs. Nevertheless, despite their long operational history, they are increasingly affected by intrinsic limitations related to energy recovery efficiency, operational costs, and environmental performance [11,26–28]. From a system perspective, conventional technologies generally operate as single-purpose solutions, focusing either on energy recovery or volume reduction. As a result, they often follow linear treatment schemes that do not fully exploit the energetic and material potential of sewage sludge, leaving significant residual streams that require further management.

4.1. Anaerobic Digestion

Anaerobic digestion (AD) is a biochemical process that converts biodegradable organic matter into biogas and stabilized digestate through hydrolysis, acidogenesis, acetogenesis, and methanogenesis [28]. In this review, AD is considered mainly as an established baseline technology and as an upstream biological platform for hybrid configurations, because its performance depends on sludge biodegradability, process stability, energy balance, and digestate management.

AD is extensively applied at wastewater treatment plants (WWTPs) to stabilize sewage sludge (SS), reduce its volatile-solids content, and recover renewable energy. The resulting biogas is commonly used in combined heat and power (CHP) units to generate electricity and heat, part of which can be consumed on site. Alternatively, biogas can be upgraded to biomethane for injection into the natural-gas grid or use as a vehicle fuel [29,30].

Biogas production and process stability during sewage sludge AD depend on feed characteristics and key operating parameters, including temperature, pH and alkalinity, the VFA-to-alkalinity ratio, organic loading rate, solids retention time (SRT), and feed volatile-solids-to-total-solids ratio (VS/TS) [31,32]. Methanogenic microorganisms are particularly sensitive to unfavourable operating conditions, which may lead to VFA accumulation

and incomplete substrate conversion [33]. Staged digestion can exploit the separation of acidogenic and methanogenic conditions to improve process control and resource recovery.

Sewage sludge AD is commonly operated under mesophilic (approximately 30–40 °C) or thermophilic (approximately 50–60 °C) conditions. Thermophilic operation can increase reaction rates and pathogen destruction and allow higher volumetric methane production, but generally involves greater heating requirements and lower process stability [31,34]. Conversely, operation below 30 °C generally reduces conversion rates. Hidaka et al. [35] reported reduced AD performance at 15–25 °C, which was partially compensated by hyperthermophilic pretreatment at 80 °C for 24 h.

Despite its technological maturity, sewage sludge AD remains constrained by the slow hydrolysis of particulate and recalcitrant organic matter. The extracellular polymeric substance (EPS) matrix surrounding activated-sludge microorganisms can affect cell disruption, substrate solubilization, and electron-transfer processes, thereby influencing sludge biodegradability [36].

Protein degradation can also release ammonia, with free ammonia potentially inhibiting methanogenic activity and reducing methane production [37]. Moreover, the resulting digestate still requires beneficial utilization, further treatment, or final disposal, with implications for the environmental performance of the overall process [38,39].

Accordingly, thermal, chemical, mechanical, biological, and enzymatic pretreatments have been investigated to improve sludge solubilization and biodegradability and enhance biogas production [40,41]. The soluble organic matter and nutrients released through these pre-treatments may also support alternative resource-recovery pathways, provided that the subsequent digestion conditions are appropriately controlled.

4.2. Thermal Treatment of Sewage Sludge

Thermal treatment is widely applied in sewage sludge (SS) management because it can substantially reduce sludge mass and volume, destroy pathogens and organic contaminants, and enable partial energy recovery. However, the high water content of mechanically dewatered sludge remains a major limitation for thermal conversion. In practice, dewatered sludge can still contain around 70–85% moisture [42], which lowers its effective calorific value and increases the energy demand for drying, transport and handling. For this reason, dewatering and drying are often required before full-scale thermal treatment [42].

Among thermal routes, incineration and co-combustion are considered here as conventional technologies because of their established full-scale application in sewage sludge management, whereas HTC, pyrolysis and gasification are discussed in Section 5 as emerging valorization routes, reflecting their comparatively more limited application to sewage sludge and their stronger focus on the recovery of specific energy and material products. Inventory data indicate that the energy balance of sludge incineration depends strongly on the degree of drying: dried sludge incineration may approach energy balance, with an energy demand of about 0.2 kWh kg^{−1} TS, whereas dewatered sludge incineration may require approximately 1–2 kWh kg^{−1} TS more energy than can be recovered [42]. Therefore, the costs and energy consumption associated with sludge dewatering and drying represent a significant operational constraint for commercial facilities. In addition, the use of SS as a fuel in conventional combustion systems is constrained by its legal classification as waste, its variable composition, and the need to comply with waste-incineration, emission-control and product-quality requirements.

4.2.1. Incineration

Incineration is a high-temperature oxidation process used for sewage sludge stabilization, mass and volume reduction, and potential energy recovery. In contrast to AD,

which converts mainly the biodegradable fraction of sludge organic matter into biogas, incineration can oxidize the total organic fraction; however, its net energy performance is strongly constrained by the drying demand discussed above. In sewage sludge incineration performed under excess oxygen conditions, operating temperatures are typically in the range of 850–950 °C [42]. Thermal treatment can reduce sludge mass by approximately 70% and volume by about 90%, while concentrating inorganic constituents in the resulting incinerated sewage sludge ash (ISSA), including phosphorus and trace metals [43]. Depending on sludge origin and drying degree, sewage sludge may show a dry-basis calorific value of approximately 12–16 MJ kg^{−1}; however, this energy potential is strongly penalized by the significant water content [43].

Fluidized-bed reactors are commonly used for sewage sludge mono-incineration because they provide efficient fuel mixing, relatively homogeneous temperature distribution and good burnout performance. Nevertheless, combustion stability can be affected by fluctuations in moisture content, ash content and heating value, confirming the need for careful control of feed characteristics and operating conditions [42,43].

Flue gases generated during incineration require advanced treatment to control particulate matter, NO_x, SO_x, acid gases, organic micropollutants and volatile metals. Air-pollution-control systems may include scrubbers, electrostatic precipitators, fabric filters and catalytic or sorbent-based units, depending on plant configuration and regulatory requirements. Air-pollution-control residues and ISSA can concentrate both recoverable nutrients and potentially hazardous elements. In a recent case study from a Polish wastewater treatment plant, ISSA contained approximately 17 wt.% P₂O₅ on average, together with relevant concentrations of Zn, Pb, Cu, Ni and Cr [43]. This dual character makes ISSA both a secondary phosphorus resource and a material requiring careful environmental assessment.

The recovery potential of phosphorus from ISSA depends not only on total P content, but also on mineral speciation. Recent mineralogical work showed that phosphorus in sewage sludge ash can exceed 7 wt.% and is mainly associated with phosphate phases, particularly whitlockite-type minerals containing Ca, Fe and Mg; these phases may limit direct bioavailability and influence the efficiency of acid extraction or thermochemical upgrading [44]. Mono-incineration is therefore preferable when phosphorus recovery is a priority, because it preserves P in a relatively concentrated and homogeneous ash stream. By contrast, co-combustion may dilute P into mixed ash matrices, complicating subsequent recovery.

Despite these advantages, incineration presents environmental and economic challenges. High drying demand, air-emission-control requirements, formation of NO_x, SO_x and trace organic pollutants, and the need for ash management, all constrain its sustainability. Research should therefore focus on integrated incineration-valorization schemes, in which ISSA is valorized through phosphorus extraction, fertilizer production, cement raw materials substitution, supplementary cementitious materials or fine aggregate replacement. These routes remain strongly dependent on ash mineralogy, heavy-metal content, leaching behaviour, particle size, water demand, mechanical performance and compliance with environmental regulations.

4.2.2. Co-Combustion

Sewage sludge co-combustion consists of blending SS with a primary fuel such as coal, municipal solid waste, biomass or alternative fuels. Compared with mono-incineration, co-combustion can partly offset the low effective heating value of wet sludge by mixing it with a more energy-rich fuel and using existing combustion infrastructure. Co-combustion has been investigated mainly in fluidized-bed systems, pulverized-coal boilers, municipal solid waste (MSW) incinerators and cement kilns. However, sludge addition must

remain compatible with combustion stability, air emissions, ash quality and downstream product requirements.

In coal-based systems, sludge can partially substitute the main fossil fuel, but the blending ratio is a key operational parameter. In a lab-scale fluidized-bed furnace, Qu et al. [45] tested dry coal-sludge co-combustion with sludge mixing ratios below 20% and observed that SO_2 , NO_x and dioxin emissions increased approximately linearly with the sludge mixing ratio. The same study found that, under low sludge fractions, the combustion behaviour remained largely dominated by coal, while higher sludge addition increased the relevance of pollutant control and ash-quality assessment. These results support the use of limited sludge shares when combustion stability and emission compliance are priorities.

Co-combustion with municipal solid waste is also technically attractive because MSW can provide additional calorific value and shared infrastructure. Recent experimental work on sludge co-combustion with MSW showed that increasing the sludge blending ratio from 0 to 10 and 20% decreased the furnace temperature and increased NO_x emissions, confirming that sludge addition requires careful control of feed characteristics and operating conditions [46]. Numerical modelling of a full-scale MSW incinerator showed that sewage sludge co-combustion ratios of 5–15% significantly affected the temperature, time of processing, and pollutant concentration fields; in that case, a 7% sludge ratio gave the most favourable combustion efficiency, while higher ratios reduced temperature uniformity and process stability [47]. These findings indicate that the optimal sludge fraction is plant-specific and depends on feedstock properties, furnace design and operating temperature.

Cement kiln co-processing represents a distinct form of co-combustion because SS can act both as an auxiliary fuel and as a mineral input. The organic fraction contributes to heat generation, while the inorganic fraction may be incorporated into the clinker, reducing the amount of separate ash residue. Recent experimental work on pretreated sludges for cement kiln co-processing used clinker-forming conditions of 1450 °C for 60 min and showed that sludge pretreatment strongly affected suitability for cement production [48]. In that study, mechanically dewatered sludge had a moisture content of about 80.3%, deeply dewatered sludge about 55.7%, and lime-dried sludge about 35.9%; the usable ash contents were 8.1%, 23.3% and 46.3%, respectively. Lime-stabilized sludge also showed a CaO content up to 57.6%, making it more similar to limestone raw material, whereas mechanically and deeply dewatered sludges were closer to iron-rich raw materials because of their Fe_2O_3 contents of approximately 15.0% and 11.6%, respectively [48].

However, cement kiln co-processing also presents environmental and product-quality constraints. High moisture lowers the usable heating value, while chlorine, sulfur, alkalis, phosphorus and heavy metals can affect kiln operation, volatilization phenomena, scaling, clinker mineralogy and cement quality. Cheng et al. [48] reported that deeply dewatered sludge had a chlorine content of 1.80%, compared with 0.10% for mechanically dewatered sludge and 0.04% for lime-dried sludge, highlighting the importance of the selected conditioning process. Field measurements from a cement kiln co-processing sewage sludge also showed increases in PAHs and low-volatile heavy metals, especially Cd and Pb, in particulate emissions and surrounding environmental compartments [49]. Therefore, although co-combustion can reduce fossil-fuel consumption and minimize separate sludge residues, its feasibility depends on strict feedstock control, flue-gas treatment, transport distance, local regulation and the quality requirements of the final ash or clinker product.

4.3. Comparative Analysis of Conventional Energy Recovery Technologies

Comparative analysis of conventional technologies reveals intrinsic trade-offs between energy recovery efficiency, environmental impact, and operational feasibility. Anaerobic digestion remains the most established biochemical route, generating biogas with

moderate energy yield but leaving a nutrient-rich digestate that requires post-treatment. Conversely, incineration and co-combustion achieve significant volume reduction and complete pathogen destruction, yet both are constrained by high energy demand for drying and potential air emissions. Sewage sludge incineration and co-combustion performance varies systematically with three primary factors: feedstock moisture content, technology configuration, and emission control system sophistication. Studies reporting energy-positive operation (85% gross efficiency, self-sufficiency with excess heat) involved dried or mechanically dewatered feedstock processed in advanced fluidized bed systems [50], while studies showing energy consumption exceeding recovery ($1\text{--}2\text{ kWh kg}^{-1}\text{ TS}$ vs. $0.2\text{ kWh kg}^{-1}\text{ TS}$ recovered) examined dewatered without aggressive moisture reduction [42]. This pattern reflects thermodynamic fundamentals: water evaporation consumes approximately 2.26 MJ kg^{-1} , and sewage sludge heating values of $16\text{--}19\text{ MJ kg}^{-1}$ [51] leave limited net energy at high moisture contents. The moisture thresholds reported in [52], including 70% for mono-incineration, 60% for coal co-firing, and 50% for cement kilns, were identified under specific feedstock and process conditions and should therefore not be interpreted as general design limits. In the same study, moisture contents above 75% were associated with up to a fourfold increase in co-incineration emissions, further illustrating the influence of sludge moisture on energy and environmental performance.

Despite their widespread implementation, these technologies face increasing economic, environmental, and regulatory pressures. AD performance is often limited by the low biodegradability of some sludge fractions, requiring pre-treatment or co-digestion strategies to enhance methane yield. Incineration, while efficient for volume reduction, is constrained by high energy input and air pollution control requirements, whereas co-combustion can benefit from energy integration with the primary fuel but suffers from feedstock variability and, again, strict emission regulations. Accordingly, emerging technologies are being investigated as complementary options: HTC can process wet sludge without complete drying; pyrolysis and gasification can provide additional routes for converting residual organic matter into carbonaceous or gaseous products; and BES can enable energy or resource recovery under relatively mild operating conditions. Their potential and limitations are discussed in Section 5.

5. Emerging Technologies for Sewage Sludge Valorization

As conventional SS management strategies face mounting economic, environmental, and regulatory pressures, emerging technologies are being investigated for their ability to recover energy and materials and to accommodate different sludge characteristics. Thermochemical processes, such as HTC, pyrolysis, and gasification, enable the conversion of wet or dry SS into energy-rich products (e.g., hydrochar from HTC, biochar from pyrolysis, and syngas from gasification), while overcoming limitations associated with traditional disposal routes. This section focuses on how the feedstock requirements, product streams, energy performance, contaminant partitioning, and integration potential of these emerging technologies affect their role in sludge biorefinery schemes.

5.1. Hydrothermal Carbonization

Hydrothermal carbonization is a wet thermochemical process that converts sewage sludge into hydrochar, process water and a minor gas fraction under hydrothermal conditions. It is typically operated at $160\text{--}250\text{ }^{\circ}\text{C}$ in sealed systems under autogenous pressure, commonly reported in the range of $2\text{--}10\text{ MPa}$. Unlike pyrolysis, gasification or incineration, HTC takes place in an aqueous environment and can therefore treat high-moisture sewage sludge without complete pre-drying [13,27]. This is a major advantage for sludge manage-

ment, because mechanical dewatering still leaves a large amount of water in the sludge and conventional thermal drying is energy-intensive.

During HTC, the organic fraction of SS undergoes hydrolysis, dehydration, decarboxylation, condensation and aromatization reactions. These reactions increase the carbonization degree of the solid phase, reduce the O/C and H/C ratios, and transfer part of the organic matter and nutrients into the liquid phase [52,53]. The relative distribution of hydrochar, process water and gas depends mainly on temperature, residence time, initial solids content, pH and sludge composition [54,55]. In sewage sludge HTC, increasing process severity generally decreases solid yield and increases the carbonization degree of the hydrochar, but it may also increase the concentration of soluble organic compounds in the process water and the immobilization of inorganic elements in the solid phase [56].

Even relatively mild HTC conditions can substantially modify sewage sludge properties, including dewaterability, carbon distribution, and solid-phase characteristics, although the extent of these changes remains strongly dependent on process severity, pH, and feedstock composition [57–59].

5.1.1. Hydrochar and Uses

Hydrochar is the primary solid product of HTC and consists of a carbonaceous matrix enriched in mineral matter, phosphorus and metals. Compared with untreated SS, hydrochar generally has lower moisture after mechanical separation, improved dewaterability, a higher degree of carbonization, and a more coal-like structure [59,60]. For this reason, SS-derived hydrochar has been investigated as a solid fuel, a precursor for activated carbon, an adsorbent and, more cautiously, as a soil amendment or nutrient carrier.

As a solid fuel, hydrochar can show improved handling and storage properties compared with raw sludge [61]. The HTC slurry is typically easier to dewater than untreated sludge, and the separated hydrochar has lower water content and higher physical stability than the original wet feedstock. However, its fuel quality remains strongly affected by the high ash content of sewage sludge. Therefore, SS-derived hydrochar is more realistically considered as a low-grade solid fuel or co-fuel for industrial applications, rather than as a direct substitute for high-quality biomass or coal. The suitability of hydrochar for energy use depends on ash content, heating value, combustion behaviour, slagging/fouling tendency and compliance with emission-control requirements [62].

HTC can also improve the carbon stability of the solid phase. Increasing severity tends to increase aromaticity and reduce the relative abundance of labile organic compounds. However, because sewage sludge contains substantial inorganic matter, the improvement in fuel properties is often less pronounced than for lignocellulosic biomass. For example, recent experiments on SS hydrothermal treatment showed that carbon enrichment was measurable but moderate, with raw sludge increasing from 36% carbon to 43% in acidified hydrochar under the tested conditions [58]. This confirms that the final hydrochar quality is constrained by the initial sludge composition and by the ash-rich nature of the feedstock [62].

Agricultural use of SS-derived hydrochar is possible only after careful assessment. Hydrochar may contain nutrients, particularly phosphorus, but it can also concentrate heavy metals and persistent contaminants. Studies on the distribution and transformation of heavy metals and phosphorus during HTC of sewage sludge show that HTC can promote the transfer of some elements into more stable solid fractions, but does not remove them from the system [63,64]. Therefore, direct land application is constrained by total metal concentration, chemical speciation, leaching behaviour, nutrient availability and national regulations.

Another relevant application is the use of hydrochar as an adsorbent or as a precursor for activated carbon. Raw SS-derived hydrochar usually has limited surface area compared with commercial activated carbon, but thermal or chemical activation can improve porosity and surface functionality [65,66]. In this context, hydrochar should be considered a precursor material rather than a finished adsorbent. Its suitability for wastewater treatment applications depends on activation method, surface area, functional groups, ash content, metal leaching and regeneration potential.

5.1.2. Process Water and Valorization

Alongside hydrochar, HTC generates a liquid by-product usually referred to as process water or HTC liquor. This stream contains dissolved organic carbon, volatile fatty acids, nitrogen species, phosphorus, potassium and a broad range of soluble organic compounds formed during hydrolysis and carbonization reactions. Its management is critical for the sustainability of HTC, because process water can represent a significant residual pollution load even when the solid fraction is successfully stabilized [67].

The composition of HTC process water is strongly dependent on treatment temperature and severity. Higher temperatures generally increase solubilization and formation of recalcitrant or inhibitory compounds. In process waters produced from HTC of sewage sludge, aerobic treatment can remove part of the biodegradable organic matter, but residual dissolved organic carbon may still be too high for direct discharge [68]. Blach et al. [69] showed that process waters generated at higher HTC temperature had greater inhibition potential; after aerobic treatment, model calculations still predicted an increase in effluent DOC of 8.3 mg C L^{-1} , indicating that additional treatment may be required before discharge or recirculation.

Because HTC process water contains soluble organic matter, it can be considered for further biological treatment or energy recovery. However, in this section the focus is on HTC applied directly to sewage sludge, while integration with anaerobic digestion and digestate management is discussed separately. For direct SS-HTC, the most conservative interpretation is that process water should be treated as a high-strength liquid residue requiring controlled biological, chemical or physicochemical treatment. Potential options include aerobic treatment, anaerobic treatment, wet oxidation, membrane filtration, adsorption or recirculation to the head of the wastewater treatment plant, but each option must account for refractory COD, nitrogen load, salinity and possible inhibitory compounds [70].

The nutrient content of process water also creates opportunities for resource recovery. Phosphorus and nitrogen can be partially mobilized during HTC, enabling downstream recovery by precipitation, membrane separation or chemical extraction [71]. However, phosphorus partitioning depends strongly on pH, calcium, iron and aluminum chemistry. Experimental work on phosphorus transformation during HTC of sewage sludge showed that pH and calcium addition can substantially influence P migration and speciation, indicating that nutrient recovery must be designed together with the HTC operating conditions rather than as a downstream add-on [72]. Similarly, Fe-assisted hydrothermal treatment can change phosphorus speciation and recovery behaviour, showing that sludge conditioning chemicals can strongly affect nutrient valorization routes [73].

5.1.3. Challenges and Integration Potential

Although HTC has important advantages for wet sewage sludge, several technical and environmental challenges remain. The first is process optimization. Temperature, residence time, pH and solids content must be selected to balance hydrochar yield, dewaterability, carbon stability, nutrient retention and process-water quality. Higher severity may improve carbonization and solid stabilization, but it can also increase soluble organic load and the formation of recalcitrant

compounds in the liquid phase. Conversely, milder conditions may preserve more biodegradable compounds but generate less carbonized hydrochar[57,58,61].

A second challenge is the fate of heavy metals and inorganic contaminants. HTC can immobilize some metals by promoting their association with more stable mineral fractions [64,74], but metals are generally retained and concentrated in the hydrochar rather than destroyed. For sewage sludge hydrochar, this is a decisive constraint for agricultural use and for any open-loop application. Washing, acid leaching, chelation or chemical stabilization may reduce metal mobility, but these treatments add cost, generate secondary liquid residues and may also remove useful nutrients such as phosphorus.

The third challenge is process-water management. HTC liquor can contain biodegradable organics, refractory compounds, nitrogen, phosphorus and potentially inhibitory substances. Direct discharge is generally not appropriate without further treatment. Thermal disposal, distillation, wet oxidation and biological treatment have been investigated as management options for process water derived from HTC of sewage sludge, but the choice depends on site-specific energy integration and regulatory constraints [75,76]. In full-scale applications, process-water treatment may therefore become one of the main determinants of environmental performance.

HTC can be integrated into wastewater treatment plants either as a post-thickening/post-dewatering treatment or as part of a broader sludge valorization line. Simulation and life-cycle studies on municipal wastewater treatment plants indicate that introducing HTC can reduce sludge disposal burdens and generate a valorized solid product, but environmental benefits depend strongly on plant configuration, electricity demand, hydrochar use and treatment of the liquid fraction [77]. Therefore, HTC should not be evaluated only as a sludge reduction technology, but as an integrated process in which hydrochar valorization, nutrient recovery, process-water treatment and energy management are optimized together.

Overall, HTC is particularly suitable for sewage sludge because it directly treats wet feedstocks and produces a mechanically separable hydrochar. Its main strengths are improved dewaterability, partial carbon stabilization, reduction in sludge disposal volume and potential recovery of nutrients and carbonaceous materials. Its main limitations are the high ash and heavy-metal content of SS-derived hydrochar, the treatment burden of process water, and the need to demonstrate robust full-scale integration with existing wastewater treatment infrastructure.

5.2. Pyrolysis

Pyrolysis is a thermochemical decomposition process that converts sewage sludge (SS) into biochar, bio-oil and pyrolysis gas by heating the feedstock under strictly oxygen-limited or inert conditions. Sewage sludge pyrolysis is commonly investigated in the range of approximately 300–700 °C, although higher temperatures can be used when carbon stability or gas production is prioritized. In contrast to incineration, which fully oxidizes organic matter, pyrolysis promotes the thermal cracking of organic compounds while retaining part of the carbon and most inorganic nutrients in the solid phase. Pyrolysis can therefore support waste-to-energy conversion, potential downstream nutrient recovery from nutrient-enriched solid residues, and the production of carbonaceous materials from SS [78].

Product distribution is strongly controlled by temperature, heating rate, residence time and sludge composition. In general, lower pyrolysis temperatures favour solid biochar production, whereas increasing temperature promotes devolatilization, secondary cracking and gas formation [79]. In a recent study on municipal sludge-derived biochar, increasing the pyrolysis temperature from 300 to 800 °C reduced biochar yield from 76.91% to 53.90%, while increasing pH from 7.05 to a maximum of 10.04 at 600 °C [80]. Similarly, sewage

sludge pyrolysis at 500, 600, 750 and 850 °C showed that temperature and residence time strongly affect carbon stability and energy recovery; in that study, optimal conditions for balancing carbon stability and energy production were identified at 750 °C and 2 h, producing a biochar with an H/C_{org} ratio of 0.54 and nutrient contents of 3.99% TN, 3.2% TP and 0.6% K [81].

Over the past decade, pyrolysis has been investigated at laboratory and pilot scale, especially because it can generate multiple products rather than a single disposal residue. Nevertheless, its full-scale application in wastewater treatment plants remains less established than incineration or co-combustion. The practical feasibility of SS pyrolysis depends on sludge drying requirements, heat integration, pollutant control, product quality and the existence of reliable markets for biochar, bio-oil or gas.

5.2.1. Biochar

Biochar is the primary solid product of SS pyrolysis and consists of a carbonaceous matrix enriched in ash, phosphorus and metal-bearing mineral phases. Compared with raw SS, pyrolysis reduces moisture and volatile organic matter, increases aromaticity and generally improves carbon stability. These changes make sludge-derived biochar potentially suitable as a solid fuel, soil amendment, adsorbent or precursor for activated carbon. However, its properties differ substantially from lignocellulosic biochars because SS usually contains higher ash, nutrient and heavy-metal contents.

For energy applications, SS-derived biochar can be considered a solid fuel or co-fuel, although its high ash content may limit its heating value and combustion performance. Higher pyrolysis temperatures tend to reduce char yield but increase aromaticity, ash concentration and carbon stability [82]. For instance, pyrolysis at 750 °C for 2 h produced a biochar with H/C_{org} = 0.54, indicating relatively stable aromatic carbon, while still retaining relevant nutrient contents [81]. These characteristics indicate increased carbon stability but may reduce fuel reactivity compared with raw sludge or low-temperature chars.

Biochar also has potential as a soil amendment because it can supply nutrients, increase pH, improve field capacity and retain carbon in the solid phase. However, agricultural use requires careful assessment of heavy metals, salts, organic contaminants and nutrient bioavailability. Pyrolysis can transform metals from more mobile fractions into more stable forms, but it does not eliminate most metals; instead, metals often become concentrated in the solid residue as organic matter is decomposed. In sewage sludge biochars produced at 350, 450 and 600 °C, increasing pyrolysis temperature promoted the transformation of metals into more stable and less available fractions, although Cd remained the main contributor to the potential ecological risk index [83]. Co-pyrolysis with biomass can further improve biochar quality: co-pyrolysis of SS with reed at 300, 500 and 700 °C reduced ash content, increased pH, carbon content and aromatic structure, and decreased the content and toxicity of heavy metals compared with single SS pyrolysis [84,85].

A further application of SS-derived biochar is environmental remediation. Its porous structure, alkaline surface and functional groups can promote adsorption of metals and organic contaminants from water. The adsorption capacity depends strongly on pyrolysis temperature and surface development. In one recent study, municipal sludge biochar produced at 800 °C achieved 95% sulfamethoxazole removal and a maximum adsorption capacity of 7033.4 mg kg⁻¹, which was 47.5 times higher than that of biochar produced at 300 °C [80]. These results indicate that high-temperature or activated sludge biochars can be promising low-cost adsorbents, but their use must be evaluated together with potential leaching of metals, regeneration options and end-of-life management.

5.2.2. Bio-Oil and Syngas

Alongside biochar, SS pyrolysis produces a liquid fraction commonly referred to as bio-oil. Sewage sludge bio-oil is a complex mixture of water, oxygenated compounds, nitrogen-containing compounds, hydrocarbons, phenols and organic acids [86]. Its composition depends on sludge origin and pyrolysis conditions, but it is generally more chemically challenging than bio-oil derived from lignocellulosic biomass because of the high nitrogen, sulfur and ash content of SS. These characteristics can reduce stability, increase corrosiveness and complicate direct use as a transportation fuel.

Bio-oil can nevertheless be used as an energy carrier or upgraded into higher-quality fuels and chemicals. Pretreatment and catalytic upgrading are particularly important because they can reduce undesirable oxygen- and nitrogen-containing compounds. In a recent experimental study, sewage sludge was hydrothermally pretreated at 160–250 °C and subsequently pyrolyzed at 550 °C. The combined process increased the yield of aliphatic hydrocarbons and aromatics in the bio-oil by 9.53% and 23.18%, respectively, while the bio-oil obtained after 190 °C pretreatment followed by 550 °C pyrolysis reached an HHV of 36.382 MJ kg^{−1} and an energy recovery rate of 44.23% [87]. These values show that SS-derived bio-oil can have relevant fuel potential, but upgrading remains necessary to improve stability, reduce heteroatoms and meet fuel-quality requirements.

The gaseous fraction of pyrolysis is mainly composed of H₂, CO, CH₄, CO₂ and light hydrocarbons [88]. This gas can be combusted on site to provide process heat, support sludge drying or contribute to electricity generation. The composition and yield of pyrolysis gas are strongly temperature-dependent. Microwave-assisted pyrolysis experiments with primary sludge, waste activated sludge and digested sludge showed that gas production and the H₂ and CO fractions increased with increasing temperature; waste activated sludge produced the largest amount of gas, while primary sludge produced the highest-quality syngas in terms of H₂ and CO content [89]. These findings confirm that sludge type and heating mode strongly influence gas quality and energy recovery.

Beyond direct combustion, pyrolysis gas can in principle be upgraded or reformed for value-added applications, including hydrogen-rich gas production, methanol synthesis or Fischer-Tropsch fuels. However, these applications require more stringent gas-cleaning and conditioning steps than simple heat recovery. Tar, ammonia, sulfur compounds, particulates and chlorine-containing species must be removed or converted to avoid catalyst poisoning, corrosion and operational instability. For this reason, the most realistic near-term use of SS pyrolysis gas in WWTP-integrated systems is internal heat recovery rather than external fuel or chemical synthesis.

5.2.3. Challenges and Limitations

Despite its potential, sewage sludge pyrolysis faces several technical, environmental and economic limitations. The first is feedstock variability which is reflected in the chemical-physical characteristics and the concrete prospects of use of the final products. SS composition depends on wastewater characteristics, treatment line, stabilization process and dewatering chemicals, which can affect product distribution, ash content, nutrient speciation, metal mobility and fuel quality. Because SS usually contains high moisture and high ash content, drying and preprocessing remain major energy and cost barriers before conventional dry pyrolysis can be implemented.

A second limitation concerns heavy metals and inorganic contaminants. Pyrolysis can reduce the bioavailability of several metals by promoting their transformation into more stable mineral fractions, but it generally concentrates metals in the biochar. This is beneficial if biochar is treated as a controlled solid product, but it becomes a constraint for agricultural use. Studies on SS biochar produced at 350–600 °C showed that higher

temperature improved metal stabilization, but Cd still dominated the potential ecological risk profile [83]. Co-pyrolysis can reduce risk by dilution and mineral interactions, but its performance depends on the type and proportion of co-feedstock, temperature and residence time [84].

A third limitation is product quality. Biochar can be useful for carbon storage, adsorption or soil amendment, but each application requires different properties and regulatory thresholds. High-temperature biochar may have better adsorption performance and stability, whereas lower-temperature biochar may retain more labile nutrients but also more organic residues. Bio-oil can show relevant HHV values but requires upgrading because of oxygenated and nitrogen-containing compounds, while pyrolysis gas requires cleaning if it is intended for advanced energy or chemical applications. Therefore, pyrolysis should not be evaluated only as a sludge disposal technology, but as an integrated product-oriented process.

Finally, process scalability remains challenging. Although laboratory and pilot-scale results are encouraging, commercial deployment requires robust reactor design, continuous feeding of dried sludge, heat recovery, emission control and reliable outlets for the products. Integration with anaerobic digestion, hydrothermal pretreatment, nutrient recovery or co-pyrolysis with biomass could improve the overall energy and resource balance [90,91]. However, these integrated configurations must be assessed through site-specific techno-economic and environmental analyses before they can be considered mature alternatives to incineration or co-combustion.

5.3. Gasification

Gasification is a thermochemical conversion process that transforms sewage sludge (SS) into a combustible gas, together with solid residues composed of char and ash, by reacting the feedstock with a limited amount of gasifying agent such as air, oxygen, steam or mixtures of these agents. Conventional dry gasification of SS is generally performed at high temperature, commonly around 700–950 °C in fixed-bed and fluidized-bed systems, although entrained-flow or plasma-based configurations may operate at higher temperatures. Unlike incineration, which aims at complete oxidation, gasification operates under oxygen sub-stoichiometric conditions and partially converts the carbonaceous fraction into a syngas mainly composed of H₂, CO, CH₄ and CO₂ [12,22].

Compared with direct combustion, gasification offers greater flexibility because the energy content is transferred to a gaseous intermediate that can be used for heat and power generation or, after appropriate cleaning and conditioning, as a precursor for fuels and chemicals. However, sewage sludge is a challenging gasification feedstock because it usually contains high moisture, high ash content, nitrogen, sulfur, chlorine, phosphorus and trace metals. These characteristics influence gas yield, syngas composition, tar formation, ash behaviour and the design of gas-cleaning systems. Experimental work on fluidized-bed gasification of sewage sludge has shown that the process can produce syngas with lower heating values in the range of 5.8–12.1 MJ Nm^{−3} and cold gas efficiencies of about 0.50–0.57, depending on sludge properties and equivalence ratio [92].

The gasification performance depends on temperature, gasifying agent, equivalence ratio, steam-to-carbon ratio, reactor configuration and feedstock composition. In steam-oxygen fluidized-bed gasification of dried sewage sludge, increasing temperature increased gas yield and H₂ and CO concentrations, while reducing tar formation. In the same study, gravimetric tar concentration decreased from 98 g m^{−3} at 659 °C to 31 g m^{−3} at 778 °C, 27 g m^{−3} at 842 °C and 21 g m^{−3} at 894 °C, indicating that operation at about 850–900 °C is preferable when ash-melting constraints allow it [93]. These results confirm that gasification

temperature is one of the most important parameters controlling both energy recovery and gas quality.

5.3.1. Syngas

The primary product of gasification is syngas, a mixture mainly composed of H_2 , CO, CH_4 , CO_2 and minor light hydrocarbons. The relative proportions of these compounds depend on gasifying agent and operating conditions. Air gasification is simpler and cheaper, but nitrogen dilution lowers syngas heating value. Oxygen- and steam-based gasification produce a nitrogen-lean gas with higher concentrations of H_2 and CO, but require oxygen supply, steam generation and tighter process control.

Fluidized-bed studies confirm the strong effect of operating conditions on syngas quality. In air/oxygen-lean gasification of two sewage sludge samples at 850 °C, [92] reported syngas compositions containing approximately 26.9–33.3 vol.% H_2 , 28.9–31.1 vol.% CO, 20.9–29.0 vol.% CO_2 and 10.2–11.5 vol.% CH_4 , with LHV values of 5.8 and 12.1 MJ Nm^{−3} for the two tested sludges. In steam-oxygen gasification, Schmid et al. [93] showed that increasing temperature enhanced fuel conversion to permanent gases and increased H_2 and CO concentrations, while higher steam-to-carbon ratios promoted tar reforming.

Syngas can be directly combusted in boilers or used in gas engines and turbines for combined heat and power generation. This is the most realistic near-term application in wastewater treatment plants because it can support sludge drying or provide process heat. More advanced applications, such as hydrogen extraction, methanol synthesis or Fischer-Tropsch fuel production, require a cleaner and more consistent syngas. For these routes, removal of tar, particulates, ammonia, H_2S , COS, chlorine compounds and volatile metals is essential to prevent corrosion, catalyst poisoning and operational instability [94,95].

5.3.2. Solid Residues

Gasification generates solid residues consisting of bottom ash, fly ash and unconverted char. In sewage sludge gasification, the solid fraction is usually highly mineral because SS contains substantial amounts of inorganic matter. For this reason, the term “biochar” should be used cautiously: in many cases the solid product is better described as char-rich ash or gasification ash rather than a conventional biomass-derived biochar.

The quantity and quality of solid residues depend on ash content, temperature, equivalence ratio and reactor design. In fluidized-bed gasification of two sewage sludge samples, bottom ashes contained approximately 90.0–95.1 wt.% ash, with residual carbon contents of 3.17–7.00 wt.% and low volatile matter contents of 4.48–6.00 wt.% [92]. These values indicate extensive organic conversion and a predominantly inorganic residue. The same study reported that bottom ash properties, including surface area and elemental enrichment, depended on the reducing conditions adopted during gasification, with a surface area up to 32 m² g^{−1} under more reducing conditions [92].

Sewage sludge gasification ash can retain relevant amounts of phosphorus, making it a potential secondary resource [96]. Migliaccio et al. [92] observed alkaline-soluble phosphorus bonds in bottom gasification ashes, suggesting that gasification may facilitate subsequent P separation through relatively simple alkaline extraction routes. In low-temperature circulating fluidized-bed gasification of municipal sewage sludge, the resulting ashes were also investigated as phosphorus fertilizers; co-gasification ashes showed improved fertilizer qualities compared with mono-sludge ashes, mainly due to higher recalcitrant carbon, phosphorus and potassium contents, lower cadmium content and improved plant P availability [97]. However, when the focus is on mono-gasification of SS, heavy-metal concentration and leaching behaviour remain decisive constraints for agricultural or construction-related uses.

5.3.3. Challenges and Limitations

Gasification offers several potential advantages over conventional sludge disposal. It can reduce sludge volume, destroy organic contaminants, recover energy as syngas and concentrate phosphorus in a solid residue suitable for further treatment [98]. Compared with incineration, gasification operates under oxygen-deficient conditions and can reduce direct flue-gas volumes. Nevertheless, it should not be assumed to be intrinsically emission-free: pollutant formation and release depend on reactor design, gasifying agent, temperature, gas-cleaning configuration and the fate of nitrogen-, sulfur-, chlorine- and metal-containing compounds.

A major limitation is syngas quality. Raw syngas from sewage sludge gasification contains tar and heteroatom-rich compounds. In steam-oxygen gasification, tar included BTX compounds, benzene and heavier gravimetric fractions, while sewage sludge tar also contained significant amounts of nitrogen-, sulfur- and chlorine-containing species [93,95]. In fluidized-bed gasification at 850 °C, measured tar contents were 29.4 and 37.5 g Nm⁻³ for two sewage sludge samples [92]. These levels require downstream cleaning if syngas is to be used in engines, turbines or catalytic synthesis. Thermal cracking, catalytic reforming, filtration and wet or dry scrubbing can reduce tar and acid gases, but they increase system complexity and cost.

Feedstock variability is another critical issue. Sewage sludge composition varies with wastewater characteristics, primary and secondary treatment configuration, chemical dosing and dewatering strategy. High moisture content increases drying demand, while high ash content lowers the fraction of convertible organic matter and can promote bed agglomeration, fouling or slagging depending on mineral composition. In steam-oxygen gasification, Schmid et al. [93] reported that ash represented almost half of the dried sewage sludge mass, and the major ash-forming elements were Si, Ca, P, Al and Fe. These characteristics make SS very different from lignocellulosic biomass and require dedicated reactor design and ash-management strategies.

The fate of heavy metals is also a key environmental constraint. Gasification reduces the volume of sludge but does not eliminate inorganic contaminants. Metals can remain in bottom ash, concentrate in fly ash or volatilize depending on temperature and reducing conditions [99]. In steam-oxygen gasification, trace elements such as Cd, Pb, Ni and Cr were found to be enriched in fine ash fractions, with some filter ash concentrations exceeding typical regulatory thresholds for direct soil application [93]. Therefore, gasification residues require chemical characterization, leaching tests and appropriate stabilization or recovery strategies before reuse.

Finally, economic feasibility remains uncertain for many WWTP applications. Compared with anaerobic digestion, composting or conventional incineration, gasification requires dried and homogenized feedstock, robust feeding systems, high-temperature reactors, heat recovery and syngas-cleaning units [100]. Commercial adoption is therefore more plausible in centralized plants, industrial symbiosis schemes or facilities where syngas can be directly used for drying and process heat. Integration with sludge drying, phosphorus recovery, ash valorization or co-gasification with selected biomass may improve overall feasibility, but these options require site-specific techno-economic and environmental assessment before full-scale deployment [101].

5.4. Bioelectrochemical Systems

Bioelectrochemical systems (BES) exploit the metabolic capacity of electroactive microorganisms to exchange electrons with electrodes, providing innovative pathways for energy generation, pollutant removal, and resource recovery. BES have emerged as a potential platform approach for nutrient isolation from waste streams by converting organic

waste into energy and bio-resource through electrochemical redox reactions mediated by microbial metabolism [102,103]. Furthermore, these systems convert chemical energy stored in organic matter into electricity, hydrogen, or other valuable products through microbial catalysis. BES can be broadly divided into Microbial Fuel Cells (MFCs) and Microbial Electrolysis Cells (MECs) [104]. MFCs directly generate electricity as microorganisms oxidize organic substrates and transfer electrons to an anode, while MECs require a small external voltage to drive electrolysis reactions that produce hydrogen or other biofuels [105]. Unlike thermochemical routes such as incineration, pyrolysis, or gasification, BES can operate under mild, near-ambient conditions and have received considerable attention for wastewater treatment and resource recovery [106].

5.4.1. Energy and Nutrient Recovery

Despite these characteristics, the direct application of BES to sewage sludge treatment and valorization is limited.

Raad et al. [107] employed a two-chamber air-cathode MFC operated in batch mode to investigate the simultaneous generation of electricity and stabilization of sewage sludge. The reactor had a working volume of 2 L per chamber, separated by a Nafion membrane. Electrodes consisted of a graphite rod wrapped in carbon cloth. Secondary excess sludge was collected from a municipal wastewater treatment plant, and the initial characterization yielded a TCOD of $2560 \pm 186 \text{ mg L}^{-1}$, TSS of $7350 \pm 527 \text{ mg L}^{-1}$, VSS of $6200 \pm 371 \text{ mg L}^{-1}$, and a pH of 6.95 ± 0.2 . MLSS concentrations tested ranged from 5000 to $15,000 \text{ mg L}^{-1}$. At the optimal MLSS of $10,000 \text{ mg L}^{-1}$, the system produced a maximum power density of 27.7 W m^{-3} and a current density of 473.5 mA m^{-3} , with a peak voltage of 0.145 V and total power of 0.055 W. TCOD removal reached approximately 59.8% in the anode (anaerobic) and 70% in the cathode (aerobic) chambers, with the aerobic cathode consistently outperforming anaerobic stabilization. MLSS reduction reached 50% and 36% under aerobic and anaerobic conditions, respectively.

Taşkan et al. [108] investigated electricity generation from sewage sludge in a sediment MFC (SMFC) using a membrane-free cylindrical glass reactor. Sewage sludge from Malatya Wastewater Treatment Plant (Turkey) was mixed with Golden Horn (Istanbul, Turkey) sludge sediment (1:10 wt/wt) as inoculum and filled to 15 cm height. The anode was a thermally decomposed Ti-TiO₂ plate, chosen for its high biocompatibility, corrosion resistance, and electrical conductivity. The cathode was supplied with a phosphate buffer solution (50 mM) and aerated up to 5–6 mg L⁻¹ dissolved oxygen. The system was monitored over 60 days of operation, during which the SMFC reached a maximum voltage of 193 mV on day 28, and a maximum power density of 187 mW m^{-2} with a charge transfer resistance (R_{ct}) of 84.7 Ω . Coulombic efficiency (CE) was 13%. In terms of treatment performance, TCOD decreased by 67% (to approximately 4100 mg L^{-1}), total nitrogen by 45%, and total phosphorus by 52% over the operation period. Molecular analysis (PCR-DGGE, FISH, SEM) identified 14 dominant bacterial taxa in the anode biofilm, including *Geobacter* sp., *Shewanella woodyi*, *Pseudomonas* sp., *Comamonas* sp., and *Clostridia*, consistent with known electrogenic communities.

These studies demonstrate the feasibility of direct electricity generation and sludge stabilization using MFC-based systems, but they also highlight the strong dependence of performance on reactor configuration, electrode materials, sludge characteristics, and operating conditions. Direct quantitative comparison of power-generation performance across studies remains difficult because different reactor configurations and normalization bases are used. Raad et al. [107] also required operational inputs such as cathode aeration, while Taşkan et al. [108] reported a relatively low Coulombic efficiency (13%), competition

from methanogenic activity, and a declining voltage profile after approximately 27 days of operation attributable to substrate depletion.

In addition to energy valorization, direct application of BES to SS can be of interest for nutrient recovery. Wang et al. [109] investigated a dual-chamber MFC to recover phosphorus directly from sewage sludge in the form of vivianite ($\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$) while simultaneously generating electricity. Dissolved P dropped from 25.52 mg L^{-1} to 0.34 mg L^{-1} within 12 h in the MFC, whereas it increased to 36.95 mg L^{-1} in the non-MFC control, indicating that recovery was driven by electrochemical Fe reduction rather than microbial activity in the catholyte. Under optimized pH conditions (pH 7.5), dissolved P removal reached 99.1%. Newly formed vivianite was estimated at approximately 2.33 mg g^{-1} dry sludge. However, this percentage referred to the removal of the dissolved P fraction rather than recovery of total sludge phosphorus, and no practical strategy for separating vivianite from the sludge was demonstrated. Therefore, although this study shows the potential of MFCs for combined phosphorus recovery and electricity generation from sewage sludge, further improvements in product separation, redox control, and scale-up are still required.

5.4.2. Challenges and Integration Potential

The analysis of recent studies indicates that BES, including MFCs and MECs, can contribute to sewage sludge stabilization, energy recovery, and nutrient valorization. High COD removal efficiencies, measurable electricity generation, and the potential for hydrogen production or phosphorus recovery (e.g., as vivianite) confirm the technical feasibility of these approaches at the laboratory scale. However, the direct application of BES as stand-alone technologies for sewage sludge valorization remains limited, especially when considering pilot- or full-scale implementation.

5.5. A Comparative Analysis of Emerging Technologies

Hydrothermal carbonization, pyrolysis, and gasification represent complementary thermochemical routes for sewage sludge valorization, whereas BES may provide a distinct treatment option. Each technology carries over its specific advantages and limitations related to operating conditions, energy efficiency, and product recovery.

HTC operates at relatively low temperatures in an aqueous environment and does not require sludge drying, making it particularly suitable for high-moisture feedstocks. It produces hydrochar with improved fuel properties and a liquid phase that can be further valorized but requires additional treatment of process water and careful management of heavy metals concentrated in the solid phase. Pyrolysis, conducted at intermediate temperatures under oxygen-limited conditions, offers a more diversified product portfolio, including biochar, bio-oil, and syngas. While this flexibility enhances resource recovery potential, the need for sludge drying and challenges related to bio-oil stability and metal distribution negatively affect its overall energy and environmental performance. Gasification, operating at higher temperatures, enables efficient conversion of sludge into syngas with high versatility for energy and fuel synthesis. However, high capital costs, feedstock variability, and complex syngas cleaning systems limit its application to large-scale and centralized facilities. From a comparative perspective, the energy and material balances of these technologies depend strongly on sludge moisture content, process conditions, product yields, and the system boundaries adopted in individual studies. HTC avoids complete pre-drying but requires thermal input for heating the wet feed and subsequent management of the process water. Pyrolysis requires a drier feedstock and therefore its overall energy balance is strongly affected by the energy required for sludge drying, although heat integration and the energetic use of gas and oil fractions can partly offset this demand. Gasification can maximize conversion of the organic fraction into syngas, but drying, high-

temperature operation, gas cleaning, and tar management represent important energy and economic requirements. BES operate under milder conditions, but their performance and costs depend on reactor configuration, electrode materials and, particularly for MECs, external electrical input. Most sewage sludge BES studies are still conducted at laboratory scale, and performance may also be affected by sludge heterogeneity, microbial competition, low coulombic efficiencies, product separation, and long-term operational stability.

Consequently, direct comparison of mass and energy balances or costs across these technologies remains difficult because the available studies use different feedstocks, scales, functional units, and system boundaries. These factors should therefore be evaluated at the level of the complete treatment train rather than from individual conversion yields alone. BES applications to sewage sludge currently appear particularly suited to integration with established treatment processes, whereas thermochemical technologies can also operate as dedicated sludge-conversion steps, depending on feedstock conditioning and downstream product management. A more detailed quantitative and process-level analysis of integrated and hybrid sludge valorization strategies is provided in Section 6.

6. Advanced and Integrated Approaches: Energy, Nutrients, and Carbon Recovery

Traditional SS management approaches have largely focused on single-purpose outcomes, such as methane production through AD or volume reduction via incineration. However, these linear pathways overlook the broader potential of sludge as a multifunctional feedstock for energy, nutrient, and material recovery. The transition from traditional sludge treatment toward integrated resource recovery systems represents a paradigm shift in wastewater management. Rather than treating SS as a waste to be disposed of, integrated approaches aim to maximize the recovery of energy (i.e., biogas, syngas, electricity), nutrients (i.e., N, P, K), and carbonaceous materials (i.e., mainly hydrochar generated during HTC and biochar generated during pyrolysis) in a synergistic manner, contributing to the development of Water Resource Recovery Facilities (WRRFs) [110]. These systems can combine biological, thermochemical, and physicochemical processes to optimize resource utilization, minimize residual streams, and close material loops in alignment with circular economy principles. In this context, the output or intermediate stream generated by one process can become the feedstock for a subsequent valorization or recovery step. However, the transfer or concentration of a resource into an intermediate stream should be distinguished from its actual recovery as an energy carrier, reusable product, or potentially valuable material. In this section, integrated sewage sludge valorization pathways are evaluated considering the different levels of evidence available in the literature. Where integrated configurations have been directly investigated, experimental results are discussed. However, for several process combinations, the available studies mainly concern the application of individual technologies to intermediate streams, particularly anaerobic digestate, rather than the operation of complete integrated treatment trains. In these cases, possible integration pathways are discussed on the basis of technical compatibility, complementary functions and main limitations of the individual processes. Therefore, a distinction is made between direct experimental integration, downstream or sidestream integration, modelled integration, and prospective integration. Quantitative results are reported according to the basis and system boundaries used in the original studies, since differences in sludge characteristics, process configuration, scale and functional units generally prevent direct normalization across the available literature.

6.1. Anaerobic Digestion as a Platform for Carbon and Nutrient Recovery

Increasing attention has been given to extending sewage sludge AD beyond conventional biogas production through the recovery of carbon and nutrients. Integrating AD with recovery technologies can transform sludge into products for fertilizers, biorefineries, and biopolymer production. From an integration perspective, AD can act as a first conversion step in which biodegradable organic carbon is directed toward methane or, under controlled acidogenic conditions, partially retained as VFAs, while the degradation of organic matter releases nutrients that can become available for subsequent recovery. Process optimization, pretreatment, and post-treatment can enhance nutrient extraction, VFA accumulation, and overall sustainability. The approaches investigated include multi-stage digestion, pH control, shorter retention times, methanogenesis inhibition, and membrane separation, supporting the development of integrated waste-to-resource systems [111,112].

6.1.1. Volatile Fatty Acids—Formation, Recovery, and Applications

As described in Section 4.1, volatile fatty acids (VFAs) are intermediates of the acidogenic and acetogenic stages of anaerobic digestion (AD) and are normally consumed during subsequent acetogenic and methanogenic conversions [113]. However, the operating parameters governing conventional AD stability can be deliberately adjusted to restrict complete methanogenesis and promote VFA accumulation. Conditions such as acidic or alkaline pH, short solids retention times (SRTs), high organic loading rates, thermal or chemical pretreatment, and the use of selective inhibitors can limit methanogenic activity and increase VFA production [111,114]. Pretreatment can enhance the release of soluble organic substrates from sludge, but appropriate acidogenic conditions are subsequently required to retain this carbon as VFAs rather than allowing its complete conversion into methane.

Quantitative studies illustrate the extent to which operating conditions and pretreatment affect VFA production from sewage sludge. Khiewwijit et al. [114] obtained a maximum yield of 440 mg VFA-COD g⁻¹ VSS from concentrated sewage organic matter by applying a pH shock to 9 at the beginning of the fermentation cycle, followed by seven days without pH control. At pilot scale, Longo et al. [115] obtained a VFA yield of 315.6 mg_{COD} g⁻¹ VS and a VFA concentration of 7453 ± 1092 mg_{COD} L⁻¹ during alkaline sewage sludge fermentation at pH 10, 35 °C, an HRT of 6 d, and an SRT of 14 d. Under these conditions, acetate, propionate, and butyrate accounted for approximately 40%, 24%, and 17% of the recovered VFA-COD, respectively. More recently, Mineo et al. [116] compared alkaline, acidic, low-temperature thermal, and potassium-permanganate pretreatments of sewage sludge. The highest VFA production was obtained with 0.1 g KMnO₄ g⁻¹ TSS, reaching 2713 mg COD L⁻¹ and 452 mg COD g⁻¹ VSS. These findings show that VFA yield and composition depend strongly on sludge characteristics, pretreatment, pH, loading conditions, and retention time.

Waste-derived VFAs can be used as carbon sources or intermediates for the production of polyhydroxyalkanoates, fuels, solvents, and other platform chemicals [111,117,118]. Polyhydroxyalkanoates, a family of biodegradable microbial polyesters, can be produced from VFA-rich streams using either pure or mixed microbial cultures [117,118]. VFAs present in dark-fermentation effluents may also be converted into hydrogen through processes such as photofermentation [119].

The feasibility of VFA valorization depends not only on biological production but also on the efficiency, selectivity, and cost of downstream clarification, concentration, and purification. Microfiltration and ultrafiltration are primarily used for solid-liquid separation and the production of clarified VFA-rich streams, whereas nanofiltration, electrodialysis, membrane contactors, and solvent extraction can provide more selective separation or concentration of dissolved acids [115,120–124].

In a two-year study involving sewage sludge from three wastewater treatment plants, Mineo et al. [123] used ultrafiltration to recover the liquid fraction following acidogenic fermentation, with VFAs accounting, on average, for 42% of the soluble COD. The study also identified membrane fouling as an important operational constraint, highlighting the influence of sludge-derived solids and extracellular polymeric substances on filtration performance.

Studies using other complex fermentation matrices provide additional benchmarks for downstream VFA separation. Conventional electrodialysis achieved up to 99% VFA removal from model solutions and real mixed-acid fermentation broths, although this percentage represented removal from the feed rather than the purity or overall recovery yield of the final product [121]. Liquid–liquid extraction produced acid-specific recoveries of 61–98% from sugar-beet-processing fermentation broth at pH 2.5 using 20% trioctylphosphine oxide in kerosene [120]. More recent membrane-integrated processes applied to food-waste fermentation maintained VFA concentrations above 6 g L^{−1} following clarification [124], while a combined electrodialysis-membrane-contactor system separated more than 94% of the VFAs with less than 2% nutrient contamination in the recovered stream [122]. Because these studies used non-sludge matrices, their results should be regarded as technology-specific benchmarks rather than direct estimates of performance for sewage sludge fermentation effluents.

The suitability of each recovery technology depends on VFA concentration and composition, pH, ionic strength, suspended-solids content, competing organic compounds, required product purity, and energy and reagent consumption. High VFA removal from a fermentation stream therefore does not necessarily correspond to high product purity, high overall recovery, or economically viable operation.

Two-stage AD systems can support the combined recovery of VFAs and biogas by separating an acidogenic stage from a subsequent methanogenic stage [33]. A literature-based analysis of 29 reported acid-stage operating conditions identified higher predicted VFA yields at temperatures of 30–34 °C, SRTs of 4–9 d, and pH values of either 5–6 or 7.7–8 [33]. Because these ranges were derived from heterogeneous published studies, they should be regarded as indicative trends rather than universally applicable optimum conditions.

In two-stage configurations, part of the acidogenic effluent can be recovered as a VFA-rich stream, while the remaining organic matter is directed to methanogenesis. This configuration can enable targeted carbon recovery while retaining energy production from the residual biodegradable fraction. Its performance nevertheless depends on the operating conditions, the proportion of acidogenic effluent diverted for recovery, the downstream separation requirements, and the integration of the acidogenic and methanogenic stages. This configuration also involves an intrinsic carbon-allocation trade-off: increasing the fraction of biodegradable carbon retained and recovered as VFAs reduces the fraction subsequently available for conversion to methane. Therefore, VFA and methane production should be considered as alternative or complementary carbon-recovery routes within the same system boundary, rather than as independently maximizable outputs.

Major technical challenges include maintaining stable acidogenic conditions, controlling VFA concentration and composition, preventing excessive acid accumulation, achieving cost-effective downstream separation, and preserving the performance of the subsequent methanogenic stage [33,111,125]. VFA recovery should therefore be assessed as part of an integrated process rather than through the isolated objective of maximizing acid production.

6.1.2. Nutrient Recovery: Phosphorus and Nitrogen Extraction from Digestate

In addition to biogas and VFAs, anaerobic digestion produces a digestate that is rich in N, P, and K. During AD, degradation of organic matter can increase the fraction of nutrients present in soluble or potentially recoverable forms; however, nutrient release or concentration in digestate does not itself constitute recovery. A downstream separation step is required to obtain a reusable nutrient product or stream. Though nutrients are essential for agriculture, direct application of digestate is often limited by high moisture content, potential contaminants, and regulatory restrictions. The physical characteristics of digestate also complicate nutrient extraction, as it may require preliminary energy-intensive dewatering before recovery. Phosphorus recovery is particularly crucial due to depleting global phosphate reserves. One of the most widely studied methods for phosphorus extraction from AD digestate is struvite (i.e., magnesium ammonium phosphate, MAP) precipitation, which produces a slow-release fertilizer suitable for agricultural use. Struvite recovery systems typically involve magnesium dosing and pH adjustment, allowing selective precipitation of phosphorus while reducing excess nutrient discharge into water bodies. However, the unbalanced presence of required ions (NH_4^+ , PO_4^{3-} and Mg^{2+}) in the liquid stream limits its techno-economic feasibility, as it requires dosing high-cost reagents [126]. Nitrogen recovery from AD effluents is equally important to mitigate ammonia emissions and promote circular nutrient use. Technologies such as ammonia stripping coupled with acid absorption are widely applied to recover nitrogen from AD effluents, although their application can require substantial energy and chemical inputs [126].

Although resource recovery enhances the value proposition of AD, implementing conventional processes such as membrane separation, chemical precipitation, adsorption, and wet-chemical processes can increase capital and operational costs, as they may require significant chemical or energy inputs and additional downstream processing [127]. Their overall performance therefore depends not only on the fraction of nutrients removed from digestate, but also on recovery efficiency, product purity, chemical and energy demand, and the management of the remaining liquid and solid streams. To overcome these challenges, hybrid treatment systems, improved process automation, and cost-effective material innovations will be needed to make integrated AD systems commercially viable at a larger scale. Within this framework, advanced nutrient recovery technologies may provide a controlled and efficient approach to extract and convert nutrients into commercially viable fertilizers, reducing reliance on synthetic fertilizers.

6.2. Coupling AD with Advanced Thermochemical Processes (AD + HTC, AD + Pyrolysis)

Hybrid configurations that integrate anaerobic digestion (AD) with thermochemical processes such as hydrothermal carbonization (HTC) or pyrolysis have been investigated for more complete sewage sludge valorization. These systems exploit the complementary strengths of biological and thermal treatment: AD converts the readily biodegradable organic fraction into biogas, whereas the residual digestate, which still contains recalcitrant organic matter, nutrients and inorganic solids, can be further transformed into carbonaceous materials, nutrient-rich liquids and energy carriers. This approach is particularly relevant because AD alone reduces the biodegradable fraction but does not fully solve digestate management, disposal costs or nutrient recovery [13]. However, the level of integration demonstrated in the literature differs between the two pathways: AD-HTC has been investigated through experimental coupling, downstream treatment of digestate and process-level modelling, whereas much of the available experimental evidence for AD-pyrolysis concerns the pyrolysis of anaerobically digested sludge rather than operation of a complete integrated treatment train.

In AD-HTC systems, sewage digestate is treated hydrothermally, typically at 180–250 °C under autogenous pressure, producing hydrochar, process water and a minor gas fraction mainly composed of CO₂. HTC is well suited to digestate because it can directly process wet sludge streams without the need for complete drying. In a study on sewage digestate treated at 250 °C for 30 min, hydrochar yields ranged from 64 to 88 wt.%, while soluble organic carbon in the process water increased from 2.6 g L^{−1} in raw digestate to a maximum of 72.3 g L^{−1} after HTC at the highest solid loading [128]. These results show that HTC can both densify part of the residual solids into hydrochar and transfer part of the organic matter to a liquid stream suitable for further biological or chemical treatment.

The liquid fraction from HTC is a critical stream in AD-HTC integration. It contains soluble organic compounds, ammonium, phosphate and other inorganic species, and can potentially be recycled to the anaerobic digester to increase biogas production. However, its effect depends strongly on HTC severity because more severe conditions can increase the formation of inhibitory compounds and ammonium. Experiments on sewage digestate treated at 190 °C for 0.5–3 h showed that increasing treatment time improved slurry dewaterability and increased ammonium concentration in the HTC liquor, but decreased the biomethane potential of the liquid fraction [129,130]. Therefore, HTC conditions should not be selected only to maximize hydrochar production, but also to preserve the anaerobic biodegradability of the process water. At a process level, Ahmed et al. [129] estimated that, for a scenario treating 100 m³ d^{−1} of digestate, anaerobic conversion of the HTC liquor could provide approximately 711 kWh of methane energy, corresponding to about 25% of the estimated 2856 kWh process-energy input.

Recycling HTC liquor and hydrochar to AD can increase methane recovery when the composition and loading are properly controlled. Ferrentino et al. [131] reported that recycling HTC liquor produced from digested sludge back to AD, together with primary and secondary sludge, increased biomethane yield to 102 ± 3 mL CH₄ gCOD^{−1}, almost doubling the value obtained from primary and secondary sludge alone, reported as 55 ± 20 mL CH₄ gCOD^{−1} [131]. This study therefore provides direct experimental evidence of reintegration of HTC-derived streams into the biological treatment train, although the observed benefit remains dependent on the composition and loading of the recycled fractions. This suggests that AD-HTC can enhance energy recovery when soluble organics released during HTC are effectively converted into methane. Nevertheless, process-water recirculation requires control of ammonia, refractory COD, phenolic compounds and salinity to avoid inhibition or accumulation of poorly biodegradable substances [70,130].

AD-HTC can also contribute to nutrient recovery. Hydrochar and HTC liquor can concentrate or mobilize phosphorus and nitrogen, creating intermediate streams potentially suitable for subsequent nutrient-recovery steps. A feasibility study on digested sewage sludge treated by HTC at 200 °C for 4 h showed that post-treatment of HTC products could extract approximately 84% of phosphorus into the liquid phase by phosphorus stripping and 71% by phosphorus leaching, while nitrogen transfer to the liquid fractions was about 53–54% depending on the route [132]. At larger scale, a simulation for the Trento 3 WWTP in Italy, with a treatment capacity of 300,000 population equivalent, estimated that integrating HTC as a post-treatment after AD could reduce sludge disposal by 70–75%, increase biogas production by up to 47% through HTC liquor recycling, and reduce sludge management costs by up to 2 M€ year^{−1} [71]. These results represent plant-scale modelling rather than operation of a full-scale integrated AD-HTC system. The values are therefore site-specific, but they illustrate the potential of AD-HTC configurations when energy, nutrient and sludge-disposal benefits are considered together.

For AD-pyrolysis, the available experimental evidence more frequently concerns the downstream pyrolysis of anaerobically digested sewage sludge rather than operation of

a complete integrated AD-pyrolysis treatment train. These studies nevertheless provide relevant information on how prior AD affects feedstock characteristics, product distribution and the potential valorization of the residual solid fraction. AD-pyrolysis systems convert solid digestate into biochar, bio-oil and pyrolysis gas through oxygen-limited thermal decomposition. Compared with raw sewage sludge, anaerobically digested sludge usually contains lower volatile matter and higher ash content because part of the biodegradable organic fraction has already been converted into biogas. This affects product distribution and quality during pyrolysis. A recent comparative study using a continuous auger reactor at 450–650 °C showed that anaerobic digestion produced a sludge feedstock with higher ash content, reported as 39.84 wt.%, and stronger mineral catalytic effects during pyrolysis. As a consequence, anaerobically digested sludge produced lower bio-oil yields, with a maximum of 15.2 wt.%, but bio-oil with higher calorific value, up to 36.96 MJ kg⁻¹, and pyrolysis gas with calorific value up to 15.5 MJ kg⁻¹, associated with hydrogen contents up to 22.9 vol.% at 650 °C. Though integrating AD with pyrolysis could offer potential economic advantages over the direct pyrolysis of undigested sludge, a comprehensive cost–benefit analysis should evaluate sludge treatment options by considering both revenue streams from biogas and pyrolysis products against the increased capital and operational costs [133].

Digestate-derived biochar can retain part of the carbon remaining after AD and may be suitable for adsorption or soil-related applications, but its use requires careful evaluation of carbon stability, ash content, nutrient content and availability, and heavy metals [134]. Carbon retention in biochar should not automatically be interpreted as long-term carbon sequestration, which also depends on biochar stability and final use. Pyrolysis of solid digestate from sewage sludge and sewage sludge–lignocellulosic biomass mixtures showed complex degradation behaviour, with activation energies ranging from 57 to 351 kJ mol⁻¹ for sewage sludge digestate and from 62 to 401 kJ mol⁻¹ for the mixed digestate; the resulting biochars were nutrient-rich, while co-digestion with lignocellulosic biomass reduced heavy metal contents compared with sewage sludge digestate alone [135]. These findings suggest that AD-pyrolysis can produce useful biochars, but feedstock composition and possible co-digestion strategies strongly affect final product quality.

From an energy-integration perspective, AD-pyrolysis may use pyrolysis gas and part of the thermal energy from char or gas combustion to support sludge drying, digester heating or plant heat demand [27,136]. At a process level, Chen et al. [136] compared raw-sludge pyrolysis, AD-pyrolysis, THP-AD-pyrolysis and AD-THP-pyrolysis using a common basis of 100 kg of dry raw sludge. The reported apparent energy efficiencies were approximately 69.6%, 75.8%, 82.7% and 91.3%, respectively. These values indicate the potential benefit of process integration within the boundaries adopted in that study. However, they represent apparent product-energy efficiencies rather than net plant energy performance and should therefore not be directly extrapolated to full-scale systems without accounting for dewatering and drying, thermal pretreatment, reactor heating, gas cleaning and product upgrading. However, this integration is technically more demanding than AD alone because pyrolysis requires sufficiently dried feedstock, continuous thermal operation, gas cleaning and stable outlets for biochar, oil or gas. Therefore, the most realistic near-term configuration is not the production of multiple high-grade fuels, but the use of pyrolysis as a digestate stabilization and carbon-recovery step, with internal heat recovery from pyrolysis gas and controlled management of biochar.

Overall, AD + HTC and AD + pyrolysis can improve the circularity of sewage sludge management by combining biogas production with residual-solids valorization and further carbon, energy or nutrient recovery. Their suitability, however, depends on different integration requirements. AD-HTC is particularly attractive for wet digestate because

it avoids full drying and can generate a process water suitable for methane or nutrient recovery. AD-pyrolysis becomes more attractive where effective dewatering/drying or surplus heat is available and where suitable outlets exist for biochar and other pyrolysis products, but it requires more intensive drying and gas-cleaning infrastructure. In both pathways, concentration of carbon or nutrients in an intermediate solid or liquid stream should not automatically be interpreted as final resource recovery. Environmental and economic performance depends on site-specific factors, including digestate composition, process severity, energy integration, product markets, transport distances, nutrient recovery strategy and regulatory acceptance [137,138].

6.3. Integration of Anaerobic Digestion with Bioelectrochemical Systems

6.3.1. Energy Recovery

Bioelectrochemical systems (BES) represent a further option for integration with anaerobic digestion in sewage sludge treatment. Among BES configurations, microbial electrolysis cells (MECs) have received particular attention for direct integration with AD, by incorporating polarized electrodes into the anaerobic treatment environment to enhance sludge conversion and methane production. By using electroactive microorganisms and polarized electrodes to facilitate extracellular electron transfer, MEC-assisted AD systems can accelerate sludge hydrolysis and organic matter conversion, enhancing methane yield and biogas production from both raw and pretreated waste activated sludge [139,140]. However, as MECs require an external electrical input to drive the bioelectrochemical reactions, increased methane production in MEC-assisted AD should not by itself be interpreted as improved net energy performance, which also depends on electrical consumption, electrode requirements and other process inputs.

This enhancement has been demonstrated by Wang et al. [141], who reported that MEC-AD increased methane production from both raw and heat-pretreated waste activated sludge. At an applied voltage of 0.8 V, methane yields reached 157 and 248 mL g⁻¹ VSS_{in} for raw and heat-pretreated waste activated sludge, respectively; although heat-pretreated waste activated sludge achieved the higher absolute methane yield, the relative enhancement was more pronounced and more stable for raw waste activated sludge, indicating that MEC-AD can partly overcome the hydrolysis limitation of untreated sludge while reducing dependence on energy-intensive pretreatment.

In addition to thermal pretreatment, alkaline-pretreated sewage sludge has also been investigated in MEC-AD systems. Xu et al. [142] showed that, in an alkaline-pretreated sewage-sludge-fed MEC-AD operated at 0.8 V, the addition of phosphate buffer solution (PBS) enhanced cumulative methane production by 44.6% compared to the MEC-AD reactor without PBS, increasing it from 837 ± 4.7 to 1211 ± 2.3 mL, while the maximum methane production rate increased from 0.18 to 0.20 mL CH₄/(mL reactor·d).

These findings also highlight the importance of applied voltage as a key operational parameter in MEC-AD, since moderate potentials can stimulate extracellular electron transfer, enrich electroactive and methanogenic microorganisms, and enhance methane production, whereas excessive voltage may increase energy demand and potentially inhibit methanogenic activity or electron-transfer bacteria. Wang et al. [141] identified 0.8 V as the most effective condition among the tested voltages for both raw and heat-pretreated WAS, while Joicy et al. [139] reported the highest methane yield at 0.6 V for pretreated waste activated sludge. In a continuous MEC-AD system fed with raw waste activated sludge and operated at a fixed voltage of 1.0 V, Kanellos et al. [140] further reported higher organic matter removal, 30–32% greater biogas production, and 5–6% higher methane content than conventional AD at elevated organic loading rates. These results indicate that

the effect of applied voltage cannot be generalized independently of sludge characteristics, pretreatment, organic loading rate and reactor configuration.

Recent studies have investigated intermittent energization as a strategy to maintain the bioelectrochemical stimulation of methane production while reducing the external electrical input required by MEC-assisted AD. Wang et al. [143] reported that a 2d-on/3d-off intermittent mode increased methane yield by 14.9% and achieved an energy efficiency of 235.5% relative to continuous operation, which was attributed to enhanced sludge hydrolysis, acidogenesis, electrochemical activity, enzymatic function, and enrichment of electroactive bacteria, particularly *Geobacter*, on the anode biofilm. In a related study, Wang et al. [144] further demonstrated that extending the power-off duration improved MEC-AD performance, with the 1d-on/5d-off mode achieving the best overall results, including higher methane production, enhanced hydrolysis, acidogenesis, methanogenic enzyme activity, and improved VSS removal. Importantly, the same study showed that methane enhancement did not necessarily correspond to positive net energy performance. Depending on the energization regime, the calculated net energy income ranged from negative values (approximately -28.4 and -7.2 kJ under the more energy-demanding conditions) to a positive value of approximately $+16.1$ kJ under a prolonged power-off regime. Although these values are specific to the experimental system and energy-balance definition adopted by the authors, they demonstrate that electrical consumption must be explicitly considered when assessing the energetic benefit of MEC-AD integration.

Similarly, Zakaria & Ranjan Dhar [145] showed that intermittent energization of a sewage-sludge-fed MEC-AD system improved methane generation and sludge degradation while upregulating EET-associated genes and promoting DIET-based syntrophy between anodic electroactive bacteria and electrotrophic methanogens. Collectively, these findings suggest that intermittent power-supply strategies can maintain or enhance methane production while reducing the duration of external electrical input. These studies are particularly relevant from an integration perspective because methane enhancement and net energy performance do not necessarily follow the same trend. Reducing the duration of external power supply can therefore be as important as maximizing methane production when evaluating the energetic advantage of MEC-assisted AD over conventional AD.

Table 2 provides a comparative overview of recent MEC-AD studies using municipal sewage sludge or waste activated sludge, showing how key operational factors, including applied voltage, substrate pretreatment, buffering, organic loading rate, and intermittent power supply, affect methane recovery, energy efficiency, and sludge degradation.

Table 2. Recent MEC-AD studies for methane recovery and valorization of municipal sewage sludge and waste activated sludge.

Study	Sludge/ Substrate	System/ Variable	Valorization Target	Main Outcome
[142]	Alkaline-pretreated sewage sludge	MEC-AD at 0.8 V; PBS vs. no PBS	Methane recovery	PBS addition increased cumulative CH_4 production by 44.6%, with a maximum rate of $0.20 \text{ mL}_{\text{CH}_4} \text{ mL}_{\text{reactor}}^{-1} \text{ d}^{-1}$.
[141]	Raw and heat-pretreated waste activated sludge	MEC-AD; 0, 0.6, and 0.8 V	Methane recovery; sludge hydrolysis enhancement	Best performance was obtained at 0.8 V, reaching 157 and $248 \text{ mL}_{\text{CH}_4} \text{ gVSSin}^{-1}$ for raw and heat-pretreated waste activated sludge, respectively.

Table 2. Cont.

Study	Sludge/ Substrate	System/ Variable	Valorization Target	Main Outcome
[139]	Pretreated waste activated sludge	MEC-AD; 0.3, 0.6, and 0.9 V	Methane recovery	Highest CH ₄ yield was obtained at 0.6 V, with a 44.8% increase compared with AD.
[145]	Mixed municipal sludge (fermented primary sludge + waste activated sludge)	MEC-AD; continuous vs. intermittent energization	Methane recovery; sludge degradation	12 h-on/12 h-off improved methane generation, methane yield, and sludge degradation compared with continuous energization.
[146]	Nitrogen-rich dewatered/thickened municipal sludge	AD-MEC; mesophilic/thermophilic; different energization times	Methane recovery under nitrogen-rich sludge conditions	12 h-on/12 h-off achieved the highest mesophilic methane yield, $133.3 \pm 6.1 \text{ mL g}_{\text{VSadded}}^{-1}$, and improved performance under thermophilic ammonia-stressed conditions.
[140]	Raw waste activated sludge	Continuous MEC-AD; fixed 1.0 V; different OLRs	Biogas/methane recovery; organic matter removal	At elevated OLRs, biogas production increased by 30–32% and CH ₄ content by 5–6% compared with conventional AD.
[143]	Pretreated waste activated sludge	MEC-AD; continuous vs. 2d-on/3d-off	Methane recovery; energy-efficiency improvement	2d-on/3d-off increased CH ₄ yield by 14.9% and achieved 235.5% energy efficiency.
[144]	Pretreated waste activated sludge	MEC-AD; different power-off durations	Methane recovery; VSS reduction; energy-efficiency improvement	1d-on/5d-off gave the best overall performance, with about 1102% energy efficiency.

6.3.2. Nutrient Release and Recovery

Evidence for nutrient recovery in sewage-sludge-based AD-MEC configurations is more limited than that available for methane enhancement and includes both direct multi-stage integration and treatment of AD-derived sidestreams. As discussed above, nutrient solubilization or transfer to the liquid phase should be distinguished from actual recovery as a separated and potentially reusable product. The combination of BES and anaerobic digestion (AD) can lead to the formation of a synergistic process to enhance nutrient recovery from waste [147,148], although the recovery route strongly depends on system configuration and downstream capture processes [103]. Hou et al. [149] proposed a coupled three-step process, including a sequential homogeneous protocatechuic acid (PCA) enhanced Fenton pretreatment, a subsequent AD process for biogas production and the release of phosphorus, and a final MEC process for further biogas and phosphorus recovery in the form of struvite from sludge fermentation liquid (SFL). In addition to biogas production, the integrated process enabled phosphorus recovery as struvite, with a reported yield of $1.72 \text{ g g}^{-1} \text{ TS}$, corresponding to 18.03% of total phosphorus, and a struvite purity of 74.4%. This study therefore represents direct experimental evidence of combined energy and phosphorus recovery within a multi-stage sewage sludge treatment train [149].

Zhou et al. [150] integrated MEC with anaerobic prefermentation to simultaneously enhance biohydrogen production and phosphorus release from waste activated sludge. The findings showed that MEC plays an important role in this combined process, accelerating the release of organic P (OP) from solid sludge and its conversion into molybdate reactive phosphorus (MRP). Furthermore, free nitrous acid (FNA) pretreatment not only led to high hydrogen yield but also enhanced the OP release [150]. However, since a final reusable

phosphorus product was not obtained, this study should be considered evidence of nutrient mobilization rather than nutrient recovery in the strict sense.

In addition to direct sludge-focused MEC-AD studies, BES-based sidestream processes have also been investigated for nutrient recovery from digested sludge centrate. Barua et al. [151] developed a two-step sidestream process for nutrient recovery from digested sludge centrate, involving MEC for ammonium transfer to the catholyte followed by chemical precipitation with the addition of Ca^{2+} or Mg^{2+} salts to recover phosphorus (about 85%) as solid precipitates in the anodic effluent. The electrical energy requirement for nitrogen transport was approximately $5.8 \pm 0.1 \text{ kWh kg}^{-1} \text{ TAN}$, with a TAN removal efficiency of $53 \pm 5\%$. This configuration represents a downstream or sidestream integration with AD rather than the direct coupling within the digester, but it is particularly relevant to the WRRF concept because an existing AD-derived liquid stream is used as the feed for subsequent nutrient recovery. Zou et al. [152] investigated a hybrid MEC-forward osmosis (MEC-FO) system for integrated nutrient-energy-water recovery from synthetic high-strength sidestream centrate, demonstrating effective recovery of fresh water, ammonium nitrogen, phosphorus as struvite, and hydrogen gas.

Despite the promising potential of BES/MEC-AD systems for sewage sludge valorization, several challenges remain for integrated energy and nutrient recovery. Energy recovery depends strongly on applied voltage, substrate pretreatment, buffering and pH control, and organic loading rate; moreover, excessive electrical input under continuous energization can result in a net energy loss, offsetting the additional methane produced [140–143]. In addition, nutrient solubilization during AD-MEC treatment does not automatically represent nutrient recovery. While Zhou et al. [150] demonstrated enhanced phosphorus release from waste activated sludge, Hou et al. [149] showed that final phosphorus recovery requires a dedicated downstream capture step, such as struvite precipitation, and should be evaluated through recovery efficiency and product purity.

6.4. Carbon Recovery Across Integrated Sewage Sludge Valorization Pathways

Carbon recovery from sewage sludge can occur through different pathways depending on the treatment sequence and the targeted products. In biological processes, biodegradable organic carbon can be converted into methane and carbon dioxide during anaerobic digestion or accumulated as VFAs when methanogenesis is restricted [31,111]. In thermochemical processes, sludge-derived carbon is distributed among solid, liquid and gaseous products: HTC produces a carbon-rich hydrochar together with dissolved organic carbon in the process water [128,129]; pyrolysis distributes carbon among biochar, bio-oil and non-condensable gases [133]; gasification predominantly converts the organic fraction into syngas, while incineration largely oxidizes organic carbon to CO_2 [27,42].

The integration of bioelectrochemical processes can further modify carbon conversion, for example by promoting methane or soluble organic compound (chain elongation) formation in MEC-AD systems, or by oxidizing organic carbon in hydrogen-producing MECs while recovering hydrogen as an energy carrier [19]. From an integrated-process perspective, these pathways should be considered as alternative or complementary routes for allocating sludge-derived carbon rather than as independently maximizable recovery options. For example, fostering VFA recovery through dark fermentation reduces the biodegradable carbon subsequently available for methane production [20,111]. Similarly, AD converts part of the initial carbon into biogas before a downstream HTC or pyrolysis step, reducing the carbon remaining in the digestate available for subsequent conversion and partitioning into hydrochar or biochar [129,136,153]. Conversely, a fraction of soluble organic carbon transferred to HTC process water may be partially redirected to methane

production through recycling to AD, although its biodegradability depends strongly on HTC operating conditions [129–131].

That said, none of the aforementioned forms of carbon conversion represents permanent, long-term storage. Even carbon retained in hydrochar or biochar does not by itself demonstrate carbon sequestration. The potential for long-term storage depends on the chemical and biological stability of the carbonaceous material, its final application and lifetime, and its suitability for reuse [13,133]. Contaminant content is also relevant because an accumulation of heavy metals or persistent contaminants may restrict land application or other uses and consequently alter the final fate of the retained carbon [13,63].

A complete quantitative comparison of carbon fate among the different pathways remains difficult because the available literature uses heterogeneous reporting approaches and study scopes, and complete carbon balances are not consistently reported [13,28]. Studies frequently report individual performance indicators, such as methane yields, hydrochar or biochar yields, bio-oil production, syngas composition, or dissolved COD/carbon, rather than tracking carbon from the initial sludge across all final products, gaseous streams, process waters, and residual solids [128,133]. Consequently, a high yield or recovery of an individual carbon-containing product should not automatically be interpreted as high overall carbon recovery. This limitation is particularly important for integrated treatment trains, where carbon is redistributed sequentially among multiple streams.

Carbon recovery should therefore be evaluated at the level of the complete treatment train, considering both the amount and form of carbon retained in useful products, the carbon converted into energy carriers, the carbon remaining in intermediate or residual streams, and the carbon ultimately released as CO₂ or other gaseous products. This system-level perspective is therefore important when evaluating whether integrated sewage sludge biorefineries may improve carbon utilization compared with conventional treatment, rather than simply transferring carbon among different process streams.

6.5. From Integrated Processes to Sewage Sludge Biorefineries

The transition from conventional sludge treatment toward integrated sewage-sludge biorefineries represents a relevant direction for achieving circular wastewater management. Rather than maximizing a single product, integrated biorefineries can combine complementary biological, thermochemical, and electrochemical processes to recover energy, nutrients, water, and carbon-based materials within a single treatment framework.

Table 3 provides a comparative overview of the conventional and emerging technologies discussed in the previous sections, summarizing their main products, operating conditions, advantages, challenges, and key research directions.

Table 3. Comparative overview of conventional and emerging technologies for sewage sludge valorization, including main products, operating requirements, advantages, challenges, and key research directions.

Technology	Main Products	Typical Operating Conditions	Advantages	Challenges	Key Research Directions	Refs.
Anaerobic Digestion	Biogas (CH ₄ , CO ₂); digestate	Anaerobic; mesophilic/thermophilic; long HRT/SRT	Mature; cost-effective; renewable energy recovery	Long reaction time; incomplete organic conversion; digestate management	Pre-treatment; co-digestion; nutrient recovery	[27,153–155]
Mono-incineration	Heat; electricity; ash	Dewatered/dried sludge; high-temperature oxidation	Pathogen destruction; volume reduction	Drying demand; air emission; ash management	Emission control; P extraction from ash	[42,156,157]

Table 3. Cont.

Technology	Main Products	Typical Operating Conditions	Advantages	Challenges	Key Research Directions	Refs.
Co-combustion	Heat; electricity; mixed ash; clinker in cement co-processing	Sludge blended with other fuels	Use of existing infrastructure; potential fuel substitution	Air emissions; sludge moisture and composition variability; mixed-ash or clinker quality	Blending optimization; emission control; residue quality	[28,45,46,48]
Hydrothermal Carbonization	Hydrochar; process water; gas	Wet feedstock; typically 180–250 °C and 2–10 MPa	Handles wet sludge efficiently; energy-dense solid	Heavy metal accumulation in hydrochar; process water treatment	Nutrient recovery; integration with AD for biogas co-production; water reuse	[155,158–160]
Pyrolysis	Biochar; bio-oil; pyrolysis gas	Dried feedstock; inert/oxygen-limited atmosphere; commonly 300–700 °C	Produces versatile carbon-rich materials	Heavy metals retention in char; bio-oil/tar upgrading	Biochar safe reuse; reactor optimization; integration with HTC or AD	[78,85,158,161]
Gasification	Syngas; char/ash	Dried/dewatered feedstock; high temperature; limited air/O ₂ /steam	Syngas production with potential for energy or chemical recovery	Tar/contaminant control; high capital cost; complex operation	Syngas cleaning; P recovery from ash; process stability; AD digestate/HTC integration	[12,14,22,162]
Microbial Fuel Cells	Electricity; treated effluent/sludge reduction	Ambient/mild aqueous conditions; anaerobic anode; no external voltage	Direct electricity generation under mild operating conditions	Low power density; material/electrode cost; scale-up challenges	Electrode design; hybridization with AD/BES	[163–166]
Microbial Electrolysis Cells	Hydrogen; methane	Ambient/mesophilic aqueous conditions; low applied voltage, commonly 0.2–0.8 V	Potential for methane, hydrogen and resource recovery	Requires external voltage; material/electrode cost; scale-up challenges	Energy optimization; scalable reactor design	[154,166–168]

The integration of these technologies may offer advantages over stand-alone processes by combining complementary routes for energy, carbon and nutrient recovery, reducing residual streams, and increasing flexibility in handling sludge with variable composition. However, the extent of these benefits depends on the specific process configuration and system boundaries. At the same time, hybrid configurations can partially overcome the limitations of individual technologies by exploiting the complementary characteristics of biological, thermochemical, and electrochemical processes. The main integrated pathways discussed in this section are summarized in Table 4, which compares their process configuration, level of evidence, scale, resource-recovery opportunities, and principal integration constraints. The comparison also highlights the substantial heterogeneity of the available evidence, ranging from direct experimental integration to downstream or sidestream treatment, process modelling, and prospective configurations.

However, it should be considered that integration does not necessarily result in a positive overall energy, environmental, or economic balance. Each additional process introduces energy and material requirements and redistributes carbon, nutrients, and contaminants among gaseous, liquid, and solid streams. This redistribution is particularly relevant for product quality and final reuse. Heavy metals may become concentrated in hydrochar, biochar, or ash, whereas ammonium, dissolved organic matter, metals, and other contaminants may be transferred to process liquors. Thermochemical processes may

also generate condensable organic compounds requiring further treatment. Therefore, the concentration of a potentially valuable resource in a specific fraction should be evaluated together with contaminant partitioning and downstream treatment requirements.

Table 4. Comparison of integrated sewage sludge valorization pathways *.

Integrated Pathway	Process Sequence/Main Streams	Evidence/Scale	Energy and Carbon Pathway	Nutrient Fate/Recovery	Main Integration Constraints
AD-HTC, including process-water recycle [18,71,128–132,137,138]	SS → AD → biogas + digestate → HTC → hydrochar + process water; process water may be recycled to AD	Laboratory experimental coupling and downstream treatment; process modelling and WWTP-scale scenario analysis	Biogas from AD; residual carbon partitioned between hydrochar and process water; HTC liquor may provide additional methane recovery through recycling to AD	P and N are redistributed between solid and liquid HTC products; downstream separation is required for actual recovery	HTC heat demand; process-water treatment/recycle; hydrochar quality; contaminant partitioning
AD-pyrolysis, including THP-assisted variants [133–136]	SS → AD → digestate → dewatering/drying → pyrolysis → biochar + bio-oil + gas; THP may be included before or after AD	Mainly downstream treatment of digestate, laboratory-scale studies and modelling	Biogas from AD followed by conversion of residual carbon into biochar, bio-oil and gas; internal heat recovery may support process energy demand	Mineral nutrients are mainly retained or concentrated in the solid residue; downstream treatment is required for recovery	Dewatering/drying; thermal demand; gas and bio-oil treatment; char quality and contaminants; product outlets
MEC-AD [139–146]	SS/WAS → AD with polarized electrodes → CH ₄ -rich biogas	Direct experimental integration; mainly laboratory-scale batch and continuous systems	Methane production can be enhanced, but net energy performance depends on electrical input and energization strategy	Nutrient mobilization may occur, but final recovery requires downstream capture	External electricity; electrode requirements; voltage optimization; scale-up; net energy balance
Pretreatment-AD-MEC-P recovery [149]	WAS → pretreatment → AD → MEC → struvite	Direct experimental multi-stage integration; laboratory scale	Biogas production through AD with additional bioelectrochemical conversion in MEC	Final P recovery as struvite has been demonstrated	Pretreatment and chemical inputs; product quality; process complexity
AD sidestream → MEC → N/P recovery [151]	AD → digested-sludge centrate → MEC → N-rich catholyte + downstream P precipitation	Downstream/sidestream integration; laboratory scale using real digested-sludge centrate	Bioelectrochemical treatment requires electrical input and can also generate hydrogen	N is transferred toward the catholyte; P can subsequently be recovered by chemical precipitation	Electrical demand; availability of biodegradable electron donors; chemical addition for P precipitation; scale-up
AD-gasification [12,22,92–101]	SS → AD → digestate → drying → gasification → syngas + char/ash	Limited/prospective integration in the sewage sludge literature; mainly inferred from individual-process evidence	Potential sequential recovery of biogas and syngas; direct integrated evidence remains limited	P and other minerals are concentrated in char/ash and require downstream recovery	Drying; high-temperature operation; syngas cleaning; ash management; limited direct integration evidence

* Evidence level and scale reflect the original studies. Differences in sludge characteristics, process scale, functional units, system boundaries, and energy-performance metrics should be considered when comparing the reported evidence.

Despite these opportunities, the implementation of full-scale sludge biorefineries still faces important technical, economic, and regulatory challenges. Further development requires improvement in process integration through advanced monitoring, modelling, and control strategies capable of dynamically managing carbon, nitrogen, and phosphorus flows and accounting for the interactions among the different treatment stages. Particular attention should also be devoted to improving the quality and functionality of hydrochar and biochar for high-value applications related to carbon management, soil remediation, and pollutant adsorption, while enhancing nutrient recovery from digestate and process waters to increase material circularity.

The evidence summarized in Table 4 also shows that the maturity of integrated pathways is heterogeneous: some configurations are supported by direct experimental integration, whereas others are based on downstream treatment of intermediate streams, process modelling, or prospective combinations inferred from individual technologies.

In parallel, comprehensive techno-economic assessments and life cycle assessment (LCA) studies are needed to identify the most sustainable integration scenarios under different operating conditions. Such evaluations should consider not only energy balances and greenhouse gas emissions, but also resource recovery efficiency, environmental impacts, operational costs, auxiliary energy and material requirements, avoided disposal, and market opportunities for recovered products, providing robust data for policy and investment decisions. As published studies differ substantially in sludge characteristics, solids content, process scale, functional units, and system boundaries, no universal ranking of the integrated pathways can currently be established. Moreover, reported energy indicators may refer to gross energy contained in recovered products, apparent energy efficiency, or net energy performance, depending on the study; these metrics should therefore not be directly compared unless equivalent system boundaries and energy inputs are considered. An additional aspect of process integration is the fate of contaminants across the treatment train. Integration does not necessarily result in contaminant removal, but may redistribute or concentrate contaminants among solid, liquid and gaseous streams. For example, metals can remain or become concentrated in char or ash [83,93], while HTC can transfer soluble compounds to the process water [68]; gasification can also generate tar and other impurities requiring appropriate downstream gas cleaning [92–95]. Therefore, the quality and final use of recovered products should be evaluated together with the contaminant content of intermediate and residual streams, particularly when recovered materials are intended for applications requiring compliance with specific quality and regulatory requirements. Their selection should instead consider sludge moisture and composition, availability of heat and electricity, dewatering and drying requirements, management of liquid and solid residual streams, targeted products, contaminant fate, plant scale, regulatory requirements, and local markets for recovered products.

Finally, the transition from laboratory- and pilot-scale systems to full-scale implementation will require coordinated technological development, supportive regulatory frameworks, and stronger collaboration among wastewater utilities, industry, and research institutions. In the short- to medium- term, the integration of emerging technologies with established processes such as AD appears more realistic than the implementation of entirely new stand-alone treatment chains. By integrating multiple recovery pathways within a single treatment platform, sewage-sludge biorefineries have the potential to transform wastewater treatment plants from waste disposal facilities into resource recovery hubs, contributing simultaneously to renewable energy production, nutrient recycling, carbon management, and the broader objectives of the circular economy.

Based on the integration pathways discussed, Figure 1 presents a conceptual sewage sludge biorefinery configuration in which biological, thermochemical, and bioelectrochemical processes are combined within a single treatment framework. The scheme is intended to illustrate possible process integration and internal stream valorization. Within such an integrated framework, sewage sludge can be directed to anaerobic digestion, potentially assisted by bioelectrochemical processes, while the resulting digestate and sidestreams can undergo further thermochemical or nutrient-recovery treatments.

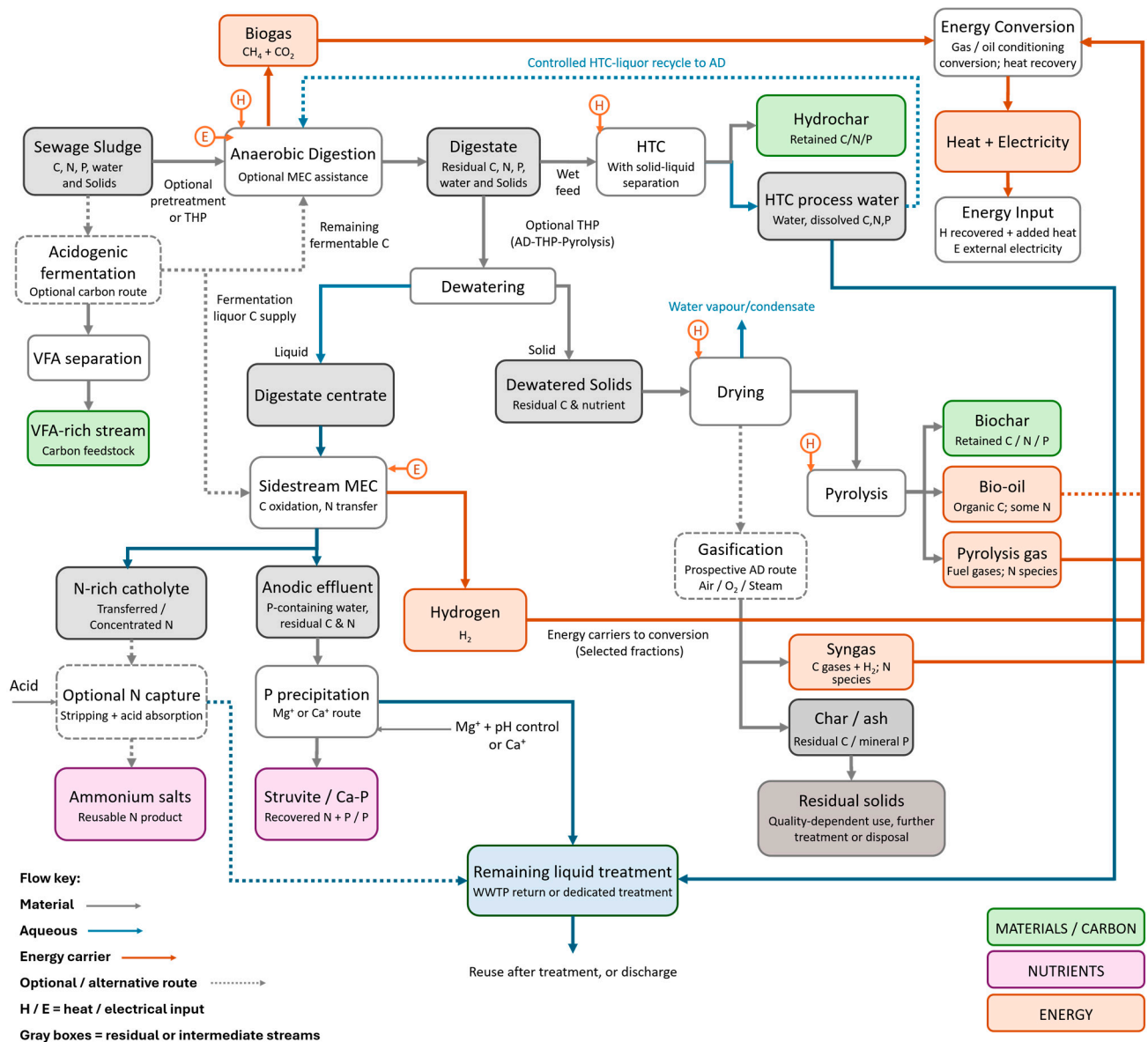


Figure 1. Conceptual sewage sludge biorefinery integrating biological, thermochemical and bioelectrochemical pathways for the recovery of energy, materials/carbon and nutrients.

7. Conclusions

Sewage sludge management represents one of the most significant cost factors in the operation of wastewater treatment plants. While solutions aimed at reducing sludge production are being studied, and in some cases already implemented, it is unrealistic to expect that such production could be eliminated or even reduced to quantities that do not require proper management.

When production is unavoidable, a modern and sustainable management approach must consider the principles of the circular economy, combining the control of potential environmental impacts with the recovery of resources that are of genuine market interest. In this respect, sewage sludge may provide energy, nutrients, and carbon-based products. Conventional technologies such as anaerobic digestion, incineration, and co-combustion remain essential components of sludge management because of their technological maturity and widespread full-scale implementation. However, each of these routes presents intrinsic limitations related to energy efficiency, environmental impact, product valorization, or management of secondary residues. Emerging technologies, including hydrothermal car-

bonization, pyrolysis, gasification, and bioelectrochemical systems, offer new opportunities to overcome some of these limitations by diversifying the range of recoverable products and providing additional routes for energy, nutrient, and carbon recovery.

On the other hand, these more innovative approaches would benefit from an integrated approach combining them with one another and/or with technologies characterized by more established applications.

In this framework, the analysis presented in this review indicates that the future of sewage sludge valorization is unlikely to rely on a single technology. Rather, substantial potential lies in the strategic integration of biological, thermochemical, and bioelectrochemical processes within sludge biorefinery concepts. The reviewed studies show that such integration can combine complementary routes for energy recovery, nutrient recycling and carbon valorization, although the magnitude of these benefits cannot be directly compared across all configurations because of differences in feedstock, scale and system boundaries. In this perspective, wastewater treatment plants may progressively evolve toward Water Resource Recovery Facilities (WRRFs), where multiple recovery pathways are combined to maximize the value extracted from sewage sludge. However, the available evidence does not indicate the same level of maturity for all integrated configurations. While AD provides an established platform for integration, combinations with HTC, pyrolysis and bioelectrochemical systems are still mainly supported by laboratory- or pilot-scale experiments, downstream treatment studies, or process modelling rather than full-scale integrated operation.

Despite these advances, several challenges still hinder large-scale implementation. These include the optimization of process integration, the treatment and valorization of intermediate streams, the quality and standardization of recovered products, economic competitiveness, and compliance with increasingly stringent environmental regulations. In particular, the integration of emerging technologies with established full-scale processes appears more realistic in the short and medium term than their stand-alone application, especially for technologies such as bioelectrochemical systems, which are still predominantly supported by laboratory-scale evidence. Among the pathways reviewed, AD-HTC appears particularly relevant for wet digestate where avoiding extensive drying and managing or recycling the HTC process water can provide integration opportunities while simultaneously benefiting from the widespread and well-established implementation of AD at full scale; AD-pyrolysis may be more suitable where dewatering or surplus heat is available and suitable outlets exist for biochar and other pyrolysis products. MEC-AD represents a further integration option for methane enhancement and, in specific configurations, nutrient recovery, although its net energy performance, electrode requirements and scale-up remain important constraints. Further development requires robust integrated process schemes supported by techno-economic and life-cycle assessments and by pilot- and full-scale demonstration studies.

The transition from linear sludge treatment to integrated sludge biorefineries represents a key step toward circular and resource-efficient wastewater management. Its success will depend on the ability to combine complementary technologies into efficient, flexible, and economically viable recovery systems capable of simultaneously producing renewable energy, recovering nutrients and carbon-based products while aiming to reduce environmental impacts. Importantly, increased resource recovery alone does not demonstrate the overall sustainability of an integrated pathway: net energy performance, recovered-product quality, regulatory compliance, contaminant management, and economic feasibility must also be considered at the level of the complete treatment train.

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Abbreviations

The following abbreviations are used in this manuscript:

AD	Anaerobic Digestion
BES	Bioelectrochemical Systems
BTX	Benzene, Toluene and Xylenes
CE	Coulombic Efficiency
CFR	Code of Federal Regulations
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
DIET	Direct Interspecies Electron Transfer
DOC	Dissolved Organic Carbon
EET	Extracellular Electron Transfer
EPA	U.S. Environmental Protection Agency
EPS	Extracellular Polymeric Substance(s)
EU	European Union
FISH	Fluorescence In Situ Hybridization
FNA	Free Nitrous Acid
GHG	Greenhouse Gas(es)
HHV	Higher Heating Value
HRT	Hydraulic Retention Time
HTC	Hydrothermal Carbonization
IED	Industrial Emissions Directive
ISSA	Incinerated Sewage Sludge Ash
LCA	Life Cycle Assessment
LHV	Lower Heating Value
MAP	Magnesium Ammonium Phosphate
MEC	Microbial Electrolysis Cell
MFC	Microbial Fuel Cell
MLSS	Mixed Liquor Suspended Solids
MRP	Molybdate Reactive Phosphorus
MSW	Municipal Solid Waste
NSPS	New Source Performance Standards
OP	Organic Phosphorus
PBS	Phosphate Buffer Solution
PCA	Protocatechuic Acid
PCR-DGGE	Polymerase Chain Reaction–Denaturing Gradient Gel Electrophoresis
PFAS	Per- and Polyfluoroalkyl Substances
PM	Particulate Matter
SEM	Scanning Electron Microscopy
SFL	Sludge Fermentation Liquid
SMFC	Sediment Microbial Fuel Cell
SRT	Solids Retention Time
SS	Sewage Sludge
SSI	Sewage Sludge Incineration/Incinerators
TAN	Total Ammonia Nitrogen

TCOD	Total Chemical Oxygen Demand
THP	Thermal Hydrolysis Process
TN	Total Nitrogen
TP	Total Phosphorus
TS	Total Solids
TSS	Total Suspended Solids
VFA/VFAs	Volatile Fatty Acid(s)
VS	Volatile Solids
VSS	Volatile Suspended Solids
WAS	Waste Activated Sludge
WWTP	Wastewater Treatment Plant
WRRF	Water Resource Recovery Facility

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