



REVIEW ARTICLE

Bioconversion of agro-industrial effluent sludge into bio-fertilisers: A sustainable waste management approach

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Abstract

The rapid growth of agro-industrial activities has led to the generation of substantial quantities of effluent sludge, posing serious environmental and waste management concerns. Despite these challenges, agro-industrial sludge contains significant amounts of organic matter and plant nutrients, making it a valuable resource for agricultural applications when properly treated. This review explores the conversion of agro-industrial effluent sludge into biofertilisers as a sustainable strategy for waste valorisation and nutrient recycling within a circular bioeconomy framework. It discusses the characteristics of sludge, associated environmental risks and the treatment processes required to ensure safe agricultural use. Major bioconversion approaches, including composting, vermicomposting, microbial inoculation, anaerobic digestion and thermochemical methods, are critically evaluated. The review also highlights the role of beneficial microorganisms in nutrient transformation and recovery, as well as emerging technologies such as biochar-based fertilisers, electrochemical nutrient recovery systems and integrated sludge biorefineries. Findings from laboratory and field studies demonstrate that sludge-derived biofertilisers can enhance soil fertility, improve microbial activity, increase nutrient availability and support crop productivity while reducing dependence on synthetic fertilisers. However, issues related to heavy metals, organic contaminants, pathogen removal, product quality and regulatory compliance remain important challenges. Overall, the bioconversion of agro-industrial sludge into biofertilisers offers a promising pathway for sustainable waste management, resource recovery, environmental protection and resilient agricultural development.

Keywords: agro-industrial sludge; biofertilisers; circular bioeconomy; nutrient recovery; sludge bioconversion; waste valorisation

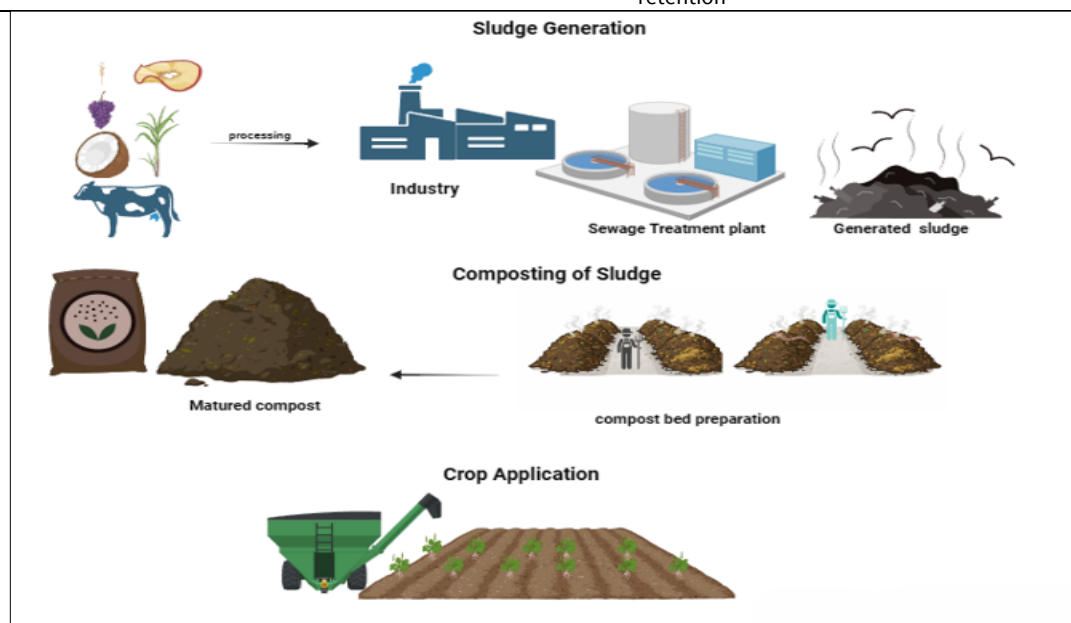
Introduction

Effluent treatment plants in agro-industrial and food processing sectors produce nutrient-dense sludges that are costly to manage but potentially beneficial for agriculture. Bioconversion technologies are designed to stabilise these residues, eliminate or immobilise pollutants and convert them into safe and effective bio-fertilisers as part of a circular, low-waste system. Sludges from agro-industrial, food and dairy sources contain high levels of organic matter and nitrogen, phosphorous and potassium (NPK) nutrients, making them strong candidates for fertiliser production (1). Utilising these resources diminishes the need for landfilling, incineration and dependence on mineral fertilisers, which is consistent with circular bioeconomy and climate objectives (2). Amendments made from bioconverted sludge enhance soil organic matter, improve water retention and increase crop yields, even in semi-arid and nutrient-poor soils (3). However, the variable composition, presence of heavy metals, organic pollutants, microplastics and pathogens necessitate stringent stabilisation, oversight and guideline-based application rates (4). Globally and nationally, regulatory frameworks increasingly advocate for the land application of appropriately treated biosolids but stress the importance of contaminant thresholds, hygiene and standardisation of products (5). Emerging systems-based and rapid

sustainability assessment tools are identifying composting and similar options as optimal circular strategies for managing sludge. Effluent sludge from agro-industrial sources can be effectively bioconverted into bio-fertilisers through various methods such as composting, microbial inoculation, digestion and biochar/encapsulation, which benefits soil health and helps close nutrient cycles. Several technological approaches such as composting, microbial inoculation, anaerobic digestion and thermochemical conversion have been explored for sludge valorisation (Table 1). In particular, Fig. 1 illustrates a typical pathway of sludge bioconversion through composting. Agro-industrial residues generated during food and dairy processing are treated in effluent treatment facilities, where sludge is generated as a by-product. Although several reviews have examined sludge management, nutrient recovery, composting technologies and biosolid reuse, most have focused on specific treatment methods, contaminant risks or fertiliser applications. In contrast, the present review provides an integrated assessment of agro-industrial effluent sludge valorisation by combining microbial and biochemical conversion mechanisms, circular bioeconomy principles, environmental risk assessment and emerging green technologies within a single framework. Particular emphasis is placed on the role of microbial consortia, nutrient mineralisation pathways and advanced.

Table 1. Major technological pathways for converting sludge into bio-fertilisers and their functional roles

Pathway / Technology	Main role in sludge → Bio-fertiliser	Citations
Composting/vermicomposting	Stabilises organics, reduces pathogens and odour, produces mature compost/vermicompost	(6)
Microbial inoculants and “bio-organic” fertilisers	Targeted consortia (e.g., lignocellulolytic, chitinolytic microbes) enhance waste degradation and plant growth.	(7)
Anaerobic digestion	Produces biogas, reduces volume; digestate used as fertiliser/soil amendment	(8)
Biochar/pyrolysis, encapsulation	Converts sludge into carbon-rich, slow-release fertilisers and improves nutrient retention	(9)

**Fig. 1.** Overall processes of bioconversion of agro-industrial effluent sludges.

Materials and Methods

Review design and scope

A systematic and multidisciplinary literature review was conducted to synthesise current knowledge on the bioconversion of agro-industrial effluent sludge into bio-fertilisers and its role in sustainable waste management. The review integrates perspectives from environmental engineering, microbiology, soil science, waste management and circular bioeconomy frameworks. The approach was designed to capture both fundamental principles and recent technological advancements, including biological, physicochemical and thermochemical conversion pathways, as well as associated environmental and regulatory considerations.

Literature search strategy

A comprehensive literature search was performed using major scientific databases, including Scopus, Web of Science, ScienceDirect, Google Scholar and PubMed. The search focused primarily on peer-reviewed articles published between 2000 and 2025, with earlier foundational studies included where necessary to support key concepts. Search keywords were systematically combined to ensure broad coverage of the topic, including: “agro-industrial sludge,” “effluent sludge valorisation,” “biofertiliser production,” “sludge composting,” “vermicomposting,” “anaerobic digestion sludge,” “biochar from sludge,” “nutrient recovery,” “circular bioeconomy sludge,” “microbial bioconversion” and “sludge contaminants.” This strategy enabled the identification of studies addressing sludge characteristics, treatment technologies, microbial mechanisms, agronomic performance and environmental risks.

Study selection and inclusion criteria

Studies were selected based on predefined inclusion and exclusion criteria. Included studies met at least one of the following criteria: (i) investigation of physicochemical properties and nutrient composition of agro-industrial or sewage sludge; (ii) evaluation of bioconversion technologies such as composting, vermicomposting, microbial inoculation, anaerobic digestion, or thermochemical processes; (iii) assessment of microbial pathways, enzymatic mechanisms or nutrient mineralisation processes; (iv) analysis of environmental risks, including heavy metals, pathogens and organic contaminants; or (v) evaluation of agronomic performance and soil health impacts of sludge-derived biofertilisers. Only peer-reviewed journal articles, review papers and high-quality conference publications were considered. Studies lacking methodological clarity, non-scientific reports and those unrelated to sludge valorisation or biofertiliser production were excluded.

Thematic categorisation and synthesis

Selected studies were systematically organised into major thematic domains to facilitate structured analysis: (i) characteristics and composition of agro-industrial sludge; (ii) contaminant profiles and environmental risks; (iii) stabilisation and hygienisation processes; (iv) microbial and biochemical pathways in sludge bioconversion; (v) technological approaches for sludge-to-biofertiliser conversion, including biological and thermochemical methods; (vi) circular bioeconomy frameworks and resource recovery systems and (vii) agronomic performance and soil impacts of sludge-derived products. This thematic framework enabled integration of experimental, field-based and modelling studies to identify trends, technological efficiencies and research gaps.

Data extraction and comparative analysis

Key data were extracted from each study, including sludge type and source, physicochemical properties (e.g., pH, organic matter, NPK content), treatment method, microbial or enzymatic mechanisms, contaminant levels and agronomic outcomes such as crop yield and soil health indicators (e.g., microbial biomass, enzymatic activity, soil organic carbon). Comparative analysis was conducted to evaluate the effectiveness of different bioconversion pathways, assess nutrient recovery efficiency and examine variations in environmental safety and regulatory compliance across studies. Particular attention was given to identifying consistent findings, technological limitations and context-specific performance differences.

Limitations of the review approach

Despite adopting a comprehensive and multidisciplinary approach, several limitations were identified. Variability in sludge composition, treatment processes and analytical methods across studies complicates direct comparison of results. Inconsistent reporting of contaminant thresholds and lack of standardised quality criteria for sludge-derived biofertilisers remain significant challenges. Additionally, long-term field studies assessing environmental impacts and nutrient dynamics are limited, particularly in developing regions. These constraints highlight the need for standardised methodologies, harmonised regulatory frameworks and integrated assessment tools to support the safe and efficient valorisation of agro-industrial sludge within circular bioeconomy systems.

Characteristics of agro-industrial effluent sludges

Physicochemical and nutrient characteristics of agro-industrial sludges

Agro-industrial and sewage sludges exhibit complex physicochemical characteristics and contain considerable amounts of plant nutrients, although their properties vary widely depending on the source, treatment process and seasonal variations. These factors ultimately influence their suitability for applications such as agricultural land use, nutrient recovery and other valorisation pathways. Typically, sludges contain high moisture content and their drying behaviour is largely determined by the initial moisture level and composition, with higher moisture

content leading to slower drying rates (10). In terms of chemical properties, many industrial and municipal sludges are close to neutral, although pH values can vary depending on the source and treatment process. Municipal wastewater sludges generally exhibit pH values within the neutral range, whereas certain industrial sludges may be slightly acidic or alkaline due to the nature of industrial effluents. Sludges rich in organic matter, particularly those derived from municipal wastewater treatment plants, typically contain volatile solids representing approximately 70–80 % of total solids. In contrast, industrial sludges exhibit greater variability in volatile solids content depending on the industry type, with food-processing and dairy sludges often showing similarly high organic fractions, while textile, paint and other industrial sludges may contain lower organic matter levels and higher proportions of inorganic constituents. These differences influence sludge stabilisation requirements, nutrient recovery potential and suitability for agricultural applications. This high organic fraction facilitates biological treatment processes and enhances soil conditioning properties when applied as soil amendments, although it may also contribute to odour generation during storage or processing (11). In addition to organic matter, these sludges generally contain significant quantities of plant macronutrients, particularly N, P and K, which contribute to their potential value as bio-fertiliser resources. The suitability of agro-industrial effluent sludge for agricultural use depends on balancing its nutrient and organic matter benefits with potential environmental risks (Fig. 2).

Municipal wastewater treatment plant (WWTP) sludges typically contain around 2–6 % N, 1.5–2.7 % P and 0.5–0.8 % K on a dry weight basis, along with high organic matter content and relatively low concentrations of heavy metals (12). Similarly, dairy industry sludges may contain relatively high N levels (about 4–7 %) and P concentrations ranging from approximately 1.5–6.5 %, although their composition may vary depending on feedstock and treatment processes. Food-processing sludges and brewery wastes are also known to contain significant N levels, typically between 2 % and 7 %, which can improve soil N availability and enhance crop productivity (13). Total P concentrations in these sludges can range from approximately 1–8 %, while K levels are generally lower but remain agronomically important.

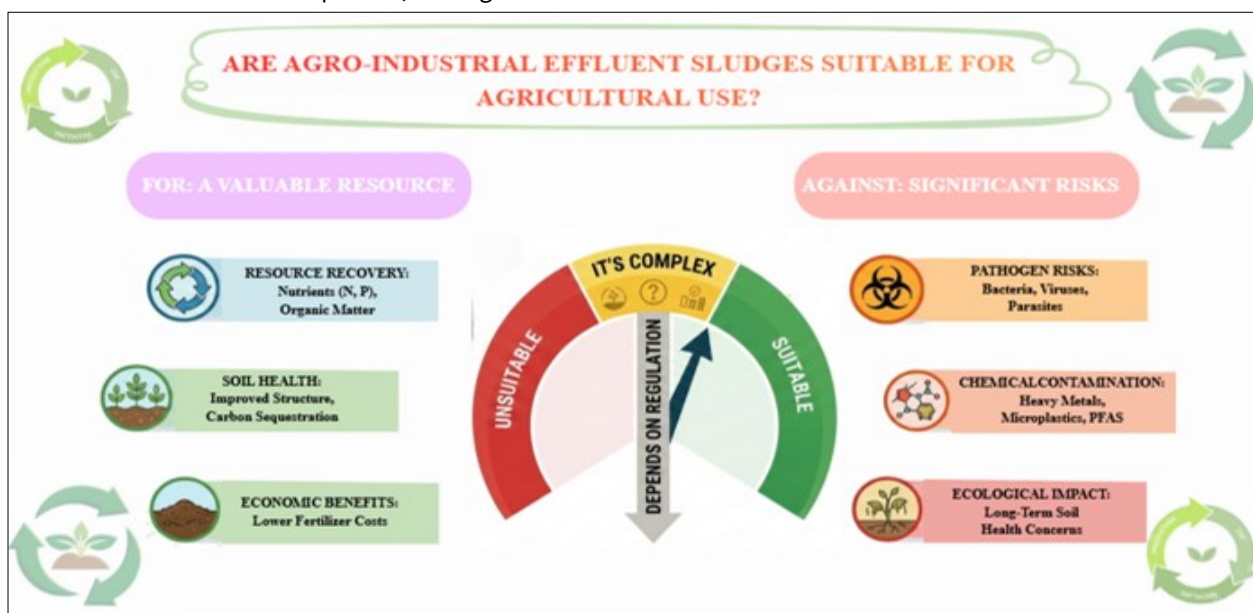


Fig. 2. Conceptual overview of the potential benefits and risks associated with the agricultural use of agro-industrial effluent sludges.

Organic carbon is another important component of agro-industrial sludge. Food and faecal sludges typically contain between 26 % and 40 % total organic carbon, which exceeds the minimum requirements for compost quality and contributes to improved soil structure, water retention and microbial activity. Secondary macronutrients such as calcium (Ca), magnesium (Mg) and sulphur (S) are commonly present at levels of approximately 1–5 %, 0.6–4 % and 0.27–1.7 % respectively, which are comparable to those found in conventional organic manures. In addition, micronutrients, including iron (Fe), manganese (Mn), zinc (Zn), copper (Cu) and boron (B), are usually present in adequate amounts for plant growth, although excessive concentrations may lead to phytotoxic effects if application rates are not properly controlled (14). Representative nutrient compositions of different agro-industrial sludge types reported in the literature (Table 2). Similarly, hydrothermal carbonisation can concentrate P and Ca in hydrochar while converting N into ammonium in the liquid phase, resulting in slow N release characteristics when applied to soils (15).

Contaminant load in agro-industrial sludges: Heavy metals, pathogens and organics

Agro-industrial and municipal sludges have been extensively studied as nutrient-rich assets within circular bioeconomy models; however, an increasing body of literature indicates that contamination levels often limit their agronomic potential. Modern reviews consistently stress that risk assessments should consider not only total contaminant concentrations but also factors such as chemical speciation, bioavailability, persistence and exposure pathways, since these characteristics govern contaminant mobility, plant uptake, groundwater leaching and long-term ecological risks more effectively than total concentration measurements alone. In various geographical regions, sewage and faecal sludges generally display a concentration typical of heavy metal hierarchy of Zn > Cu > chromium (Cr)/nickel (Ni) > lead (Pb) > cadmium (Cd)/mercury (Hg)/arsenic (As) (17). Zinc and Cr tend to occur in the highest concentrations, sometimes reaching several thousand milligram per kilogram, while Cd and Ni often dominate indices assessing ecological and human health risks due to their heightened toxicity and mobility. Although numerous municipal and agro-industrial sludges adhere to national agricultural limits, certain subsets particularly those affected by industrial effluents exceed allowable levels for Cu, Zn or Cd and show moderate to very high contamination indices (18). Notably, sequential extraction studies reveal that while a significant portion of metals may be bound in relatively stable or residual forms, elements like Zn, Ni and Cd frequently exist in exchangeable or reducible fractions, increasing their potential for plant uptake and groundwater leaching (19). These outcomes highlight the importance of risk assessment based on speciation rather than

merely concentration. The microbiological aspect of sludge contamination has received growing focus in recent years. Sewage and faecal sludges often harbour pathogenic bacteria, viruses, helminths and protozoa, in addition to antibiotic resistance genes (ARGs) and heavy metal resistance genes that might contribute to co-selection processes in soil (20).

Safe valorisation of sludge: Stabilisation, hygienisation and contaminant control

The safe agricultural reuse of sewage and agro-industrial sludge necessitates a comprehensive treatment approach focused on three primary goals: (i) reducing volume and stabilising the material, (ii) eliminating pathogens (hygienisation) and (iii) managing or eliminating heavy metals and organic contaminants (21). Current research highlights that these processes are interconnected and should be assessed within a risk-based regulatory framework.

Volume reduction and stabilisation: The initial treatment often includes mechanical processes such as thickening, dewatering and homogenisation, which help decrease sludge volume and enhance handling properties. These processes are typically followed by biological stabilisation via anaerobic or aerobic digestion, which aims to break down biodegradable organic materials, reduce odours and improve material stability. Anaerobic digestion is one of the most used stabilisation methods, especially when paired with post-treatment techniques such as thermal hydrolysis, advanced oxidation, or acidic aerobic digestion. Such integrated systems are known to enhance dewaterability, increase pathogen reduction and sometimes alter the patterns of metal solubilisation (22). However, alterations in metal speciation during these processes necessitate thorough downstream evaluations before land application.

Hygienisation: Meeting regulatory pathogen standards: The overall sequence of major sludge pretreatment and processing technologies is illustrated in Fig. 3. The figure presents the progression from raw sludge through stages such as dewatering, digestion, composting or thermal stabilisation, alkaline treatment and advanced chemical processing. These processes collectively transform raw sludge into stabilised biosolids or treated sludge products suitable for agricultural application, energy recovery, or further resource valorisation. Untreated sewage sludge often surpasses regulatory limits for pathogens like *Salmonella*, *Escherichia coli* and helminth eggs, making targeted hygienisation essential before agricultural application (23). Anaerobic digestion combined with pretreatment methods, such as thermal, hybrid disintegration, electrochemical, or oxidative approaches, enhances the disruption of microbial cells and increases the efficiency of pathogen elimination.

Table 2. Physicochemical and nutrient composition of selected agro-industrial and sewage sludges reported in the literature

Sludge type	TOC (% DW)	N (% DW)	P (% DW)	K (% DW)	Notes	Sources
Anaerobic food industry sludges (soy milk, distillery)	–	1.8–2.7	~0.25–0.42 (as P ₂ O ₅)	~0.10–0.17 (as K ₂ O)	Nutrient-rich food-processing sludge	(16)
Faecal/food co-compost	26–40	2–3	~1	0.44–3.5	High organic carbon and balanced nutrients	(16)
Municipal WWTP sludge	–	2–6	1.5–2.7	0.5–0.8	High organic matter; often metal-compliant	(16)
Dairy industry sludges	–	~4–7 (57–70 g kg ⁻¹)	~1.5–6.5	0.3–0.7	Strong variation depending on sludge type	(16)
HTC hydrochars from sewage sludge	–	0.9–1.5 (organic N)	1.95–2.35	0.19–0.21	Higher C : N ratio; slow nitrogen release	(16)

WWTP: wastewater treatment plant; HTC: hydrothermal carbonisation; N: nitrogen; C: carbon; P: phosphorous; K: potassium; DW: dry weight.

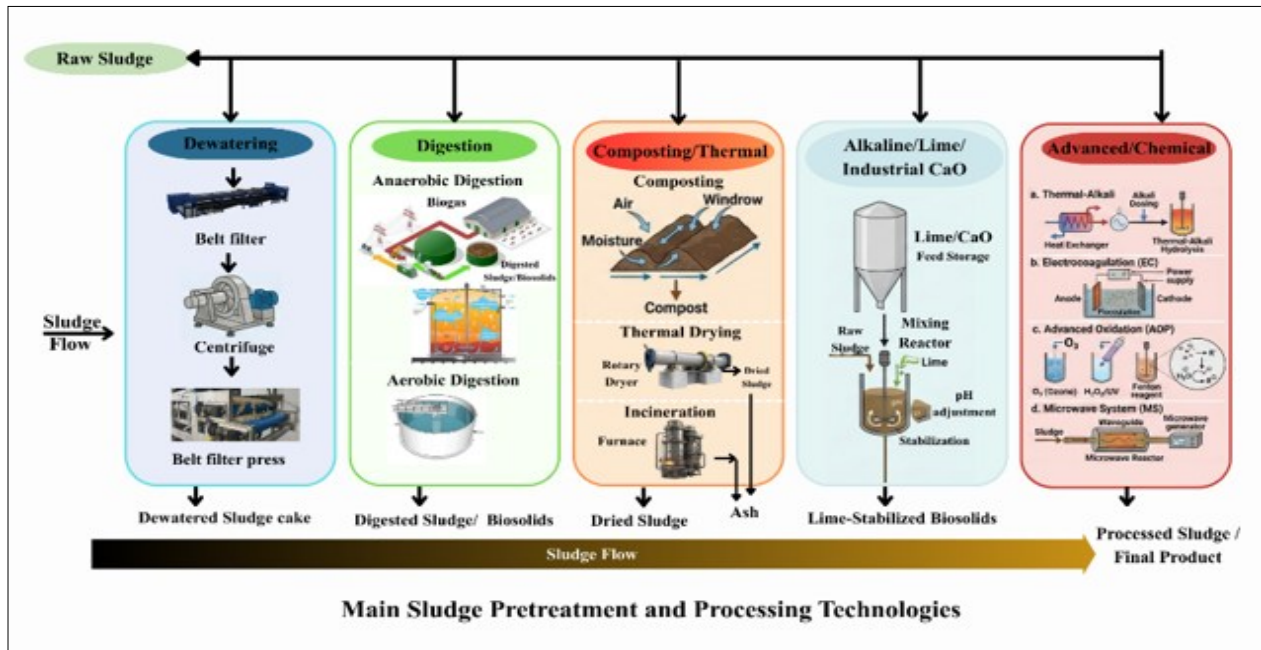


Fig. 3. Major sludge pretreatment and processing technologies used for stabilisation, hygienisation and resource recovery prior to sludge valorisation.

Alkaline or lime stabilisation, employing quicklime or alkaline industrial by-products, raises the sludge pH beyond 10–12, creating conditions unfavourable for faecal coliforms and *Salmonella*, which can often meet Class A biosolids criteria (24). Nonetheless, while these advancements improve pathogen inactivation, they do not address chemical contaminants, underscoring the necessity for integrated treatment approaches. Contaminant control and process-related considerations. In instances where heavy metals like Cd, Ni and Cu reach or exceed regulatory limits, alternative removal technologies or the selective diversion of sludge from agricultural reuse may be required (25). Source control at the point of industrial discharge remains a vital early intervention. Various chemical and physical pretreatment methods including alkali-thermal treatment, metabisulfite conditioning, electrochemical disintegration, ultrasonic irradiation and microwave-assisted processes are often utilised to improve solubilisation and boost biogas or volatile fatty acid yields. However, these methods can alter metal speciation and mobility, potentially raise environmental risks if not properly assess before application to soil. Regulatory frameworks are increasingly requiring ongoing monitoring of nutrients, heavy metals, pathogen indicators and more recently emerging contaminants and antibiotic-resistant bacteria or genes before unrestricted field application. This shift reflects a growing understanding that sludge valorisation must reconcile the goals of a circular economy with the imperative of environmental protection. Table 3 summarises the key pretreatment groups used in sludge valorisation, their primary functions and their roles in ensuring environmental safety. Common approaches include dewatering and digestion, which reduce sludge volume and partially stabilise organic matter.

Composting and thermal treatments further enhance stabilisation and sanitation by destroying pathogens and producing safer soil amendments. Chemical stabilisation methods such as lime addition can increase pH levels to achieve effective hygienisation and pathogen reduction. More advanced chemical and physicochemical treatments, including thermal alkaline processes, electrocoagulation (EC), advanced oxidation processes (AOP) and microwave-assisted treatments are also used to solubilise organic matter, recover energy products and reduce contaminant levels in sludge.

Circular bioeconomy framework for sludge valorisation

Turning sewage and industrial sludge into valuable resources is a central pillar of the circular bioeconomy, in which waste streams are redirected from landfill or simple disposal toward the recovery of energy, materials and nutrients. Contemporary research integrates biorefinery concepts, advanced treatment technologies and systems-level assessment tools to design circular frameworks that maximise resource efficiency while minimising environmental risk. Biological pathways particularly anaerobic digestion are widely applied to produce biogas or biomethane, often enhanced through co-digestion with food waste and other organic substrates to improve methane yields and process stability (27).

Policy, regulatory and socio-economic drivers of sludge valorisation

Policy, regulation and socio-economic conditions largely determine whether sludge is managed as a waste-disposal expense or as a circular resource. Recent work highlights that technology alone is insufficient; incentives, standards, public acceptance and market structure are decisive.

Table 3. Key pretreatment technologies and their functions in sludge stabilisation and safe valorisation

Pretreatment group	The main purpose of valorisation	Typical role in safety	Citations
Dewatering, digestion	Volume↓, stabilisation	Odour↓, partial pathogen↓	(26)
Composting/thermal	Stabilisation + sanitisation	Pathogen kill to Class A	(26)
Alkaline/lime/industrial CaO	Hygienisation, conditioning	Strong pathogens kill, odour↓	(26)
Advanced/chemical (thermal-alkali, EC, AOP, MS)	Solubilisation, energy products	Must assess metals and by-products	(26)

CaO: calcium oxide; EC: electrical conductivity; AOP: advanced oxidation process; MS: municipal sludge.

Policy and regulatory drivers

●**Economic instruments:** Renewable energy incentives, green certificates, gate fees and subsidies increase the attractiveness of sludge-to-energy and co-digestion routes, but their absence or instability creates investment barriers (28).

●**Command-and-control rules:** Landfill bans, tighter limits on land application and stricter contaminant standards push utilities toward energy recovery and advanced treatment (29).

●**Regulatory uncertainty:** Changing or unclear rules on land spreading and disposal prices strongly shape utilities' choices, often favouring incineration and vertical integration to hedge risk.

End-of-waste criteria and product standards: Clear criteria for biobased fertilisers, hydrochar, P-products and construction materials are crucial to convert sludge outputs into marketable products (30).

Socio-economic and market drivers

The financial viability of valorisation scenarios often hinges on subsidies, as revenues are influenced by energy prices, the scale of operations and market demand for biogas, volatile fatty acids (VFAs), polyhydroxyalkanoates (PHAs) and fertilisers (31). In many cases, especially within faecal sludge systems, product revenues only cover a small fraction of the associated costs, making it essential to recognise and support co-benefits such as improvements in public health, environmental quality, sanitation equity and access to safe sanitation services through public investment and policy support rather than relying solely on market-based revenues. Additionally, the preferences of stakeholders and civil society play a crucial role, with citizens, municipalities and farmers impacting the direction of waste management strategies, whether it be agricultural reuse or incineration, alongside determining acceptable levels of risk (32). Consumer perception and trust are also significant factors, as skepticism regarding "waste-derived" products and low awareness of circular economy initiatives can hinder their acceptance; therefore, implementing certification and information campaigns could help improve uptake. The circular bioeconomy approach aims to promote the sustainable management of sludge through these transformative practices (33). The circular bioeconomy approach promotes the sustainable management of sludge by transforming waste streams into valuable resources such as energy, nutrients and bio-based materials. The key elements of sludge circular bioeconomy frameworks, including resource recovery, biorefinery concepts, systems-based assessment tools and supportive policy and market mechanisms (Table 4). These components collectively support efficient sludge valorisation, promote sustainable waste management and facilitate the transition toward circular and resource-efficient bio-based systems. To guide this transition, research increasingly employs circularity indicators, resource recovery metrics, life cycle assessment (LCA), life cycle costing (LCC) and sector-level monitoring frameworks to evaluate

environmental, economic and social performance over time. Collectively, the literature demonstrates that sludge valorisation within a circular bioeconomy is not solely a technological challenge but a systemic transformation requiring coordinated innovation, policy coherence, financial instruments and societal engagement.

Microbial and biochemical pathways in sludge bioconversion of agro-industrial effluents

Agro-industrial wastewater is usually abundant in biodegradable organic materials, such as carbohydrates, proteins, lipids and phenolic compounds, while also containing inhibitory contaminants such as pesticides, antibiotics, synthetic dyes, heavy metals and elevated salt concentrations that may impair microbial processes and sludge bioconversion efficiency. In treatment systems based on sludge, the bioconversion process relies on a diverse range of microbial communities that function through interconnected metabolic networks, whether in aerobic or anaerobic environments. Recent studies emphasise that the effectiveness of the system is influenced not by individual organisms, but rather by syntrophic relationships, metabolic adaptability and environmental pressures acting on the sludge microbiome. Fig. 4 shows key microbial pathways across sludge treatment types and processes. Table 5 summarises the major microbial pathways involved in agro-industrial sludge treatment and bioconversion.

Role of microbial consortia in organic matter decomposition

Division of labour and synergy

In processes like anaerobic digestion and sludge fermentation, various microbial groups specialise in different tasks: hydrolytic and acidogenic bacteria (e.g., *Bacteroidota*, *Firmicutes*) convert polymers into soluble substances and volatile fatty acids, while other microbes transform these products into methane or additional metabolites (40). During the composting and biodrying phases, thermophilic bacteria and fungi (e.g., *Bacillus*, *Actinobacteria*, *Aspergillus*, *Streptomyces*) are prevalent, facilitating the rapid breakdown of lignocellulose, lipids and polyphenols found in sludge and agricultural wastes (41). Developed thermophilic consortia consisting of *Bacillus* and *Geobacillus* strains exhibit superior extracellular polymer degradation, enhanced enzyme activities and more effective sludge hydrolysis compared to isolated strains (42).

Enzymes and substrate range

Consortia collectively produce lipases, cellulases, amylases and glycoside hydrolases, allowing for the breakdown of waste rich in lipids and polysaccharides; mixed consortia have been shown to remove greater amounts of solid waste than individual strains (43). In the biodrying of sludge, genes associated with carbohydrate-active enzymes (CAZyme) are predominantly found within a few key genera (*Bacillus*, *Tetrasphaera*, *Streptomyces*) which are directly associated with the degradation of lignocellulose and starch.

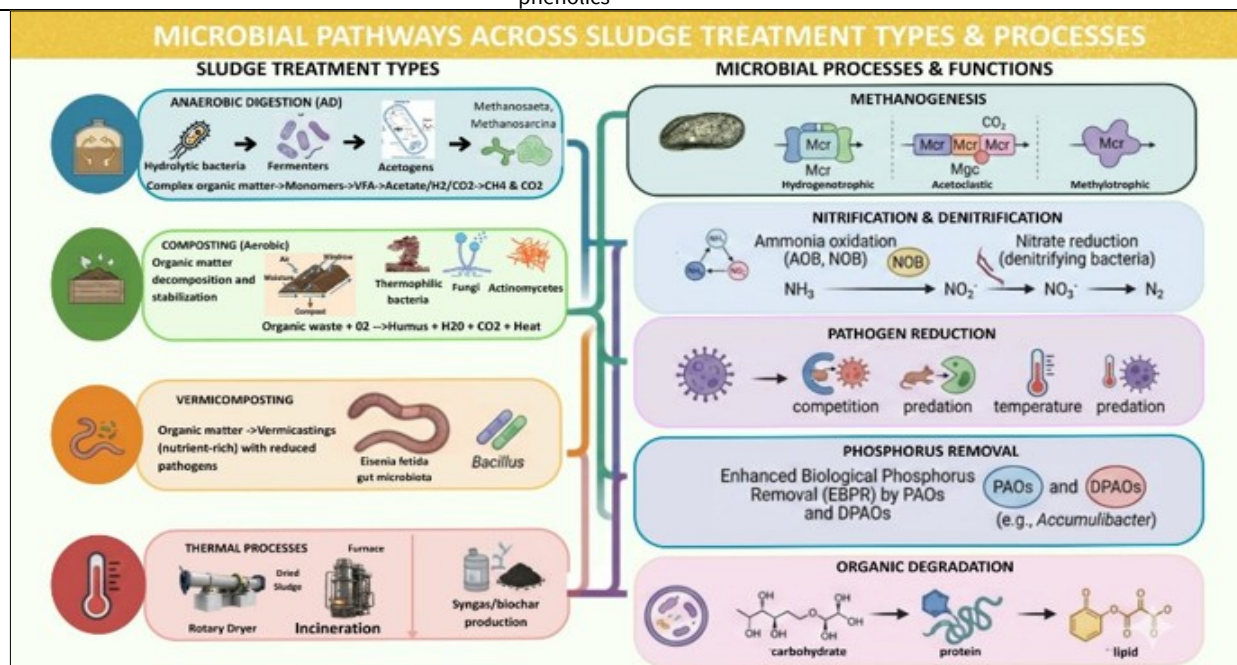
Table 4. Key components of sludge-based circular bioeconomy frameworks

Element	Focus in sludge systems	Citations
Resource recovery	Energy (biogas, biofuels), nutrients (N, P), materials (biopolymers, biochar)	(34)
Biorefinery concept	Cascading use of sludge to multiple high-value products	(35)
Systems assessment	LCA, LCCA, multi-criteria and SWOT-based decision tools	(36)
Policy and markets	End of waste criteria, business models, SDG alignment	(36)

LCA: life cycle assessment; LCCA: life cycle cost analysis; SWOT: strengths, weaknesses, opportunities and threats; N: nitrogen; P: phosphorus; SDG: sustainable development goal.

Table 5. Major microbial pathways involved in agro-industrial sludge treatment and bioconversion

Process / Condition	Dominant pathways and roles	Typical microbes	Citations
Aerobic activated sludge treating agro-effluents	Carbohydrate and amino acid metabolism; nitrification–denitrification; xenobiotic degradation	Proteobacteria, Bacteroidota, specialized degraders	(37)
Anaerobic digestion of vinasse, swine and meat wastes	Hydrolysis → acidogenesis → acetogenesis → methanogenesis; syntrophic acetate oxidation; hydrogenotrophic methanogenesis	Clostridia, Syntrophomonas, Methanosarcina, Methanobacterium	(38)
Phenolic/plant-waste bioconversion	Enzymatic hydrolysis of cell walls; deconjugation and transformation of phenolics	Diverse fermentative and ligninolytic bacteria/fungi	(39)

**Fig. 4.** Key microbial pathways across sludge treatment types and processes.

Metabolic cross-feeding and pollutant catabolism

Consortia can break down complex organic materials and pollutants through shared metabolic pathways (e.g., phthalic acid, benzoate, catechol intermediates), with different consortium members managing various stages of the degradation process (44). Cross-feeding allows the complete breakdown of compounds such as the antibiotic sulfamethoxazole: one microbial group cleaves the original compound, another degrades the heterocyclic intermediate, while non-degrading microbes enhance degradation rates through their interactions (45). Using mixed inocula in food waste digestion (combining cow dung and sewage sludge) results in higher production of biogas, VFAs and soluble chemical oxygen demand (COD) removal compared to single sources, indicating a broader metabolic capacity.

Community-level effects on stability and maturity

Microbial community composition influences compost stability and maturity through its effects on organic matter degradation pathways and nutrient cycling. During sludge composting, shifts from readily degradable substrates to more recalcitrant compounds are often accompanied by succession from fast-growing heterotrophic bacteria to specialised microbial groups capable of degrading lignocellulosic materials and humic precursors. These changes affect the transformation of dissolved organic matter (DOM), leading to reductions in phytotoxic organic acids and the formation of more stable humified compounds. Network analyses have shown that highly connected microbial communities promote carbon, N and P cycling through complementary metabolic functions and cross-feeding interactions, thereby accelerating compost maturation

and improving nutrient stabilisation. More diverse and interconnected consortia (e.g., biofilms) exhibit richer networks and functional groups for cycling carbon, N and P, which supports effective organic matter conversion (46).

Key enzymatic mechanisms driving nutrient mineralisation

Carbon depolymerisation occurs through extracellular cellulases and β -glucosidase that sequentially break down cellulose into cellobiose and glucose, which are essential for carbon cycling in the soil and the breakdown of biomass relevant to biofuels (47). For N mineralisation, endo- and exopeptidases, aminopeptidases and carboxypeptidases release amino acids, while urease breaks down urea into NH_4^+ , which is closely linked to N availability in the soil and the turnover of N in sludge and wastewater (48). Nutrient mineralisation in sludge-amended systems is largely mediated by microbial enzymes that break down complex organic compounds into plant-available forms. Table 6 summarises the major enzyme groups involved in the mineralisation of key nutrients such as carbon, N, P and S. Enzymes such as cellulases and amylases contribute to carbon cycling by hydrolysing complex carbohydrates, while proteases and chitinases convert organic N into ammonium through ammonification. Similarly, phosphatases release inorganic phosphate from organic P compounds and arylsulfatase enzymes play an important role in S mineralisation. These enzymatic processes are essential for nutrient recycling and improving the agronomic value of sludge-derived fertilisers. The chitin pathway involves LPMOs (lytic polysaccharide monooxygenases) that oxidatively cleave crystalline chitin; chitinases break the chains; N-acetylglucosamine (NAG) is released, providing easily mineralisable carbon and N (49). The coupling of activities from phosphatases and

Table 6. Major enzyme groups involved in nutrient mineralisation in sludge systems

Nutrient	Key enzymes	Mechanism of mineralisation	Citations
Carbon (C)	Cellulases, β -glucosidase, amylase, invertase, phenol oxidase	Hydrolyse cellulose, starch and other polysaccharides to sugars; oxidise lignin/phenolics, feeding microbial respiration and CO ₂ release	(51)
Nitrogen (N)	Proteases, peptidases, chitinases, N-acetylglucosaminidase (NAG) and urease	Convert proteins/chitin to amino acids and amino sugars, then to NH ₄ ⁺ (ammonification) via deamination and urease activity	(51)
Phosphorus (P)	Acid/alkaline phosphatases, phytases	Hydrolyse organic phosphomonoesters/diesters, releasing inorganic phosphate (PO ₄ ³⁺) for plant uptake and biomineralisation (e.g. struvite)	(51)
Sulfur (S)	Arylsulfatase	Cleaves ester sulphates, releasing SO ₄ ²⁺ from organic S esters	(51)

ureases can generate local increases in phosphate ion (PO₄³⁻), ammonium ion (NH₄⁺) and pH, promoting the formation of P minerals like struvite, which aids in nutrient recovery from waste streams (50).

Technological advances in sludge-to-biofertiliser conversion from agro-industrial effluents

Biological conversion routes

Biological pathways remain the most established route for sludge-to-biofertiliser transformation. Composting of sewage and agro-industrial sludges, particularly when co-composted with plant residues and inoculated with targeted phosphate-mobilising bacteria such as *Microbacterium barkeri* LP-1, has demonstrated nutrient enrichment beyond conventional compost standards (52). Microbial consortia-based reactor systems represent an emerging approach for the biological conversion of agro-industrial effluents into value-added biofertiliser products. These systems utilise synergistic interactions among diverse microbial communities to enhance organic matter degradation, nutrient transformation and resource recovery. Biofilm-based and mixed-culture reactors can facilitate the production of nutrient-rich liquid biofertilisers while simultaneously improving wastewater treatment efficiency. The integration of microbial consortia into sludge management systems offers opportunities for sustainable nutrient recycling and the development of environmentally friendly agricultural inputs (53). Microalgae-based systems further broaden the scope of biological sludge conversion technologies. By integrating microalgae cultivation with sludge and wastewater treatment processes, these systems facilitate nutrient recovery, organic matter utilisation and biomass production. The resulting microalgal biomass is rich in proteins, carbohydrates and essential nutrients, making it suitable for use as a biofertiliser or bio stimulant. In addition to supporting nutrient recycling, microalgae-integrated approaches contribute to sustainable wastewater management and resource valorisation within circular bioeconomy frameworks (54, 55). These systems align nutrient removal with biomass valorisation, bridging wastewater treatment and agricultural productivity.

Thermal and carbonaceous product pathways

Thermochemical technologies such as pyrolysis and hydrothermal carbonisation (HTC) convert sludge into carbon-rich materials, including biochar and hydrochar. Subsequent nutrient enrichment and encapsulation strategies allow the production of slow- or controlled-release fertilisers, improving nutrient use efficiency while reducing leaching losses. These carbonaceous matrices also enhance soil structure and carbon sequestration potential, positioning sludge-derived biochar within climate mitigation strategies (56).

Electrochemical recovery and encapsulation technologies

Emerging electrochemical processes offer promising routes for direct nutrient recovery from sludge streams. Electrically assisted systems can recover N and P as concentrated fertiliser salts, with modelling studies suggesting the potential to supply up to 9 % of N and 32 % of P fertiliser demand in the United States under optimised deployment scenarios (57). Such approaches support the electrification and decarbonisation of sludge management. Complementary material-engineering innovations include polymer coating and encapsulation of sludge-derived granules. The application of natural or biodegradable polymer coatings enables controlled nutrient release while simultaneously reducing contaminant mobility and metal leaching, thereby enhancing environmental safety and agronomic precision.

Process integration, economics and circularity

Beyond technical feasibility, techno-economic analyses indicate that composting and lime stabilisation of biosolids can achieve economic viability at biofertiliser market prices of approximately 19 €/m³, with payback periods of around three years under favourable conditions (58). Integrated energy systems further improve sustainability: biogas generated from anaerobic digestion can be reused for sludge drying and plant operations, moving toward energy self-sufficient fertiliser production facilities.

Composting and co-composting of sludge to biofertiliser

Composting and co-composting convert nutrient-rich but risky sludges and agro-industrial residues into stabilised, safer biofertilisers. Key advances focus on feedstock mixing, process control and microbial inoculation to maximise nutrient retention, humification and pathogen reduction.

These processes rely on aerobic microbial activity to decompose organic matter, reduce pathogens and stabilise sludge into a mature compost suitable for agricultural use. As illustrated in Fig. 5, sludge composting involves the formation of compost piles where organic materials undergo controlled aeration and periodic turning for several weeks, allowing microorganisms to degrade complex organic compounds and produce stabilised compost.

Process control and optimisation

Critical parameters: C/N ratio (~20–30), moisture (~50–60 %), aeration, temperature profile (clear thermophilic phase) and turning frequency (59).

Full-scale thermophilic co-composting of algae sludge, straw and chicken manure (C/N≈20; 60 % moisture) met national organic fertiliser standards and achieved >99.5 % toxin reduction with high germination index and strong economic returns (60).

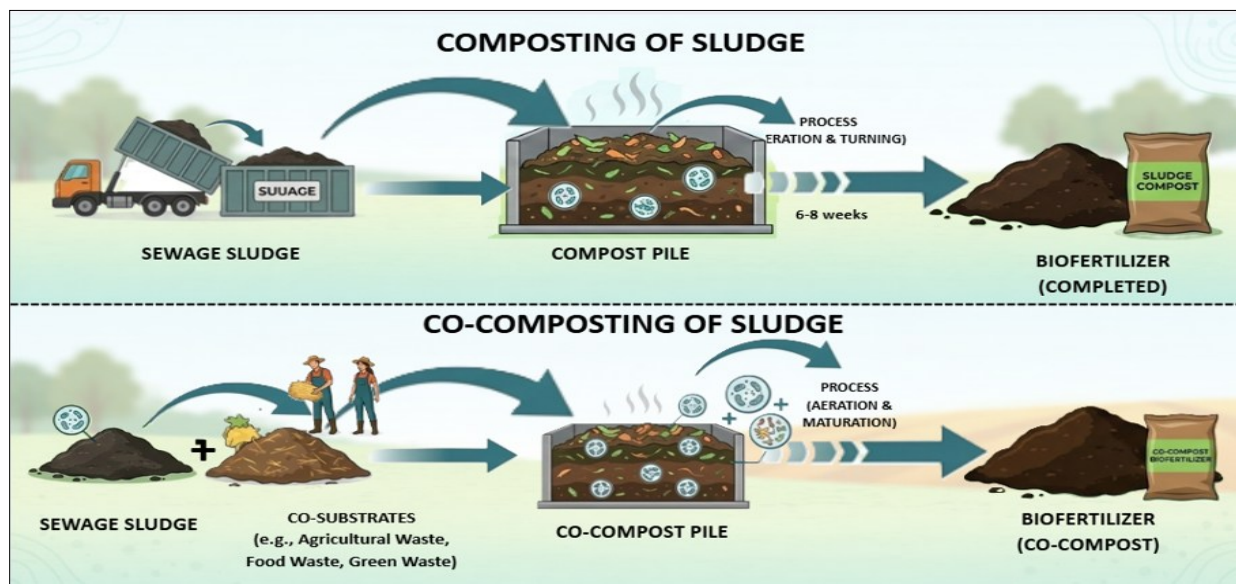


Fig. 5. Schematic representation of composting and co-composting pathways for converting sewage sludge into biofertiliser.

Response surface methodology has been used to optimise time, mix ratio and moisture for maximum NPK in sludge-sawdust-vegetable waste composts, reaching very high nutrient levels and demonstrating predictive process control.

Kinetic studies show composting of digestate + sawdust follows second-order kinetics and Arrhenius behaviour, allowing quantitative prediction of degradation and maturation (61).

Role of microbial inoculation and “microbial composts”

- **Meta-analysis across many systems:** inoculants increase total N (+30 %), P (+46 %), humification (+60 %), lignocellulose degradation and germination index (+28 %), while accelerating cellulose/hemicellulose/lignin breakdown (62).
- In sludge composting, tailored inoculants suppress denitrification, enhance ammonia assimilation genes and raise total kjeldahl nitrogen (TKN) and humic acids, improving fertiliser value (63).
- Microbial co-composts and “bio-organic” fertilisers deliberately fortify compost with plant-growth-promoting microbes, adding functions like P solubilisation, hormone production and stress resilience (64).
- Microbial fertiliser from co-composted municipal/dairy sludge (MK50, sludge + woodchips) achieved heavy metals below limits and high densities of phosphate-solubilising and cellulose-degrading bacteria, with vegetable yields comparable to commercial fertilisers, though with relatively low N content (65).

Safety, soil health and long-term performance

- Properly composted sludge-based products generally meet heavy metal and pathogen standards and are microbiologically safe for agricultural use when process temperatures and times are adequate (61).
- Long-term field study (20 years) shows composted sludge fertiliser markedly increases wheat yield and soil microbial biomass and provides higher overall soil health index than uncomposted sludge or mineral fertiliser alone, with metals remaining below national limits (66).
- Co-composting can reduce biosecurity risks relative to composting some wastes alone; e.g., a balanced sludge-food-waste mix (carbon-to-nitrogen (C/N) 25) lowered pathogen risk while improving nutrient content compared with food-waste-only compost (67).
- Composting and co-composting strategies often involve mixing sludge with various organic substrates to improve compost stability, nutrient balance and process efficiency. Table 7 summarises common composting configurations used for sludge treatment, including the use of bulking agents, food waste, agricultural residues and agro-industrial by-products. These mixtures help optimise key composting parameters such as C/N ratio, aeration, moisture content and microbial activity, which are essential for effective decomposition and pathogen reduction. The selection of suitable co-substrates not only enhances compost quality but also minimises environmental risks such as heavy metal

Table 7. Core composting and co-composting configurations used for sludge valorisation

Technique/mix	Purpose and features	Compost quality/risks	Citations
Sludge + bulking agents (woodchips, sawdust, straw, green waste)	Adjust C/N, porosity, moisture; typical for sewage, dairy, brewery sludge	Stable compost/biofertiliser; heavy metals and pathogens generally within standards when managed well	(68)
Sludge + food waste	Balances low C/N sludge with high-moisture, acidic food waste; improves structure	C/N≈25 mix (T3) gave the highest nutrients and lower pathogen risk than food-waste-only piles	(69)
Agro-residues + manures + sludges	Multi-residue co-composting (e.g., olive pomace, agro-sludge, artichoke waste and straw)	Mature, microbiologically safe compost; good tomato and wheat yields, especially when combined with mineral N	(70)
Brewery / agro-industrial sludges	Aerobic composting of brewery sludges or dairy/municipal sludge	Products met nutrient and pathogen standards; suitable as organic fertiliser	(71)

C: carbon; N: nitrogen.

accumulation and odour generation, ultimately producing stable biofertilisers suitable for agricultural applications.

Vermicomposting: Nutrient stabilisation and humification

Vermicomposting, which utilises earthworm species (e.g., *Eisenia fetida*, *Eudrilus eugeniae*), which offers distinct advantages in stabilising organic matter and enhancing nutrient availability through the process of humification. The procedure involves the breakdown of organic waste by earthworms and microorganisms, resulting in a final product called vermicast, which is a fine, nutrient-dense material that provides better soil conditioning properties than standard compost (72). This bioconversion results in a significant reduction in waste volume, while simultaneously enriching it with plant growth-promoting compounds and stable humic acids (73). Vermicomposting serves as an effective method for lowering pathogen levels and enhancing the physico-chemical attributes of various agro-industrial sludges, including dairy effluent (74). The increased enzymatic activity within the earthworm gut and its associated microbial communities boosts decomposition and humification, yielding a consistent and biologically active end product (75). This system operates effectively within a temperature range of 10–32 °C, conditions that favour the degradation of organic solid waste and the humification of fertilisers (74). It is particularly suitable for agro-industrial effluents like coconut food processing and dairy sludge, resulting in high-quality, nutrient-rich biofertilisers (76). The vermicompost produced is rich in essential plant nutrients, organic matter, beneficial microorganisms and growth-regulating compounds, all of which improve soil structure, increase water retention capacity, enhance nutrient retention and promote microbial growth (77). In the absence of thermophilic activity, this biological conversion involving earthworms and microorganisms yields a fertiliser with enhanced porosity and water capacity (78). These epigeic species possess a remarkable ability to consume a variety of organic wastes such as industrial and sewage sludges, transforming them into nutrient-rich vermicompost through the shredding of larger particles and aiding microorganisms through their synergistic action. The resulting vermicompost demonstrates greater microbial diversity and enzymatic activity, facilitating the mineralisation of nutrients and the production of phytohormones that promote plant development (79). In addition to nutrient enrichment, vermicomposting significantly addresses environmental challenges and mitigates N loss compared to traditional composting; it also reduces greenhouse gas emissions, including nitrous oxide and methane.

Bioaugmentation and enzymatic treatment approaches

When compared to the previously mentioned methods, bioaugmentation (i.e., the addition of specific microbial cultures to enhance degradation processes) and the employment of enzymatic treatments to introduce targeted enzymes into sludge represent more advanced techniques for enhancing the transformation of sludge into biofertiliser. These biotechnological approaches are crucial for encouraging the breakdown of resistant organic matter and minimising inhibitory substances that could affect the effectiveness and safety of the biofertiliser product. Bioaugmentation can also include the addition of specific groups of microorganisms that can break down persistent organic pollutants or improve nutrient cycling in sludge. Commonly referenced genera consist of *Bacillus*, *Pseudomonas*, *Streptomyces*, *Azotobacter* and *Rhizobium*, which play a role in contaminant breakdown, nutrient

mineralisation, N fixation and P solubilisation. This would enhance its fertilising potential while minimising environmental risks (80). This combined approach of bioaugmentation and enzymatic hydrolysis has been recognised as a significant advancement in converting agro-industrial waste into higher-quality biofertilisers, promoting sustainable waste management and agricultural productivity (81). However, these biological processes face challenges such as lengthy processing times and the actual choice of suitable microbes or enzymes, especially when dealing with polymeric materials in the flocs that obstruct substrate access (82). To tackle these issues, various pretreatments have been utilised, including thermal, physical and biological methods, among others, or a combination of treatments aimed at facilitating hydrolysis and the stabilisation of biosolids. Physical and chemical pretreatments, such as ultrasonication, thermal treatment, NaOH and ozonation, have been reported to improve the solubilisation of sludge and its biodegradability by accelerating the hydrolysis step, which is the rate-limiting stage in anaerobic digestion (82). Some of these techniques can present challenges, such as high energy consumption, issues related to pH fluctuations and the generation of toxic by-products, necessitating careful optimisation. In contrast to the rudimentary nature of physical-chemical treatments, enzymatic hydrolysis is an eco-friendly and selective method, with potential benefits for enhancing the bioavailability of complex organic molecules found in sludge (83). Merging enzymatic pretreatments with bioaugmentation may further enhance sludge conversion by improving the solubilisation of organic compounds and increasing microbial activity, ultimately leading to better biofertiliser quality and increased resource recovery. This dual-benefit approach focuses on hydrolysis as a critical step in biological degradation, especially in scenarios where extracellular enzymes are integrated with sludge flocs (84). Enzymatic pre-treatments are particularly effective for lignocellulosic waste, breaking down cellulose, hemicellulose, lipids, proteins and starch (85).

Emerging green technologies

Economic sustainability can be enhanced through on-site enzyme recovery and bioaugmentation, which effectively lower operating costs associated with enzymatic biodegradation and improve the efficiency of the process by allowing the reuse of catalysts and the enhancement of microbial communities (86). Anaerobic digestion plays a key role in these integrated biorefining strategies as it significantly reduces sludge volume and produces biogas, a raw material for renewable energy. Another crucial technology in biorefineries is hydrothermal pretreatment, which optimises the efficient use of biowaste for producing value-added products like biofertilisers and biofuels, thus supporting a circular economy. This aligns with the broader biorefinery ideology focused on transforming agro-industrial waste into a variety of valuable end-products, including biofuels, biofertilisers and biochemicals, while minimising waste and maximising resource use (87). By combining biochemical and anaerobic digestion techniques, biorefineries can effectively convert both dry and wet biomass residues into a range of useful co-products, thereby ensuring the efficient use of agrochemical resources and improving energy efficiency. These innovative biorefinery models endeavour to minimise the ecological impact of agricultural-industrial activities while simultaneously generating additional income through waste valorisation (88). This approach aligns with "zero-waste" principles by integrating systems that minimise residues while producing valuable gas streams. Emerging green technologies, such as

supercritical fluid extraction and membrane separation, offer environmentally friendly methods for extracting valuable compounds from agro-industrial sludge, reducing reliance on hazardous solvents and energy. Green extraction technologies, such as liquid biphasic systems, allow for the sustainable recovery and purification of valuable compounds, including enzymes, from agro-industrial slurries. Combining metabolomics with these methods enhances the characterisation of metabolomic complexity, leading to better recovery strategies for specific bioactive compounds (89). The rise of green and sustainable separation technologies is crucial for energy conservation and utilising renewable sources for extractions, yielding high-quality, safe product fractions from agro-industrial residues. Novel green solvents, such as subcritical water and gas-expanded liquids, broaden the potential for sustainable extraction and valorisation of various biomolecules from complex waste streams. These innovative extraction processes are essential steps toward economically viable and eco-friendly biorefining of agro-industrial sludge

Quality assessment and agronomic performance of sludge-derived biofertilisers

Biofertilisers sourced from sludge and agro-industrial waste streams are increasingly being endorsed within circular nutrient management frameworks due to their ability to recycle N, P, K and organic carbon back into agricultural soils while decreasing reliance on synthetic fertilisers. However, their effectiveness in agriculture and safety for the environment largely hinge on the quality of the product, especially regarding contaminant levels, biological stability and reduction of pathogens. Sludge-derived biofertilisers have been widely evaluated for their effects on crop productivity and soil health. Table 8 summarises selected studies reporting agronomic outcomes and soil biological responses following the application of sludge-based fertilisers. Fig. 6 shows a graphical abstract of the agronomic and soil impacts of sludge-derived biofertiliser. Most field studies show composted or treated sludge improves crop yields, biomass production and nutrient availability due to its high organic matter and nutrient content. Additionally, several studies report increased microbial biomass, enzymatic activity and improved soil biochemical indicators after sludge application. Although some sludge types may introduce elevated nutrient concentrations or microbial contaminants, proper stabilisation and controlled application rates generally ensure safe use while enhancing soil fertility and crop performance.

Physical, chemical and biological indicators of agro-industrial sludge

Agro-industrial and municipal sludges are inherently heterogeneous materials whose agronomic suitability depends on a comprehensive set of physical, chemical and biological indicators. Across brewery, textile, olive mill, food industry and municipal sludge studies, the literature converges on a core parameter group that determines fertiliser value, environmental safety and regulatory compliance. From a physical perspective, moisture content, dry solids concentration and texture govern dewaterability, transport logistics, handling efficiency and composability. Many sewage sludges exceed optimal composting moisture thresholds, necessitating mechanical or electro-dewatering; electro-dewatering technologies have been shown to increase dry solids content to approximately 43–45 %, thereby improving stability and reducing volume (96). Bulk density and water-holding capacity (WHC) are critical for evaluating soil amendment performance, as they influence soil structure, porosity and moisture retention. Reported WHC values of approximately 50–55 % are typical for municipal and brewery sludges, indicating potential benefits for improving soil water balance (97). Chemical indicators are central to risk assessment and agronomic evaluation. Electrical conductivity (EC) serves as a proxy for salinity stress; agro-industrial and brewery sludges with EC values around 2–3 mS/cm generally fall within fertiliser salinity limits, while certain liquid or anaerobically digested sludges may exceed recommended thresholds and pose risks to salt-sensitive crops (98). Beyond salinity, heavy metal concentrations and speciation remain key determinants of safe land application. Composite assessment tools such as pollution load index (PLI), geoaccumulation index (I_{geo}), potential ecological risk index (PERI) and human health risk models (dermal and ingestion pathways) provide more nuanced classification than total metal concentration alone (99).

Biological parameters are crucial for assessing sludge safety. Pathogenic bacteria and helminth eggs, such as *Salmonella* and faecal coliforms, often exceed regulatory limits in raw municipal and brewery sludges, necessitating thermal or advanced stabilisation before reuse (100). Indicators like microbial biomass, enzyme activity, colony-forming units (CFUs) and physiological profiles help evaluate sludge stability and its ability to enhance soil biological processes. Ecotoxicological assays, including germination index (GI) testing, assess chemical and biological hazards, classifying sludges from phytotoxic to phyto stimulant. Emerging frameworks recommend incorporating indicators for antimicrobial resistance (AMR) genes, PFAS and

Table 8. Agronomic performance and soil biological effects of sludge-derived biofertilisers

Sludge/biofertiliser type	Main agronomic outcomes	Key soil/biological effects	Citations
Composted sewage sludge	Wheat yield + 124 % vs. control; best soil health index	Higher microbial biomass, enzymatic activity; metals below standards	(90)
Sewage sludge, 10-yr use	Maize yield maintained; P and micronutrients fully replaced	Biogeochemical indicators similar to mineral fertiliser	(91)
Sewage sludge biofertiliser (maize, foliar)	Grain yield + 17 %, protein + 30 % at higher dose	Leaf macro/micronutrients increased; soil nutrients little changed	(92)
Biofertiliser + sewage sludge (banana)	Not yield-focused; strong soil improvement	Higher respiration, microbial and phosphatase activity	(93)
Anaerobic sludge digestates	Cucumber biomass, photosynthesis $\geq$ control; best at mid N rate	Stronger effects on poor sandy soil than peat	(94)
Sweet potato with SS	Productivity and biomass increased; soil pH, CEC and $\text{NO}_3\text{-N}$ improved; Pb still critical in tubers	No major heavy metal rise in soil; most edible-metal levels fell	(94)
HSTAD digestate (field)	Maize performance similar to urea	No ecotoxic risk; better stabilised OM and nutrients	(95)

N: nitrogen; OM: organic matter; HSTAD: high-solids thermophilic anaerobic digestion; P: phosphate.

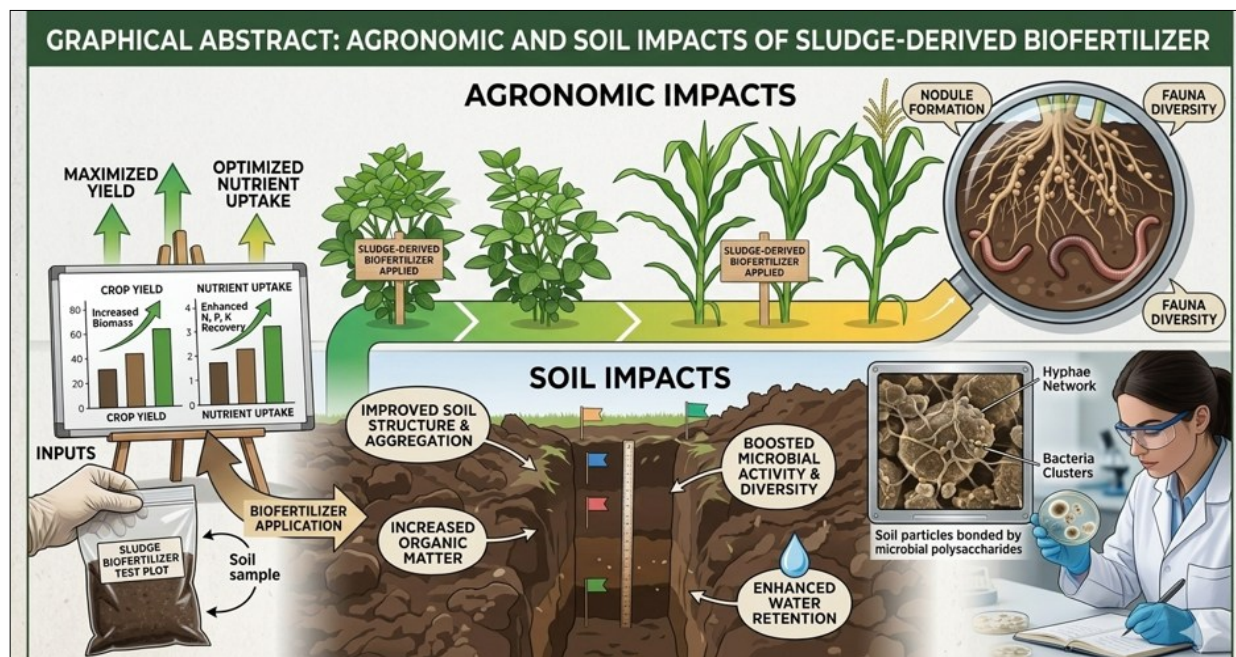


Fig. 6. Agronomic and soil impacts of sludge-derived biofertiliser.

other contaminants, alongside traditional metrics, for comprehensive assessments (101). The literature emphasises that combined physical, chemical, microbiological and ecotoxicological indicators are essential for determining the safe and effective use of agro-industrial sludge as a soil amendment in circular bioeconomy systems.

Standard testing protocols for maturity and stability

Sludge- and biowaste-derived composts, the assessment of stability (extent of biodegradable organic matter decomposition) and maturity (absence of phytotoxicity and plant safety) relies on a suite of standardised and semi-standardised testing protocols. The literature consistently emphasises that no single parameter can reliably certify compost quality; therefore, integrated evaluation frameworks combining physical, chemical, biological and increasingly spectroscopic indicators are recommended. Among biological assays, the germination index (GI) is the most widely adopted maturity indicator. It evaluates seed germination and root elongation commonly using cress, cucumber, or ryegrass in aqueous compost extracts. The GI value greater than 70 % is frequently used as a threshold for maturity, indicating low phytotoxicity and suitability for plant growth (102). However, variability in seed species, extract preparation and incubation conditions necessitates careful protocol harmonisation. Chemical indicators complement bioassays in maturity evaluation. The C/N ratio serves as a practical operational indicator, with values below 15 often associated with advanced composting stages. Nevertheless, C/N alone cannot confirm stability and must be interpreted alongside other parameters (103). The $\text{NH}_4^+/\text{NO}_3^-$ ratio provides insight into nitrogen transformation dynamics; ratios approximately ≤ 1 reflect advanced nitrification and are commonly associated with mature compost (102). More comprehensive “maturity packages” have been proposed for agro-industrial composts, integrating multiple criteria such as organic matter (OM) loss greater than 42 %, C/N ratio below 15, water-extractable carbon to organic N ratio (Cw/Norg) below 0.55, humic acid to fulvic acid ratio (HA/FA) above 1.9, humification index (HI) exceeding 30 %, cation exchange capacity to total organic carbon ratio (CEC/TOC) above 1.7 and GI above 70 %.

Nutrient release and bioavailability from sludge-derived biofertilisers

Agro-industrial sludge applications typically produce an initial ammonium (NH_4^+) flush, with peak concentrations occurring within hours of soil incorporation, followed by a gradual decline as nitrification proceeds. Nitrate (NO_3^-) concentrations often peak between 60 and 100 days, indicating slower N mineralisation compared to urea and consequently lower leaching risk. This delayed release pattern enhances synchronisation between crop demand and N availability. Advanced formulations further refine release kinetics. Sewage sludge hydrogel spheres demonstrate moisture-, temperature and pH-dependent N release profiles that align well with diffusion and polymer relaxation models. These systems support sustained ryegrass growth by delivering N gradually over time (104). Similarly, iron-loaded sludge biochar materials release approximately 28–54 % of total N under controlled testing conditions, primarily via chemically mediated mechanisms, qualifying them as slow-release fertilisers (105).

Phosphorus bioavailability is another key advantage of sludge-derived amendments. Long-term field trials indicate that sewage sludge serves as a strong source of plant-available P, often outperforming farmyard manure (FYM) or mineral NPK fertilisers in terms of Mehlich-3 extractable P levels. In contrast, FYM tends to contribute relatively higher K and Mg inputs (106). Nitrogen replacement studies further demonstrate that dairy and municipal sludges can substitute a substantial fraction of mineral N and P fertilisers while sustaining grass yield and N uptake. Reported N fertiliser replacement values reach up to approximately 54 %, highlighting their practical agronomic value (107). Processed sewage sludge-based nutrients and bio stimulant formulations show high extractable N and P fractions and reported bioavailability ranging from 60–100 %, alongside improvements in soil enzyme activity and beneficial microbial community structure (108). Table 9 describes the P and K dynamics. These findings suggest that sludge-derived products may function not only as nutrient sources but also as soil biological enhancers.

Environmental and economic perspectives on agro-industrial sludge valorisation

Environmental perspectives

Agro-industrial and sewage sludges contain substantial organic matter and nutrients (N, P, K), supporting their use in biorefineries, energy recovery and soil amendment rather than landfilling or incineration (112). Anaerobic digestion of food industrial or sewage sludge can cut sludge volume by ~70 % and generate significant biogas energy, reducing greenhouse gas emissions compared with conventional disposal. Thermochemical routes such as pyrolysis, gasification and hydrothermal carbonisation convert sludge into biochar or hydrochar, enabling carbon sequestration and P-rich products; pyrolysis biochar has been reported to sequester up to 3 t CO₂ per ton of biochar (113). Land application of sewage and industrial sludges improves soil organic matter, nutrient status and structure, especially in degraded or manure-scarce regions, but must be carefully managed due to heavy metals, organic micropollutants, pharmaceuticals and pathogens (114). Reviews emphasise emerging contaminants (e.g., pharmaceuticals, microplastics) as a growing constraint for agricultural reuse and a key research gap. For some streams (e.g., tannery sludge), Cr speciation makes valorisation particularly sensitive, demanding robust control to avoid Cr (VI) formation (115). Overall, sludge valorisation aligns strongly with the circular economy and SDGs on clean water, clean energy and responsible production, but requires stringent quality control, monitoring of long-term soil and ecosystem impacts and updated regulatory frameworks.

Economic perspectives

From an economic standpoint, sludge is a low- or negative-cost resource that can reduce treatment and disposal expenses through energy and product generation. However, profitability often depends on context and may require subsidies. For instance, a study in Scandinavia found that none of the five sludge valorisation scenarios were financially viable without subsidies, though biological separation routes (like PHA production) came closest to breaking even. Optimising sewage sludge use for carbon reduction revealed that anaerobic digestion followed by land application is the most cost-effective for domestic sludge, while a combination of digestion and controlled landfilling is preferred for mixed sludge due to

contamination issues (116). Economic viability hinges on factors like capital costs, energy prices, policy incentives and gate fee potential. Various valorisation strategies offer diverse revenue sources like biogas, biofuels and fertilisers while also presenting challenges such as high water content and complex downstream processing costs. Key methods include anaerobic digestion (with renewable energy benefits), land application (cost-effective but with regulatory concerns), thermochemical treatments (higher costs but with environmental benefits) and biorefineries (technologically complex). Integrated assessments generally show that valorisation options are environmentally preferable to simple disposal but require regulatory support and public acceptance for economic viability. Fig. 7 highlights the comparison of key sludge valorisation routes and impacts on the environment.

Although several sludge valorisation pathways offer environmental benefits, their economic viability is often strongly influenced by policy support. Incentives such as renewable energy subsidies, carbon credit schemes, landfill taxes and nutrient recovery programs can substantially improve project feasibility. The effectiveness of these mechanisms varies across regions, with European countries generally providing stronger support for circular bioeconomy initiatives than many developing economies. Therefore, future economic assessments should evaluate the influence of regional policy frameworks and subsidy levels on the long-term competitiveness of sludge valorisation technologies. Different sludge valorisation strategies offer various environmental benefits and economic considerations. Table 10 summarises key sludge management routes and their impacts. Anaerobic digestion with biogas recovery promotes greenhouse gas reduction and renewable energy, often aided by subsidies. Land application as fertiliser is cost-effective and enhances soil quality but may face regulatory issues. Thermochemical treatments like pyrolysis provide carbon sequestration but involve higher costs. Biorefinery methods aim to recover valuable products, although they are technologically complex and expensive. These trade-offs underscore the need for integrated assessments in selecting sustainable sludge management strategies. Overall, valorisation pathways are more environmentally favourable than simple disposal but require supportive regulations, financing and public acceptance to be economically viable.

Table 9. Phosphorus and potassium dynamics

Product type	Phosphorus (P) and potassium (K) behaviour vs mineral fertiliser	Citations
Struvite-/ash-based P fertilisers	Often match soluble Ca(H ₂ PO ₄) ₂ for plant P uptake over rotations; clearly outperform phosphate rock; efficacy strongly process-dependent	(109)
Sewage-sludge biochars / industrial sludge biochar (ISB)	Meet slow-release criteria for NH ₄ ⁺ , PO ₄ ³⁻ , K; release increases at low pH and high temperature but risks remain acceptable below certain doses	(110)
K-enriched sludge biochar (pellets/granules)	K release up to 77 % slower than KCl; pellets usually slowest, with more K retained in wetter, clayey soils; reduced K leaching vs KCl	(111)

P: phosphorous; K: potassium; KCl: potassium chloride; NH₄⁺: ammonium ion; PO₄³⁻: phosphate ion; Ca(H₂PO₄)₂: calcium dihydrogen phosphate.

Table 10. Environmental and economic trade-offs in sludge valorisation

Valorisation route	Main environmental effects	Economic notes (typical issues/opportunities)	Citations
Anaerobic digestion + biogas	GHG reduction, volume reduction, nutrient reuse	Often, most cost-effective; improved by co-digestion, subsidies	(117)
Land application as	Soil quality improvement; risk of contaminants	Low processing cost; constrained by	(117)
Pyrolysis/gasification / HTC	Carbon sequestration, pollutant concentration	Higher CAPEX/OPEX; product markets and scale critical	(117)
Biorefinery for chemicals/ bioplastics	High resource recovery, reduced waste	Higher complexity; downstream separation often cost-limiting	(117)

GHG: greenhouse gas; CAPEX/OPEX: capital expenditure / operating expenditure; HTC: hydrothermal carbonisation.

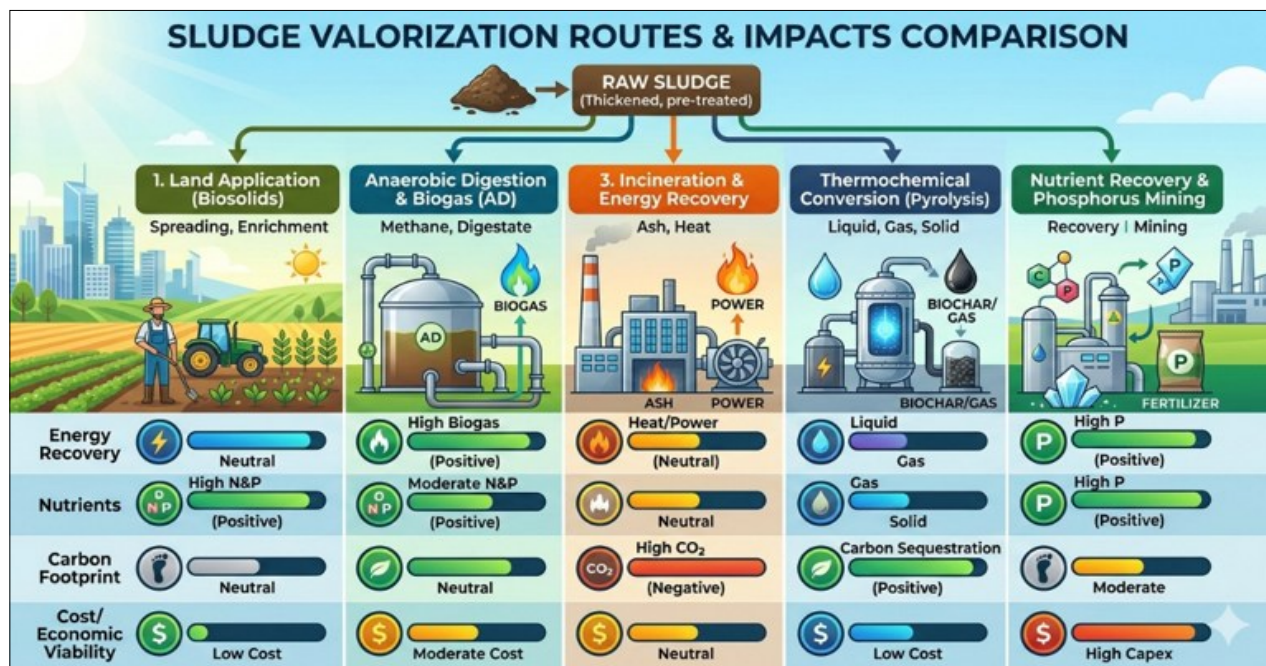


Fig. 7. Comparison of key sludge valorisation routes and impacts.

Environmental and economic perspectives: Comparative analysis of composting, landfilling and incineration

This section evaluates the environmental impacts and economic viability of three primary sludge management options: composting, landfilling and incineration. Although all these methods decrease waste volume, their energy demands, operational intricacies and potential for resource recovery differ significantly. Conventional techniques are increasingly challenged by stricter regulations that encourage innovation in sustainable waste management. Incineration significantly reduces sludge volume and generates energy; however, it raises environmental concerns related to air emissions (such as dioxins and furans) and the complexity of managing ash residues containing heavy metals. These issues necessitate advanced emission control and more complex monitoring, impacting the overall operational costs. Landfilling was historically a common practice in regions like Russia, but recent attention has shifted towards agricultural use and energy recovery via incineration and biogas production (118). While landfilling may be cost-effective in certain contexts, it poses a long-term environmental risk due to methane emissions during anaerobic breakdown and the potential for groundwater contamination from leachate. Such issues demand sophisticated emissions abatement systems and stringent monitoring, which lead to higher operational costs and increased technical complexity. Composting represents a more sustainable approach that transforms sludge into stabilised organic material through aerobic decomposition. When managed properly, ensuring appropriate moisture levels, aeration and carbon-to-N ratios, composting eradicates pathogens, stabilises organic content and produces valuable soil amendments as a final product.

Challenges and knowledge gaps

Although there is acknowledged potential for recovering resources from agro-industrial sludge, various widespread challenges and considerable knowledge deficits hinder its broad and sustainable application. These challenges include the natural variability in sludge composition, which makes scaling processes more complex, as well as significant risks related to the accumulation of heavy metals and

the survival of pathogens (119). Additional difficulties arise from the absence of standardised processing techniques and quality certification, which result in limited acceptance in the market and a lack of supportive policy mechanisms. Moreover, the integration of these processes into existing agro-industrial supply chains introduces logistical and operational obstacles, complicating the shift from waste disposal to resource valorisation (120). The lack of comprehensive policies and regulatory frameworks specifically focused on sludge management frequently results in unregulated and improper disposal methods. Such practices not only present environmental risks but also emphasise the critical need for a shift towards a circular economy perspective, viewing sludge as a valuable resource instead of waste (121). This change in perspective requires addressing the significant gap in creating comprehensive models that illustrate the complex interactions among treatment technologies and different sludge components, which are essential for both scalability and environmental impact evaluations (122). In particular, the long-term ecological effects of repeated sludge applications on soil health and microbial communities remain poorly understood, necessitating deeper exploration of potential cumulative impacts like soil compaction or nutrient imbalances. Gaining a better understanding of these intricate interactions is crucial for optimising treatment processes and ensuring the safe and beneficial reuse of sludge in agricultural settings.

Conclusion

This review demonstrates that the bioconversion of agro-industrial effluent sludge into bio-fertilisers is a promising and sustainable approach for waste valorisation, nutrient recovery and the advancement of a circular bioeconomy. Evidence from the literature indicates that biological conversion technologies, such as composting, vermicomposting, microbial inoculation, anaerobic digestion and emerging biorefinery-based processes, can effectively convert nutrient-rich sludge into valuable agricultural inputs while minimising the environmental impacts associated with sludge disposal. When properly treated, sludge-derived biofertilisers can improve soil fertility, stimulate microbial activity, enhance nutrient

availability and increase crop productivity, thereby reducing reliance on synthetic fertilisers and highlighting the importance of microbial consortia, nutrient-mineralising enzymes and advanced stabilisation techniques in enhancing the quality, safety and agronomic effectiveness of sludge-derived products. In addition, innovative technologies, including biochar-based fertilisers, electrochemical nutrient recovery systems, hydrothermal carbonisation and integrated sludge biorefineries, provide new opportunities for maximising resource recovery and promoting sustainable agricultural production. Despite these advances, challenges related to heavy metals, pathogens, antibiotic resistance genes and other emerging contaminants continue to pose significant concerns and require effective treatment strategies, continuous monitoring and strict regulatory oversight. Overall, the findings emphasise that agro-industrial sludge should be viewed not as a waste product but as a valuable resource that can contribute to sustainable nutrient management, environmental protection and climate-resilient agriculture. The successful implementation of sludge valorisation technologies can support circular economy goals by closing nutrient cycles, reducing dependence on landfills and encouraging resource-efficient agricultural practices.

Future research should focus on developing standardised protocols and quality standards for sludge-derived biofertilisers, as well as investigating the long-term impacts of their repeated application on soil health, microbial diversity, contaminant accumulation and ecosystem functioning. Further studies are needed to optimise microbial consortia and bioaugmentation approaches for enhanced nutrient recovery and contaminant degradation. Research should also evaluate the occurrence, fate and risks of emerging contaminants, including antibiotic resistance genes, pharmaceuticals, microplastics and per- and polyfluoroalkyl substances (PFAS). In addition, large-scale field trials and life-cycle assessments are necessary to validate the agronomic, environmental and economic performance of these products under diverse agroecological conditions. Finally, the development of integrated policy frameworks and market mechanisms will be essential to facilitate the safe commercialisation and widespread adoption of sludge-derived biofertilisers. Addressing these priorities will play a crucial role in advancing sludge bioconversion technologies and unlocking their full potential within sustainable and circular agricultural systems.

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Authors' contributions

MSA and JP conceived the study and were responsible for conceptualisation and manuscript writing. BA, EM, TN and BP reviewed the manuscript and provided supervision. EM, TN and TKT reviewed the manuscript and contributed to visualisation. TKT and BP performed the data analysis and visualisation. All authors have read and approved the final manuscript.

Compliance with ethical standards

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References

- Engida T, Mekonnen A, Wu J, Xu D, Wu Z. Review paper on beverage agro-industrial wastewater treatment plant bio-sludge for fertilizer potential in Ethiopia. *Applied Ecology and Environmental Research*. 2020;18(1):33–57. https://doi.org/10.15666/aeer/1801_033057
- Hidalgo D, Martín-Marroquín J, Corona F, Verdugo F. Waste-derived fertilizers: conversion technologies, circular bioeconomy perspectives and agronomic value. *Agronomy*. 2025;15(9):2167. <https://doi.org/10.3390/agronomy15092167>
- Anisimova T. Agroecological assessment of fertilizers obtained on the basis of bioconversion of sewage sludge. *Agricultural Chemistry*. 2025;9:40. <https://doi.org/10.7868/S3034496425090051>
- Aryanfar Y, García Alcaraz JL, Keçebaş A, Fernandez JB, Arslan B, Ilbas M, et al. Transforming food industrial sludge into sustainable resources: innovations in waste management and renewable energy recovery. *Business Strategy and the Environment*. 2025;34(3):3672–700. <https://doi.org/10.1002/bse.4170>
- Pereira W, Lyra MRCC, Netto AM, Rodrigues SSFB. Characterization of biological sludge waste from industrial wastewater treatment plant for soil reuse purposes. *Revista de Gestão Social e Ambiental*. 2025;19(1):1. <https://doi.org/10.24857/rgsa.v19n1-014>
- Lee L, Wu T, Shak K, Lim S, Ng K, Nguyen M, et al. Sustainable approach to biotransform industrial sludge into organic fertilizer via vermicomposting: a mini-review. *Journal of Chemical Technology & Biotechnology*. 2018;93(4):925–35. <https://doi.org/10.1002/jctb.5490>
- N JMK, Saeid A. An insight into microbial inoculants for bioconversion of waste biomass into sustainable "bio-organic" fertilizers: a bibliometric analysis and systematic literature review. *International Journal of Molecular Sciences*. 2022;23(21):13049. <https://doi.org/10.3390/ijms232113049>
- Upadhyay S, Singh G, Rani N, Rajput V, Seth CS, Dwivedi P, et al. Transforming bio-waste into value-added products mediated microbes for enhancing soil health and crop production: perspective views on circular economy. *Environmental Technology & Innovation*. 2024;34:103573. <https://doi.org/10.1016/j.eti.2024.103573>
- Jagaba A, Kutty S, Abubakar S, Birniwa A, Lawal I, Umaru I, et al. Synthesis, characterization and performance evaluation of hybrid waste sludge biochar for COD and color removal from agro-industrial effluent. *Separations*. 2022;9(9):258. <https://doi.org/10.3390/separations9090258>
- Zheng Q, Ni L. Analysis of the effect of intrinsic sludge properties on sludge drying characteristics from both sludge composition and type scales. *Waste Management*. 2024;183:278–89. <https://doi.org/10.1016/j.wasman.2024.05.020>
- Degu A, Shiferaw T, Feyisa T. Assessment of physio-chemical properties of Bahir Dar textile sludge and its impact on the growth of *Lactuca sativa* and soil nutrient improvement. *Journal of Tropical Crop Science*. 2025;12(1):25–36. <https://doi.org/10.29244/jtcs.12.01.25-36>
- Valdés MÁ, Disla JS, Gambuzzi E, Martínez GC. Innovative circular biowaste valorisation—state of the art and guidance for cities and regions. *Sustainability*. 2024;16(20):8963. <https://doi.org/10.3390/su16208963>
- Shi W, Healy M, Ashekuzzaman S, Daly K, Leahy J, Fenton O. Dairy processing sludge and co-products: a review of present and future re-use pathways in agriculture. *Journal of Cleaner Production*. 2021;314:128035. <https://doi.org/10.1016/j.jclepro.2021.128035>

14. Ramakrishna G, Patil B. Characterisation of faecal sludge from different nature-based treatment processes for agricultural application. *Sustainability*. 2025;17(13):5683. <https://doi.org/10.3390/su17135683>
15. Cwalina P, Obidziński S, Sienkiewicz A, Kowczyk-Sadowy M, Piekut J, Bagińska E, et al. Production and quality assessment of fertilizer pellets from compost with sewage sludge ash (SSA) addition. *Materials*. 2025;18(5):1145. <https://doi.org/10.3390/ma18051145>
16. Espinosa BG, Currás AC, Alonso J. Composición de lodos generados en la depuración anaerobia de residuales de la industria alimentaria. I: Macronutrientes. *Alimentaria*. 2002;37(329):129–32. <https://doi.org/10.1007/s12272-014-0335-3>
17. Eliyan C, McConville J, Zurbrugg C, Kootatet T, Sothea K, Vinnerås B. Heavy metal contamination of faecal sludge for agricultural production in Phnom Penh, Cambodia. *Journal of Environmental Management*. 2023;349:119436. <https://doi.org/10.1016/j.jenvman.2023.119436>
18. Balkrishna A, Ghosh S, Kaushik I, Arya V, Joshi D, Semwal D, et al. Sequential distribution, potential sources and health risk assessment of persistent toxic substances in sewage sludge used as organic fertilizer in Indo-Gangetic region. *Environmental Science and Pollution Research*. 2025;32(5):2324–58. <https://doi.org/10.1007/s11356-024-35706-4>
19. Janaszek A, Kowalik R. Analysis of heavy metal contaminants and mobility in sewage sludge-soil mixtures for sustainable agricultural practices. *Water*. 2023;15(22):3992. <https://doi.org/10.3390/w15223992>
20. Van Dongen K, Spaans G, Foekema EM, Van Groenestijn J, Kootstra A, Brouwer MSM, et al. Towards circular food production systems: identification of chemical, microbial and physical food safety hazards in municipal sludge and excess aerobic biomass of the food industry. *Environment International*. 2025;202:109624. <https://doi.org/10.1016/j.envint.2025.109624>
21. Izydorczyk G, Mikula K, Skrzypczak D, Trzaska K, Moustakas K, Witek-Krowiak A, et al. Agricultural and non-agricultural directions of bio-based sewage sludge valorization by chemical conditioning. *Environmental Science and Pollution Research*. 2021;28:47725–40. <https://doi.org/10.1007/s11356-021-15293-4>
22. Wang M-H, Chen C-F, Ju Y, Tsai M, Chen C-W, Dong C. Distribution and environmental risk assessment of trace metals in sludge from multiple sources in Taiwan. *Journal of Environmental Science and Health Part A*. 2021;56:481–91. <https://doi.org/10.1080/10934529.2021.1887687>
23. Birendar AKS, Kuppusamy S, Sellappa K, Pandian GK. Physico-chemical, nutrient and contaminant profile of sewage sludge from sewage treatment plants in Tamil Nadu, India: implications for agricultural reuse. *Environmental Monitoring and Assessment*. 2025;197(11):1235. <https://doi.org/10.1007/s10661-025-14685-0>
24. Khelladi M, Abaidia M, Debab A. Utilizing industrial waste for the microbiological decontamination of sewage sludge. *Engineering, Technology & Applied Science Research*. 2025;15(4):24752–7. <https://doi.org/10.48084/etasr.11593>
25. Hoang S, Bolan N, Madhubashani A, Vithanage M, Perera V, Wijesekara H, et al. Treatment processes to eliminate potential environmental hazards and restore agronomic value of sewage sludge: a review. *Environmental Pollution*. 2021;293:118564. <https://doi.org/10.1016/j.envpol.2021.118564>
26. Liang X, Wen X, Yang H, Lu H, Wang A, Liu S, et al. Incorporating microbial inoculants to reduce nitrogen loss during sludge composting by suppressing denitrification and promoting ammonia assimilation. *Science of the Total Environment*. 2024;915:170000. <https://doi.org/10.1016/j.scitotenv.2024.170000>
27. Uddin MN, Hartog C, Murray E, Loveless J, Roberson L, Aslan A, et al. Advancing circular bioeconomy through a systems-level assessment of food waste and industrial sludge codigestion. *ACS Environmental Au*. 2025;5(5):479–89. <https://doi.org/10.1021/acsenvironau.5c00049>
28. Romano P, Zuffranieri A, Di Giacomo G. Energy valorization and resource recovery from municipal sewage sludge: evolution, recent advances and future prospects. *Energies*. 2025;18(13):3442. <https://doi.org/10.3390/en18133442>
29. Lucia C, Badalucco L, Corsino S, Galati A, Iovino M, Muscarella S, et al. Management and valorisation of sewage sludge to foster the circular economy in the agricultural sector. *Discover Soil*. 2025;2(1). <https://doi.org/10.1007/s44378-025-00105-9>
30. Villagrán-Zaccardi Y, Carreño F, Granheim L, De Gea AE, Minke US, Butera S, et al. Valorisation of aggregate-washing sludges in innovative applications in construction. *Materials*. 2024;17(19):4892. <https://doi.org/10.3390/ma17194892>
31. Fernando-Foncillas C, Varrone C. Potential of the sewage sludge valorization in Scandinavia by co-digestion with other organic wastes: a techno-economic assessment. *Journal of Cleaner Production*. 2021;324:129239. <https://doi.org/10.1016/j.jclepro.2021.129239>
32. Nguyen MD, Thomas M, Surapaneni A, Moon E, Milne N. Beneficial reuse of water treatment sludge in the context of circular economy. *Environmental Technology & Innovation*. 2022;28:102651. <https://doi.org/10.1016/j.eti.2022.102651>
33. Kathi S, Singh S, Yadav R, Singh A, Mahmoud A. Wastewater and sludge valorisation: a novel approach for treatment and resource recovery to achieve circular economy concept. *Frontiers in Chemical Engineering*. 2023;5. <https://doi.org/10.3389/fceng.2023.1129783>
34. Kiselev A, Magaril E, Magaril R, Panepinto D, Ravina M, Zanetti M. Towards circular economy: evaluation of sewage sludge biogas solutions. *Resources*. 2019;8(2):91. <https://doi.org/10.3390/resources8020091>
35. Kowalski Z, Makara A, Kulczycka J, Generowicz A, Kwaśnicki P, Ciula J, et al. Conversion of sewage sludge into biofuels via different pathways and their use in agriculture: a comprehensive review. *Energies*. 2024;17(6):1383. <https://doi.org/10.3390/en17061383>
36. Camargo F, Sakamoto I, Delforno T, Midoux C, Duarte ICS, Silva E, et al. Microbial and functional characterization of granulated sludge from full-scale UASB thermophilic reactor applied to sugarcane vinasse treatment. *Environmental Technology*. 2022;44(21):3141–60. <https://doi.org/10.1080/09593330.2022.2052361>
37. Remmas N. Biotreatment potential and microbial communities in aerobic bioreactor systems treating agro-industrial wastewaters. *Processes*. 2022;10(10):1913. <https://doi.org/10.3390/pr10101913>
38. Zhou M, Zhu W, Zheng Z, Wu H, Cong H, Feng S. Material conversion, microbial community composition and metabolic functional succession during algal sludge composting. *Water*. 2025;17(19):2904. <https://doi.org/10.3390/w17192904>
39. Gulsunoglu-Konuskan Z, Kilic-Akyilmaz M. Microbial bioconversion of phenolic compounds in agro-industrial wastes: a review of mechanisms and effective factors. *Journal of Agricultural and Food Chemistry*. 2022;70(23):6901–10. <https://doi.org/10.1021/acs.jafc.1c06888>
40. Cheng X, Wei Z, Cao W, Feng Q, Liu J, Wu Y, et al. Untangling the interplay of dissolved organic matter variation with microbial symbiotic network in sludge anaerobic fermentation triggered by various pretreatments. *Water Research*. 2024;260:121930. <https://doi.org/10.1016/j.watres.2024.121930>
41. Bouhia Y, Hafidi M, Ouhdouch Y, Boukhari MEME, Fels E, Zeroual Y, et al. Microbial community succession and organic pollutants removal during olive mill waste sludge and green waste co-composting. *Frontiers in Microbiology*. 2022;12:814553. <https://doi.org/10.3389/fmicb.2021.814553>
42. Sui M, Miao K, Tang L, Zhao J, Jin C, Zhao Y, et al. Synergistic mechanisms of compound thermophilic bacteria on waste sludge hydrolysis and reduction: extracellular polymers degradation, enzyme activity and microbial community changes. *Science of the Total Environment*. 2025;999:180311. <https://doi.org/10.1016/j.scitotenv.2025.180311>
43. Pundir H, Balu R, Shah P, Satish R. Role of crude enzymes and microbial consortia in the degradation of organic matter. *World Journal of Biology Pharmacy and Health Sciences*. 2025;24(1):287–98. <https://doi.org/10.30574/wjbphs.2025.24.1.0914>
44. Qi M, Liang B, Zhang L, Xiao D, Yan L, Dong W, et al. Microbial

- interactions drive the complete catabolism of the antibiotic sulfamethoxazole in activated sludge microbiomes. *Environmental Science & Technology*. 2021;55(5):3270–82. <https://doi.org/10.1021/acs.est.0c06687>
45. Zhang T, Zhang H. Microbial consortia are needed to degrade soil pollutants. *Microorganisms*. 2022;10(2):261. <https://doi.org/10.3390/microorganisms10020261>
 46. Godzieba M, Żubrowska-Sudoł M, Walczak J, Ciesielski S. Development of microbial communities in biofilm and activated sludge in a hybrid reactor. *Scientific Reports*. 2022;12(1):12558. <https://doi.org/10.1038/s41598-022-16570-z>
 47. Datta R. Enzymatic degradation of cellulose in soil: a review. *Heliyon*. 2024;10(1):e24022. <https://doi.org/10.1016/j.heliyon.2024.e24022>
 48. Khan S, Ray A, Bhakta J, Lahiri S. Bacterial multi-enzyme signature assessment for wastewater reclamation and ecological resilience in tropical waste stabilization pond. *International Journal of Environmental Science and Technology*. 2024;21(3):3201–8. <https://doi.org/10.1007/s13762-023-05177-0>
 49. Daunoras J, Kačergius A, Gudiukaitė R. Role of soil microbiota enzymes in soil health and activity changes depending on climate change and the type of soil ecosystem. *Biology*. 2024;13(2):85. <https://doi.org/10.3390/biology13020085>
 50. Leng Y, Soares A. The mechanisms of struvite biomineralization in municipal wastewater. *Science of the Total Environment*. 2021;799:149261. <https://doi.org/10.1016/j.scitotenv.2021.149261>
 51. Xiong W, Wang S, Jin Y, Wu Z, Liu D, Su H. Insights into nitrogen and phosphorus metabolic mechanisms of algal-bacterial aerobic granular sludge via metagenomics: performance, microbial community and functional genes. *Bioresource Technology*. 2022;369:128442. <https://doi.org/10.1016/j.biortech.2022.128442>
 52. Krutiakova V, Pyliak N, Nikipelova O. Optimized technology of obtaining biofertilizers based on sewage sludge. *Visnyk Ahrarnoi Nauky*. 2022;100(1):50–6. <https://doi.org/10.31073/agrovysnyk202201-07>
 53. Gogoi M, Biswas T, Biswal P, Saha T, Modak A, Gantayet L, et al. A novel strategy for microbial conversion of dairy wastewater into biofertilizer. *Journal of Cleaner Production*. 2021;293:126051. <https://doi.org/10.1016/j.jclepro.2021.126051>
 54. Álvarez-Montero X, Mercado-Reyes I, Castillo-Chamba W, Santos-Ordóñez E. Harnessing dairy wastewater to cultivate *Scenedesmus* sp. for biofertilizer applications in *Phaseolus vulgaris* L.: a sustainable agrobiotechnological approach. *Frontiers in Plant Science*. 2025;16:1568057. <https://doi.org/10.3389/fpls.2025.1568057>
 55. Martínez LM, Mamani CC, Merino AR, González-Sánchez A andia JM. Synergistic bioremediation of agro-industrial wastewater by microalgae and activated sludge for biofertilizer production: influence of photoperiod and inoculation ratio. *Environmental Technology*. 2025;46(26):5297–312. <https://doi.org/10.1080/09593330.2025.2534199>
 56. Azeem B. Converting wastewater sludge into slow-release fertilizers via biochar and encapsulation technologies. *Applied Sciences*. 2025;15(20):10954. <https://doi.org/10.3390/app152010954>
 57. Botte G, Donneys-Victoria D, Alvarez-Pugliese C, Adjei J, Sahin S, Wilson N, et al. Innovative approach to sustainable fertilizer production: leveraging electrically assisted conversion of sewage sludge for nutrient recovery. *ACS Omega*. 2024;9:49692–706. <https://doi.org/10.1021/acsomega.4c07926>
 58. Hassan M, Senko S, Villa A, Grafova E, Pappinen A, Kuittinen S. Techno-economic evaluation of biofertilizer production using wastewater biosolids: case study from municipal wastewater treatment plants in northwest region of Russia. *Journal of Material Cycles and Waste Management*. 2023;25:3380–94. <https://doi.org/10.1007/s10163-023-01766-w>
 59. Zainudin M, Zulkarnain A, Azmi AS, Muniandy S, Sakai K, Shirai Y, et al. Enhancement of agro-industrial waste composting process via microbial inoculation: a brief review. *Agronomy*. 2022;12(1):198. <https://doi.org/10.3390/agronomy12010198>
 60. Zhang Z, Hu M, Bian B, Yang Z, Yang W, Zhang L. Full-scale thermophilic aerobic co-composting of blue-green algae sludge with livestock faeces and straw. *Science of the Total Environment*. 2020;753:142079. <https://doi.org/10.1016/j.scitotenv.2020.142079>
 61. Ezemagu I, Ejimofor M, Menkiti M, Diyoke C. Biofertilizer production via composting of digestate obtained from anaerobic digestion of post-bioagulation sludge blended with sawdust: physicochemical characterization and kinetic study. *Environmental Challenges*. 2021;5:100288. <https://doi.org/10.1016/j.envc.2021.100288>
 62. Nigussie A, Dume B, Ahmed M, Mamuye M, Ambaw G, Berhiun G, et al. Effect of microbial inoculation on nutrient turnover and lignocellulose degradation during composting: a meta-analysis. *Waste Management*. 2021;125:220–34. <https://doi.org/10.1016/j.wasman.2021.02.043>
 63. Lin B, Zhang Y, Hao Y, Lu M, Xiang H, Ding D, et al. Insights into nitrogen metabolism and humification process in aerobic composting facilitated by microbial inoculation. *Environmental Research*. 2025;269:120894. <https://doi.org/10.1016/j.envres.2025.120894>
 64. Ahmed T, Noman M, Qi Y, Shahid M, Hussain S, Masood HA, et al. Fertilization of microbial composts: a technology for improving stress resilience in plants. *Plants*. 2023;12(20):3550. <https://doi.org/10.3390/plants12203550>
 65. Van Quang T, Bao ND, Xuan NTM. Microbial fertilizer from co-composted sludge using Mishimax-50 system. *University of Danang Journal of Science and Technology*. 2025:86–91. [https://doi.org/10.31130/ud-jst.2025.23\(9d\).570e](https://doi.org/10.31130/ud-jst.2025.23(9d).570e)
 66. Li L, Li H, Tong L, Lv Y. Sustainable agriculture practices: utilizing composted sludge fertilizer for improved crop yield and soil health. *Agronomy*. 2024;14(4):756. <https://doi.org/10.3390/agronomy14040756>
 67. Chen Z, Li Y, Peng Y, Mironov V, Chen J, Jin H-X, et al. Feasibility of sewage sludge and food waste aerobic co-composting: physicochemical properties, microbial community structures and contradiction between microbial metabolic activity and safety risks. *Science of the Total Environment*. 2022;825:154047. <https://doi.org/10.1016/j.scitotenv.2022.154047>
 68. Demeke M, Gabbiye N. Organic biofertilizer from brewery wastewater sludges via aerobic composting process. In: *Sustainable Organic Agriculture for Developing Agribusiness*. 2020. p. 3–15. https://doi.org/10.1007/978-3-030-43690-2_1
 69. Manea E, Bumbac C. Sludge composting—is this a viable solution for wastewater sludge management? *Water*. 2024;16(16):2241. <https://doi.org/10.3390/w16162241>
 70. Greff B, Szigeti J, Nagy Á, Lakatos E, Varga L. Influence of microbial inoculants on co-composting of lignocellulosic crop residues with farm animal manure: a review. *Journal of Environmental Management*. 2021;302(Pt B):114088. <https://doi.org/10.1016/j.jenvman.2021.114088>
 71. Amaral EJ, Pereira LMS, Lorençon E, Poggere GC, Agustini MAB, Edwiges T. Valorization of biowastes through pre-composting followed by vermicomposting with the addition of effective microorganisms. *International Journal of Environmental Research*. 2025;19(1):9.
 72. Ejileugha C, Onyegbule UO, Osuoha JO. Use of additives in composting promotes passivation and reduction in bioavailability of heavy metals (HMs) in compost. *Reviews of Environmental Contamination and Toxicology*. 2024;19(1). <https://doi.org/10.1007/s41742-024-00689-0>
 73. Tiong YW, Sharma P, Xu S, Bu J, An S, Foo JBL, et al. Enhancing sustainable crop cultivation: the impact of renewable soil amendments and digestate fertilizer on crop growth and nutrient composition. *Environmental Pollution*. 2024;342:123132. <https://doi.org/10.1016/j.envpol.2023.123132>
 74. Xu M, Sun H, Chen E, Yang M, Wu C, Sun X, et al. From waste to wealth: innovations in organic solid waste composting. *Environmental Research*. 2023;229:115977. <https://doi.org/10.1016/j.envres.2023.115977>
 75. Mhamdi R, Trabelsi D. The rise of the worm: bibliometric insights into the growing significance of vermicomposting for sustainable agriculture and environmental management. *International Journal of Recycling of*

- Organic Waste in Agriculture. 2025. <https://doi.org/10.57647/ijrowa-md30-c35t>
76. Mohite DD, Chavan SS, Jadhav VS, Kanase T, Kadam M, Singh AS. Vermicomposting: a holistic approach for sustainable crop production, nutrient-rich biofertilizer and environmental restoration. *Discover Sustainability*. 2024;5(1). <https://doi.org/10.1007/s43621-024-00245-y>
 77. Gazi A, Maity A, Khatua N, Sengupta S, Kundu S, Sarkar T. Effect of vermicompost on soil quality and crop productivity. *International Journal of Agriculture Extension and Social Development*. 2024;7:13–23. <https://doi.org/10.33545/26180723.2024.v7.i4sa.517>
 78. Pereira MMA, Moraes LC, Mogollón MCT, Borja CJF, Duarte M, Buttrós VHT, et al. Cultivating biodiversity to harvest sustainability: vermicomposting and inoculation of microorganisms for soil preservation and resilience. *Agronomy*. 2023;13(1):103. <https://doi.org/10.3390/agronomy13010103>
 79. Rahman M, Hajam YA. Selection and evaluation of optimal medium for *Eisenia fetida* in sustainable waste recycling. *Discover Animals*. 2024;1(1):20. <https://doi.org/10.1007/s44338-024-00021-2>
 80. Vaidyanathan VK, Venkataraman S, Kumar PS, Rajendran DS, Saikia K, Rathankumar AK, et al. Mycoremediation of lignocellulosic biorefinery sludge: a reinvigorating approach for organic contaminants remediation with simultaneous production of lignocellulolytic enzyme cocktail. *Bioresource Technology*. 2022;351:127012. <https://doi.org/10.1016/j.biortech.2022.127012>
 81. Ariffin H, Ahmed OH, Marsal CJ. Food wastes for enhancing soil and crop productivity in tropical acid soils. *Pertanika Journal of Tropical Agricultural Science*. 2025;48(2). <https://doi.org/10.47836/pjtas.48.2.10>
 82. Vaithyanathan VK, Cabana H. Integrated biotechnology management of biosolids: sustainable ways to produce value-added products. *Frontiers in Water*. 2021;3:729679. <https://doi.org/10.3389/frwa.2021.729679>
 83. Cheng D, Liu Y, Ngo HH, Guo W, Chang SW, Nguyen DD, et al. A review on application of enzymatic bioprocesses in animal wastewater and manure treatment. *Bioresource Technology*. 2020;313:123683. <https://doi.org/10.1016/j.biortech.2020.123683>
 84. Nguyen VK, Chaudhary DK, Dahal RH, Trinh NH, Kim J, Chang SW, et al. Review on pretreatment techniques to improve anaerobic digestion of sewage sludge. *Fuel*. 2021;285:119105. <https://doi.org/10.1016/j.fuel.2020.119105>
 85. Caballero Jiménez P, Ágabo García C, Solera R, Parrado Rubio J, Pérez M. Eco-energetic management of activated sludge derived from slaughterhouse wastewater treatment: pretreatments for enhancing biogas production under anaerobic conditions. *Sustainable Energy & Fuels*. 2020;4(10):5072–9. <https://doi.org/10.1039/D0SE00992J>
 86. Vu HP, Nguyen LN, Zdzarta J, Jesionowski T, Nghiem LD. Valorizing agricultural residues as biorefinery feedstocks: current advancements and challenges. In: *Clean Energy and Resources Recovery*. Elsevier; 2021. p. 25–48. <https://doi.org/10.1016/B978-0-323-85223-4.00021-X>
 87. Prado-Acebo I, Cubero-Cardoso J, Lu-Chau T, Eibes G. Integral multi-valorization of agro-industrial wastes: a review. *Waste Management*. 2024;183:42–52. <https://doi.org/10.1016/j.wasman.2024.05.001>
 88. Petridi A, Fragkouli D-N, Mejias L, Paredes L, Bistue M, Boukouvalas C, et al. Assessing the overall sustainability performance of the meat processing industry before and after wastewater valorization interventions: a comparative analysis. *Sustainability*. 2024;16(22):9811. <https://doi.org/10.3390/su16229811>
 89. Ogbu CC, Okey SN. Agro-industrial waste management: the circular and bioeconomic perspective. In: *Agricultural Waste—New Insights*. 2023. <https://doi.org/10.5772/intechopen.109181>
 90. Cucina M, De Nisi P, Sordi S, Adani F. Sewage sludge as N-fertilizers for crop production enabling the circular bioeconomy in agriculture: a challenge for the new EU Regulation 1009/2019. *Sustainability*. 2021;13(23):13165. <https://doi.org/10.3390/su132313165>
 91. Melo W, Delarica D, Guedes A, Lavezzo L, Donha R, De Araújo A, et al. Ten years of application of sewage sludge on tropical soil: a balance sheet on agricultural crops and environmental quality. *Science of the Total Environment*. 2018;643:1493–501. <https://doi.org/10.1016/j.scitotenv.2018.06.254>
 92. Tejada M, Rodríguez-Morgado B, Gómez I, Franco-Andreu L, Benítez C, Parrado J. Use of biofertilizers obtained from sewage sludges on maize yield. *European Journal of Agronomy*. 2016;78:13–9. <https://doi.org/10.1016/j.eja.2016.04.014>
 93. De Barros JA, Stamford N, Da Silva EVN, Da Costa D, De Freitas MI, Da Silva Oliveira W, et al. Biofertilizer combined with sewage sludge increases the quality of soil cultivated with banana. *Journal of Soil Science and Plant Nutrition*. 2023;23:6273–83. <https://doi.org/10.1007/s42729-023-01483-1>
 94. Ragonezi C, Nunes N, Oliveira M, De Freitas J, Ganança J, De Carvalho M. Sewage sludge fertilization—a case study of sweet potato yield and heavy metal accumulation. *Agronomy*. 2022;12(8):1902. <https://doi.org/10.3390/agronomy12081902>
 95. Carraturo F, Siciliano A, Giordano A, Di Capua F, Barone F, Casaletta E, et al. Ecotoxicological assessment of waste-derived organic fertilizers and long-term monitoring of fertilized soils using a multi-matrix and multi-species approach. *Science of the Total Environment*. 2024;912:169341. <https://doi.org/10.1016/j.scitotenv.2023.169341>
 96. Rumky J, Visigalli S, Turolla A, Gelmi E, Necibi C, Gronchi P, et al. Electro-dewatering treatment of sludge: assessment of the influence on relevant indicators for disposal in agriculture. *Journal of Environmental Management*. 2020;268:110689. <https://doi.org/10.1016/j.jenvman.2020.110689>
 97. Alayu E, Leta S, Aragaw T. Characterization of the physicochemical and biological properties of Kombolcha brewery wastewater treatment plant biosolid in relation to agricultural uses. 2018;3:1–7. <https://doi.org/10.4172/2475-7675.1000154>
 98. Badza T, Tesfamariam E, Cogger C. Agricultural use suitability assessment and characterization of municipal liquid sludge: based on South Africa survey. *Science of the Total Environment*. 2020;721:137658. <https://doi.org/10.1016/j.scitotenv.2020.137658>
 99. Sundha P, Basak N, Rai A, Chandra P, Bedwal S, Yadav G, et al. Characterization and ecotoxicological risk assessment of sewage sludge from industrial and non-industrial cities. *Environmental Science and Pollution Research*. 2023;30:116567–83. <https://doi.org/10.1007/s11356-022-21648-2>
 100. Wei C, Liu L, Yi W, Yu R, Xu Y, Zeng S. Characteristics of nutrients and heavy metals release from sewage sludge biochar produced by industrial-scale pyrolysis in the aquatic environment and its potential as a slow-release fertilizer and adsorbent. *Journal of Environmental Management*. 2024;366:121871. <https://doi.org/10.1016/j.jenvman.2024.121871>
 101. Martínez-Gallardo M, Jiménez R, Suárez-Estrella F, Toribio A, Estrella-González M, Mira-Urios M, et al. Cataloging olive oil mill wastewater sludge based on toxicological profiles and functional microbial diversity. *Science of the Total Environment*. 2025;976:179348. <https://doi.org/10.1016/j.scitotenv.2025.179348>
 102. Glauoi GEME, Hayany BE, Fels E, Faiz AE, Ezzari A, Rihani M, et al. Physico-chemical and spectroscopy assessment of sludge biodegradation during semi-industrial composting under semi-arid climate. *Waste and Biomass Valorization*. 2020;11:1217–28. <https://doi.org/10.1007/s12649-018-0442-3>
 103. Leil IAE, Duheri IAYE. Evaluation of biosolids compost maturity as fertilizing substance for soil. 2020;1. <https://doi.org/10.37376/1570-000-034-004>
 104. Huang D, Gao Y, Zhang L, Zhang R, Wu Y, Guan H, et al. Enhancing waste management and nutrient recovery: preparation of N slow-release fertilizer using sewage sludge and its release behavior, effects on ryegrass (*Lolium perenne* L.) growth. *Biochemical Engineering Journal*. 2025;216:109664. <https://doi.org/10.1016/j.bej.2025.109664>
 105. Yang L, Zhao J, Huang Q, Wang J, Xu C, Xu Y, et al. Release behavior of

- fertilizers and heavy metals from iron-loaded sludge biochar in the aqueous environment. *Environmental Pollution*. 2023;334:122163. <https://doi.org/10.1016/j.envpol.2023.122163>
106. Kulhánek M, Balík J, Černý J, Vašák F, Shejbalová Š. Influence of long-term fertilizer application on changes of the content of Mehlich-3 estimated soil macronutrients. *Plant Soil and Environment*. 2014;60(4):151–7. <https://doi.org/10.17221/930/2013-PSE>
 107. Zhou X-M, Zhang B, Li L. From waste to resource: assessing the feasibility of municipal sludge as a fertilizer from a soil and microbial perspective. *Chemical Engineering Journal Advances*. 2024;19:100630. <https://doi.org/10.1016/j.cej.2024.100630>
 108. Hao J, Li B, Tan J, Zhang Y, Gu X, Wang S, et al. Double advantages of nutrients and biostimulants derived from sewage sludge by alkaline thermal hydrolysis process for agricultural use: quality promotion of soil and crop. *Advanced Science*. 2024;11(13):e2307793. <https://doi.org/10.1002/advs.202307793>
 109. Wollmann I, Gauro A, Müller T, Möller K. Phosphorus bioavailability of sewage sludge-based recycled fertilizers. *Journal of Plant Nutrition and Soil Science*. 2018;181:158–66. <https://doi.org/10.1002/jpln.201700111>
 110. Ndoung OCN, Souza L, Fachini J, Leão T, Sandri D, Figueiredo C. Dynamics of potassium released from sewage sludge biochar fertilizers in soil. *Journal of Environmental Management*. 2023;346:119057. <https://doi.org/10.1016/j.jenvman.2023.119057>
 111. Fachini J, Figueiredo C, Vale A. Assessing potassium release in natural silica sand from novel K-enriched sewage sludge biochar fertilizers. *Journal of Environmental Management*. 2022;314:115080. <https://doi.org/10.1016/j.jenvman.2022.115080>
 112. Nesterov D, Barrera-Martínez I, Martínez-Sánchez C, Sandoval-González A, Bustos E. Approaching the circular economy: biological, physicochemical and electrochemical methods to valorize agro-industrial residues, wastewater and industrial wastes. *Journal of Environmental Chemical Engineering*. 2024;12(5):113335. <https://doi.org/10.1016/j.jece.2024.113335>
 113. Kumar V, Verma P. Pulp-paper industry sludge waste biorefinery for sustainable energy and value-added products development: a systematic valorization towards waste management. *Journal of Environmental Management*. 2024;352:120052. <https://doi.org/10.1016/j.jenvman.2024.120052>
 114. Ammar E, Maury H, Morin L, Sghir A. Environmental, economic and ethical assessment of the treated wastewater and sewage sludge valorization in agriculture. In: *Sustainable Agriculture Reviews*. 2020. p. 49–78. <https://doi.org/10.1007/978-2020-606>
 115. Moktadir MA, Ren J, Zhou J. A systematic review on tannery sludge to energy route: current practices, impacts, strategies and future directions. *Science of the Total Environment*. 2023;901:166244. <https://doi.org/10.1016/j.scitotenv.2023.166244>
 116. Woo DCY, Goh Q, Poh P, Chew I. A techno-economic analysis of sewage sludge valorization for carbon emission reduction. *Biomass Conversion and Biorefinery*. 2023;13:13591–604. <https://doi.org/10.1007/s13399-022-02922-2>
 117. Rajaniemi K, Tuomikoski S, Lassi U. Electrocoagulation sludge valorization-a review. *Resources*. 2021;10(12):127. <https://doi.org/10.3390/resources10120127>
 118. Fini EH, Kazemi M, Poulikakos L, Lazorenko G, Akbarzade V, Lamanna A, et al. Perspectives on innovative non-fertilizer applications of sewage sludge for mitigating environmental and health hazards. *Communications Engineering*. 2024;3(1):178. <https://doi.org/10.1038/s44172-024-00298-x>
 119. Chen B, Zeng H, Yang F, Yang Y, Qiao Z, Zhao X, et al. Functional biochar as sustainable precursors to boost the anaerobic digestion of waste activated sludge from a circular economy perspective: a review. *Biochar*. 2024;6(1):60. <https://doi.org/10.1007/s42773-024-00345-y>
 120. Bakan B, Bernet N, Bouchez T, Boutrou R, Choubert J-M, Dabert P, et al. Circular economy applied to organic residues and wastewater: research challenges. *Waste and Biomass Valorization*. 2022;13(2):1267–76. <https://doi.org/10.1007/s12649-021-01549-0>
 121. Binder PM, Frison N, Guerra-Gorostegi N, Hidayat I, Paredes L, Llenas L, et al. Innovative multiple resource recovery pathways from EBPR wastewater treatment-derived sludge. *Biomass Conversion and Biorefinery*. 2023;13(18):16421–40. <https://doi.org/10.1007/s13399-023-03849-y>
 122. Li Y, Campos LC, Hu Y. Microwave pretreatment of wastewater sludge technology-a scientometric-based review. *Environmental Science and Pollution Research*. 2024;31(18):26432–51. <https://doi.org/10.1007/s11356-024-32931-9>

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