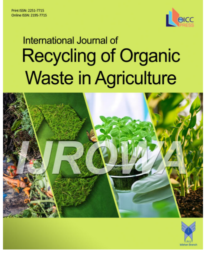

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Sustainable methodical approaches to recycling sludge waste: value-added products, and their agricultural applications

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Review Paper

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Abstract:

Purpose: This review addresses the important global issue of increased sludge accumulation from wastewater treatment plants, which poses serious environmental challenges due to heavy metals and high levels of organic pollution. The study provides a thorough review of sludge-to-value-added product recovery methods, including anaerobic digestion, composting, vermicomposting, and pyrolysis.

Method: The review highlights recent advances and examines the strengths and weaknesses of each approach. Given the significant loss of organic components before sludge generation, a unified strategy for value-added product recovery management is crucial, as the study emphasizes.

Results: The study provides important standards for choosing the best technique for sustainable sludge management from a waste-to-resources standpoint.

Conclusion: The study shows sewage sludge's potential as a valuable organic resources with higher nutrient compositions (Nitrogen $2.5-5.5\%$, Phosphorus $0.8-2.5\%$, Potassium $1.5-3.5\%$, Calcium $1.2-4.5\%$, and Magnesium $0.3-0.8\%$ respectively) and its possible uses in agriculture.

Keywords: Agriculture; Recycling; Soil application; Treatment practices; Environmental impact

1. Background

Sustainable administration of sludge waste is crucial for environmental protection and resource conservation. However, the efficient management of sludge waste presents a critical challenge in modern waste treatment practices, particularly in the context of sustainability and environmental stewardship (Nascimento et al., 2020). Sludge, a byproduct of wastewater treatment processes, poses significant disposal concerns owing to its higher organic content and possible environmental contamination (Hana et al., 2019; Marzougui et al., 2022; Sugurbekova et al., 2023). However, advancements in recycling practices offer promising avenues to not only mitigate the environmental impact of sludge but also extract valuable resources for beneficial reuse, particularly in agriculture (Lamastra et al., 2018; Ouassif et al., 2024). Several studies have highlighted the potential for recycling sludge waste into value-added products and their agricultural applications (Pegoraro et al., 2024). Emphasized the significance of closing nutrient loops in civilization through the complementation of organic waste recycling with nutrient extraction, permitting further ecological agronomic creation (Kirchmann et al., 2017). Similarly, discussed the 5Rs criteria (Recycle, recover, reuse, reduce, and reprocess) as an ecological solution for managing aluminum-based waterworks sludge waste (Tony, 2022). These approaches align with the concept of viable progress and efficient resource recycling, as emphasized by (Durdevic et al., 2022).

Similarly, discussed different methods of sludge treatment, including anaerobic digestion, agriculture application, incineration, and landfill highlighting the diverse approaches to cracking the nutrient significance of sludge (Singh et al., 2021).

Furthermore, the agricultural consumption of sludge has been identified as an ecologically justifiable methodology for handling sludge produced from sewage handling facilities (Stachowicz et al., 2016). This aligns with the concept of resource recovery, which aims to extract value from waste materials, as discussed by (Pradel et al., 2018). Additionally, highlighted the significance of ecological solid waste administration, emphasizing the proficient recycling of possessions without causing environmental harm (Mejia et al., 2021).

The current review highlighting in detail to discourse the current methods (anaerobic digestion, composting, vermicomposting, and pyrolysis) for appropriate administration, recycling and management of sewage sludge to value added nutrients enriched products (digestate, compost, vermicompost, and biochar) and to discover its suitable applications concerning agriculture. In addition to this, prospects, current trends, challenges, and environmental impacts related to the investigation are discussed in detail. As a result of the present review, related industries and the scientific community will gain an understanding of the potential and barriers associated with sewage sludge waste, allowing future research and sustainable agricultural applications utilizing sewage sludge waste for value added products to be advanced.

2. Current scenario of sewage sludge generation and characteristics

The current scenario of SS generation and characteristics is influenced by factors such as increasing population, urbanization, and industrialization, prominent to a manifold rise in wastewater production and SS generation (Usman et al., 2012). A wide range of properties are exhibited by sewage sludge, which are determined by multiple factors such as the wastewater composition, treatment procedures utilized, and local environmental requirements (Zhang et al., 2017). Moreover, the impact of alkali catalyst addition, reaction temperature, and steam to bio-mass mass proportion on the steam gasification properties of raw sewage sludge have been assessed, offering insights into the main components of the gasification efficiency, gas yield, generated gas, and energy-density (Gai et al., 2016). Rich in organic content, sewage sludge contains biodegradable substances like proteins, carbohydrates, and fats. Energy recovery through anaerobic digestion or bio fuel conversion is possible thanks to its organic component. In addition to micronutrients like iron, zinc, and copper, sewage sludge also contains important nutrients including potassium, phosphorus, and nitrogen (Shaddel et al., 2019). These nutrients, which are necessary for plant growth, can be recovered and used in agricultural applications as fertilizers or soil supplements (Sugurbekova et al., 2023). Sewage sludge is also produced in large quantities and with regularity each year, which makes it a reliable addition to the feedstock used to make biodiesel (Choi et al., 2019). As to Karolinczak et al. (2021) the present situation entails treating the sewage sludge mechanically and with dissolved air, treating it biologically in batch reactors in sequence, stabilizing the sludge through aerobic means, and finally using it for farming purposes. Furthermore, studies are being conducted to investigate the possibility of producing energy from sewage sludge; the results show that this might contribute 0.9% and 2% of total energy output in 2030 and 2050, respectively (Durdevic et al., 2022).

The claim of sewage sludge in agronomic soils has remained researched in terms of its effects on the environment. Results indicate that this practice improves soil biology and reverses negative trends in soil biology because it reduces metal contamination after repeated applications of sewage sludge (Kirchmann et al., 2017). In addition to viruses, heavy metals, and medicines, SS might also comprise various pollutants from industrial and home sources. To avoid contaminating the environment and guarantee the security of products made from recycled sludge, proper treatment of these contaminants is essential (Kominko et al., 2018).

Plants require fertilizer to provide essential nutrients that are not well available in the soil. Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are required for plant growth and are often represented as N-P-K on packaging Fang et al. (2023) Optimum Nitrogen, Phosphorous, and Potassium Fertilizer Application Increased Chrysanthemum Growth and Quality by Reinforcing the Soil Microbial Community and Nutrient Cycling Function. In addition, secondary nutrients like calcium (Ca), magnesium (Mg), and sulphur (S) are required, as well as trace amounts of micronutrients like iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), boron (B), and chlorine (Cl) (White and Brown, 2010). For these nutrients to be useful, fertilizers must release them in forms that can be readily absorbed by plants and that are compatible with plant growth cycles. So nutrient losses and environmental impacts are prevented. Fertilizers also need to have the right pH to optimize nutrient absorption and be soluble so that plants can absorb them more easily when they are needed (Bindraban et al., 2015). Slow-release fertilizers provide them with long-term stable nutrients, beneficial for long-term growth. Additionally, the fertilizer must be safe, free of harmful contaminants, and harmless to beneficial soil microorganisms or insects (Wang et al., 2020). The addition of organic matter to fertilizers can improve soil structure, water retention, and microbial activity, increasing overall soil health and plant growth (Wei et al., 2024).

Sewage sludge from wastewater treatment plants can be treated as fertilizer. It often contains significant amounts of nitrogen and phosphorus, making it a good source of these essential nutrients, as well as trace elements such as copper, zinc, and iron, which are beneficial for plant growth. Sewage sludge rich in organic matter, improves the soil structure, water retention, and microbial activity. Nutrients in sewage sludge are generally slow-releasing, providing a stable supply of nutrients with time, which is beneficial for the long-term fertility of the soil (Marin and Rusanescu, 2023; Usman et al., 2012). Generally, treated sewage sludge

is pH neutral, helping to balance soil pH and enhance nutrient availability (Achkir et al., 2023). However, one major concern of sewage sludge is the potential for heavy metals such as lead (Pb), cadmium (Cd), and mercury (Hg) to accumulate in the soil and enter the food chain, and it has caused health hazards. In addition, poorly treated or untreated sewage sludge can be harmful to plants, animals, and humans, making appropriate treatment methods very important to ensure safety (Agoro et al., 2020).
The study reported by Zhang et al. (2017) on the immobilization of heavy metals in SS through the agricultural land solicitation practice. This investigation highlights the necessity for good management strategies and potential environmental implications. Additionally, investigation has remained finished on the possible uses of SS in the building of roads and the creation of novel materials, demonstrating the variety of uses and advantages of sewage sludge usage (Wojcik et al., 2018).

3. Nutrient status of sewage sludge

An encouraging way to recycle nutrients and organic matter, lessen reliance on chemical fertilizers, and support sustainable soil management techniques is through the utilization of SS in farming activities. On the other hand, SS nutrient status varies greatly based on various factors such as wastewater composition, treatment methods, and local laws. Research has indicated that valuable nutrients like potassium, nitrogen, and phosphorus, found in municipal sewage sludge are necessary for plant growth (Antonkiewicz et al., 2019; Cheng et al., 2021; Duan et al., 2020; Hana et al., 2019; Iticescu et al., 2021; Ladanyi et al., 2020; Lamastra et al., 2018; Mezhevova et al., 2023; Suric et al., 2022; Voca et al., 2021; Zapalowska et al., 2017).The majority of these nutrients are found in organic forms, which can be progressively mineralized in the mud and enthralled by plants (Voca et al., 2021). Sewage sludge's nutritional content is determined by the amount of nutrients that are added from commercial, industrial, and residential sources as well as by how well wastewater treatment systems concentrate and hold onto these nutrients.
It has been discovered that applying sewage sludge increases the amount of nutrients in the soil, which boosts the soil-fertility and increases yield of agricultural products (Iticescu et al., 2021; Mezhevova et al., 2023; Stachowicz et al., 2016; Suric et al., 2022). But using sewage sludge as fertilizer also brings up the possibility of heavy-metal buildup in soil and plants (Nunes et al., 2021; Lavado et al., 2004).
Accordingly, sewage sludge's nutritional stability and sorption are important elements to take into interpretation before using it in agriculture (Duan et al., 2020; Prabhu et al., 2023). Sewage sludge, when applied properly, serves as a valuable foundation of nutrients and organic matter for soil improvement and crop production, promoting plant growth, enhancing soil-fertility, and increasing crop-yields (Lamastra et al., 2018). Table 1 summarizing the ranges of various nutrient status and their composition found in sewage sludge with its agricultural purpose. Furthermore, research has evaluated the effects of applying sewage sludge using various techniques, including co-composting and direct ponding, on the attenuation and redistribution of soil nutrients (Sun et al., 2016). All things considered, the nutritional status of sewage sludge poses both advantages and disadvantages for its application in agriculture, emphasizing the necessity of sustainable management techniques to optimize its advantages and reduce any.

Table 1. Overview of the nutrient composition found in sewage sludge, their ranges, and agricultural purposes.

S.No	Nutrient	Range in sewage sludge	Composition(%)	Agricultural purposes	References
1.	Nitrogen (N)	2 - 6%	2.5 - 5.5%	Essential for plant growth and protein synthesis	(Kacprzak et al., 2017)
		6.2 ± 0.5	-	-	(Alvarenga et al., 2015)
		17 - 61	-	-	(Nascimento et al., 2020)
2.	Phosphorus (P)	0.5 - 3%	0.8 - 2.5%	Vital for root development and flowering	(Singh et al., 2020; Zhu et al., 2022)
		13.5 ± 0.4	-	-	(Alvarenga et al., 2015)
		7.6 - 21	-	-	(Nascimento et al., 2020)
3.	Potassium (K)	1 - 4%	1.5 - 3.5%	Important for overall plant health and stress resistance	(Ndoung et al., 2023)
		7.1 ± 0.03	-	-	(Alvarenga et al., 2015)
		0.5 - 4.6	-	-	(Nascimento et al., 2020)
4.	Calcium (Ca)	1 - 5%	1.2 - 4.5%	Very essential for the cell wall structure development and nutrient uptake	(Izydorczyk et al., 2021)
		12.0 ± 0.1	-	-	(Alvarenga et al., 2015)
		7.2 - 143	-	-	(Nascimento et al., 2020)
5.	Magnesium (Mg)	0.2 - 1%	0.3 - 0.8%	More critical for chlorophyll production and enzyme activation	(Qin et al., 2022)
		4.6 ± 0.5	-	-	(Alvarenga et al., 2015)
		1.0 - 4.5	-	-	(Nascimento et al., 2020)

4. Heavy metal status of SS

Heavy-metals can enter SS by various means. May be from industrial runoff, agricultural runoff, domestic wastewater, or other sources. These metals usually persist in the environment and can accumulate in the sludge due to their limited biodegradation and limited removal during wastewater treatment (Agoro et al., 2020; Das and Poater, 2021; Feng et al., 2023; Aziz et al., 2023). The heavy metals usually originate in wastewater are copper (Cu), cadmium (Cd), chromium (Cr), mercury (Hg), lead (Pb), nickel (Ni), and zinc (Zn) (Kinuthia et al., 2020; Yang et al., 2017). Concentrations of these metals in wastewater are able to differ reliant on aspects such by way of the category of impacted wastewater, treatment methods, and the location of the wastewater treatment plant (Feng et al., 2018).
To evaluate the level of heavy-metals in the pollution, tests, and analyses are carried out to determine the concentration of these metals (Balakrishnan et al., 2019; Hosry et al., 2023; Shahbazi and Beheshti, 2019). Most of the countries have developed regulations and guidelines to limit heavy metal concentrations in sewage effluents. These regulatory standards are intended toward the environment and protect human health during sludge management and disposal.
Limits generally specify maximum allowable amounts of heavy-metals in sludge intended for land disposal, landfill disposal, or other uses on (Duan and Feng, 2022; Tytla, 2019; Tytla and Widziewicz-Rzonca, 2023). A variety of treatment and remediation methods remain used to deal with heavy metal contamination. These may include immobilization methods such as chemical immobilization or hardening to reduce the bioavailability and mobility of heavy metals (Feng and Cheng, 2023; Li et al., 2023; Xu et al., 2021). Some companies are also implementing advanced wastewater treatment systems to focus on heavy metal removal such as advanced oxidation or ion exchange (Aziz and Mustafa, 2024; Qasem et al., 2021). It is significant to note that heavy metal status in wastewater can vary spatially and over time due to changes in wastewater composition, treatment methods and regulatory framework. Table 2 displays the heavy metal status of SS in numerous sludge disposal plants.

5. Sustainable sludge management practices

There are numerous sludge management practices such by way of anaerobic digestion(AD), composting, vermicomposting, and the practice of pyrolysis deals sustainable solutions for the beneficial reuse of sewage sludge into value-added products for agricultural applications, in addition to promoting soil health, crop productivity, and environmental sustainability (Bagheri et al., 2023; Grobelak and Spinosa, 2023; Poinen and Bokhoree, 2022). Various practices are utilized for sludge management precised as trials in Fig. 1. Table 3 demonstrates the pros, cons, and limitations of various sludge management practices.

Anaerobic digestion

In order to process complex organic feedstocks to value added products, anaerobic microorganisms are used to separate the components. Numerous ranges of biomass feedstocks such by way of agricultural (harvest residues, energy crops), municipal waste and industrial wastes (sludge) are utilized as a substrate for the anaerobic digestion (AD) practice (Chozhavendhan et al., 2023). With several advantages including trash reduction, nutrient recycling, and the production of bioenergy with digestate, anaerobic digestion is a viable technique for managing sludge sustainably in agriculture (Kocar, 2008).
Furthermore, applying organic soil amendments like sewage sludge or digestate made from biowaste can enhance soil quality and replenish agricultural soil with essential nutrients, supporting sustainable farming methods (Picariello et al., 2020). The creation of digestate, trash reduction, and

Table 2. Heavy metal status of sewage sludge in various sludge disposal plants.

S.No	Type of industry	Heavy metals									Reference
		Unit	Ni	Zn	Cu	Pb	Cd	Cr	Mn	Fe	
1.	Textile	mg/kg	10.3	367.1	164.1	9.7	0.3	17.7	122.9	4245	(Nessa and Shammi, 2016)
		mg/kg	-	348.97	103.14	-	-	116.72	196.32	-	(Zhang et al., 2021)
2.	Food processing	%	–	90	70	-	-	-	-	-	(Geng et al., 2020)
3.	Municipal wastewater treatment plants	mg/kg	34.28	331.50	100.53	11.59	0.65	147.72	-	-	(Duan et al., 2017)
		mg/kg	-	-	0.74	0.099	0.13	-	-	39	(Agoro et al., 2020)
4.	Paper and pulp	ppm	-	1.3	-	1.39	-	-	-	18.5	(Verma et al., 2005)
		mg/kg	-	-	110.5	59.6	9.29	124.4	-	-	(Suthar et al., 2014)
5.	Mining and mineral processing	ppm	-	2179.2	59.0	2879.3	17.6	80.6	-	12.43	(Navarro and Andres, 2008)
6.	Electrical and electronic manufacturing	mg/L	7.1	48.9	3.7	-	-	6.4	-	1.83	(Alseroury and Wahaab, 2018)
		%		1.6	0.6	-	-	-	-	4.6	(Gunarathne et al., 2019)
7.	Automotive manufacturing	mg/L	2.04	19.38	14.50	2.91	6.09	0.46	9.81	-	(Akpomie and Dawodu, 2015)

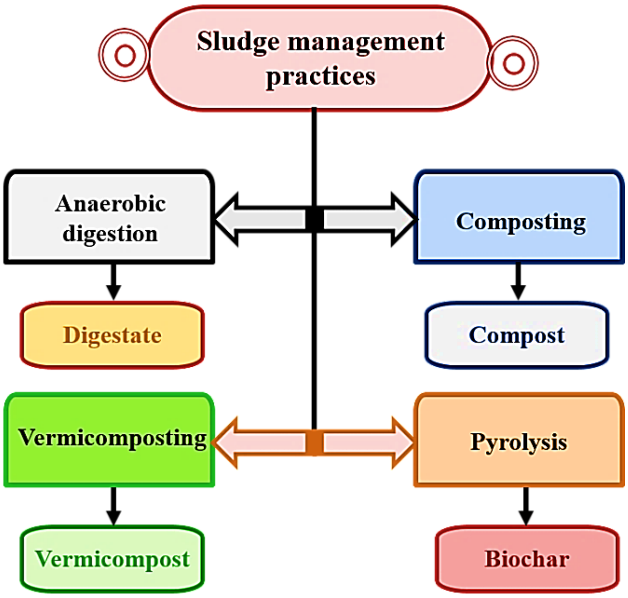

Figure 1. Various practices are utilized for sludge management.

nutrient recycling are just a few advantages that anaerobic digestion offers as a viable method for managing sludge sustainably in agriculture. The need for further technology to solve nutritional imbalances in wastewater effluent, problems with disease propagation, and the poor fluidity behavior of some waste materials must all be addressed.

Composting

Practice of composting is a one of the controlled biological decay practices that comprises numerous species of invertebrate animals and microorganisms (Murshid et al., 2024; Prakash et al., 2008). Composting biodegradable organic waste materials, such as sewage sludge, is an environmentally friendly way to create new materials that can be utilized as adsorbents or biofertilizers in wastewater treatment (Dumitrescu et al., 2014). A sustainable agricultural production system can benefit from high-quality compost by boosting crop productivity and enhancing soil health (Kekong and Ibrahim, 2024; Sultana et al., 2020; Trujillo-Gonzalez et al., 2024). The investigation reported by Nazir et al. (2007), reusing sewage sludge and using composted aquatic weeds are two excellent methods for managing agriculture sustainably.

In overall, the practice of composting SS for utilization in agriculture is intricate and necessitates thorough analysis of the possible possessions on the atmosphere, crops, and soil. Although it has a lot to offer in terms of managing nutrients and improving soil fertility, there are some possible drawbacks that must be addressed, like the spread of genes that confer resistance to antibiotics and the requirement for appropriate conditioning treatments to reduce these risks.

Vermicomposting

Vermicomposting practice is utilized for stabilization and bio oxidation of organic material (sewage sludge) comprising the combined action of earthworms(EWMs) and microorganisms (Hiranmai and P Vats, 2023; Maharjan et al., 2022). Though microorganisms are more accountable for the bio-chemical digestion of the organic-materials, EWMs are the more significant characters of the practice, altering biological activity and conditioning the substrate (Jayakumar et al., 2011). Although a lot of study has been done on the vermicomposting of different organic wastes, not much is known about the vermi-composting practice of primary SS, which is readily available in large quantities (Gupta and Garg, 2008).

Nonetheless, a great deal of study has been done on the vermicomposting of a diversity of organic-wastes, such us SS, industrial sludge, and animal manure, in addition agronomic and industrial trashes, suggesting the possibility of using vermicomposting for sustainable sludge management (Karmegam et al., 2021; Lee et al., 2018; Syarifinnur et al., 2024). Besides, vermicomposting application is crucial for horticulture and organic farming since it gives crops balanced nutrition and improves soil sustainability by boosting microbiological activity (Ose et al., 2021). As a result, vermicomposting addresses environmental issues related to conventional sludge management techniques while offering a sustainable solution for handling sewage sludge and other organic wastes. It also produces useful organic amendments for use in agriculture.

Pyrolysis

One of the viable techniques for the long-term handling of wastewater sludge in agriculture is pyrolysis. Compared to conventional techniques like landfilling and direct agricultural utilization, it has a number of advantages. As per the investigation by Hossain et al. (2011), pyrolysis decreases the amount of solid residue, gets rid of microorganisms, and breaks down any problematic organic components in the sludge. Additionally, it has remained acknowledged that pyrolysis practice of SS presents a significant chance for safe, sustainable nutrient recycling, with the possibility of negative emission technology (Buss, 2021). Pyrolysis also offers environmental benefits. Biochar as a good soil conditioner, biomass waste management, longer period carbon seizure, and the production of renewable energy are all possible when applied to pyrolyzed soils (Roberts et al., 2009).

As a thermo-chemical practice that breaks down organic-wastes at high temperatures and in an-aerobic environments, full-scale municipal sewage pyrolysis has garnered more interest recently (Jayakumar et al., 2023; Luo et al., 2021). Sludge toxicity has been reduced by the pyrolysis-produced material, making it appropriate for use in agriculture (Zaharioiu et al., 2021). When compared to gasification and incineration procedures, comparative analyses have demonstrated that pyrolysis is the most advantageous method for the management of SS (Zaharioiu et al., 2021). Ultimately, pyrolysis presents a sustainable and eco-friendly technique for getting rid of sewage sludge, with the added benefit of having the ability to recycle nutrients and recover energy. It offers several advantages for the environment and the economy by providing a workable technique for managing wastewater sludge in agriculture.

Table 3. Pros, cons and limitations of various sludge management practices.

S.No	Sludge management practices	Pros	Cons	Limitations	Reference
1.	AD	Biogas generation (methane) from renewable-energy cradles. Reduces the volume of sludge. Destroys pathogens and reduces odor. Produces a richer nutrient digestate that be able to utilized as a soil conditioner	Requires energy inputs for heating and mixing. High capital costs for setup and maintenance. Compassion to operating conditions and feedstock composition. Limited elimination of heavy-metals and persistent to organic-pollutants.	Requires proper management of digestate to prevent environmental contamination. Digestate may still contain pathogens and require further treatment. Not suitable for all types of sludge (e.g., highly toxic or contaminated sludge).	(Ibarra-Esparza et al., 2023) (Subbarao et al., 2023)
2.	Composting	Converts organic matter into stable humus-rich material. Soil structure improvement, water retention, and aeration. Decreases pathogens and weed seeds through microbial activity. Enhances nutrient availability for plants.	Requires proper carbon-to-nitrogen (C/N) ratio for efficient decomposition. Longer processing time compared to anaerobic digestion. May produce odors and attract pests if not managed properly. Limited elimination of persistent organic pollutants and heavy metals.	Requires adequate space and monitoring for proper composting. Unsuitable for sludge with high heavy metal concentrations or chemical contaminants.	(Muscarella et al., 2023) (Ofei-Quartey et al., 2023) (Waqas et al., 2023)
3.	Vermicomposting	Accelerated decomposition through earthworm activity. Produces high-quality vermicompost rich in nutrients and beneficial microorganisms. Reduces sludge volume and odors. mproves soil structure and water retention	Requires suitable earthworm species and environmental conditions. Limited capacity for large-scale processing. May attract predators and pests.	Slow process compared to other methods. Limited capacity to handle large volumes of sludge. Earthworms may be sensitive to certain	(Chang et al., 2022) (Maharjan et al., 2022)
4.	Pyrolysis	Converts organic matter into value added biochar, an established carbon richer material for agricultural applications. Produces syngas and bio oil as valuable by-products. Destroys pathogens and reduces odor. Improves soil fertility, structure, and water retention.	High energy input required for heating. Capital-intensive setup and maintenance. Limited scalability for large-scale operations. Slow process compared to anaerobic digestion or composting	Requires careful control of temperature and heating rate for optimal pyrolysis. Biochar may contain residual contaminants from the original sludge feedstock. Cost-effectiveness and environmental impact depend on feedstock composition and end-use applications.	(Chang et al., 2022) (Giwa et al., 2023)

6. Value-added products recovered from sludge waste

Valuable sludge products offer an innovative solution to conventional waste management and add value to agricultural systems (Spinosa et al., 2011). Sludge, also known as biosolids, is the residual by-product of waste-water handling facilities (Fijalkowski et al., 2017). Instead of just disposing of sludge, it can be made into valuable inputs that improve soil fertility, improve crop growth, and contribute to circular economic principles (Mabrouk et al., 2023).

Digestate

One of the most common excipients derived from sludge is digestate. The residue obtained after anaerobic digestion is a digestate, a practice that utilizes microbes to digest/degrade the constituents of the sludge (Chozhavendhan et al., 2023). Digestate contains many nutrients, organic matter, and beneficial microorganisms. When used on farms, the digestate provides a nutrient-rich amendment that improves soil-fertility, enhances microbial activity, and organic matter (Holatko et al., 2023). The gradual release of nutrients from the digestate ensures continuous delivery of nutrients to plants over time (Ehmann et al., 2018; Skrzypczak et al., 2023).

Compost

Compost is another valuable by-product of sludge. Through a composting process where sludge is diversified with additional organic matter and exposed to controlled decomposition, nutrient-dense compost is produced (Mengistu et al., 2017). Compost from sludge waste increases water holding capacity, soil structure, and retains nutrients. It also promotes soil microbial diversity, benefiting plant health and overall soil fertility (Shirish and Kalamdhad, 2020).

Vermicompost

Vermicomposting is a special type of compost generated by the action of earthworms. Sludge can serve as a feedstock for vermicomposting, where ketchup worms digest the organic matter and turn it into more nutrients (Ahmad et al., 2023). Vermicomposting is highly beneficial for soil health, as it increases nutrient availability, improves soil structure, and promotes microbial activity (Oyege, 2023). The casting produced by earthworms contains beneficial enzymes, micronutrients, and beneficial microorganisms that positively affect plant growth (Stress et al., 2023).

Biochar

Biochar is a carbon richer end product produced by the practice of pyrolysis or thermal-decomposition of sludge at controlled environmental conditions (Prabhu et al., 2023). Biochar is a carbon-rich material produced by pyrolysis or thermal decomposition in sludge under controlled conditions (Jayakumar et al., 2023). When biochar is applied to agricultural land, it improves water-retention, enhances nutrient-availability, and stimulates soil microbial-activity (Alkharabsheh et al., 2021; Bekchanova et al., 2024). It also aids in carbon-sequestration, aiding to alleviate climate-change by keeping carbon in the soil over time.
The use of value-added sludge products in agriculture, such as digestate, compost, vermicompost, and biochar for agricultural applications aligns with circular economic principles that turn waste into valuable end products with higher nutrition contents reported by numerous researchers illustrated in Table 4, in addition reduce the environmental burden of discharges, and support sustainable agriculture practices. However, it is important to ensure proper treatment, quality control, and compliance with regulatory guidelines to mitigate potential risks associated with heavy metals or disease in the sludge.

7. Agricultural applications

Sewage sludge in agricultural applications, also known as bio-solids, includes an extensive and well-managed process

Table 4. Nutritional status of digestate, compost, vermicomposting, and biochar.

S.No.	Parameters	C	N	C/N	P	K	Ca	Mg	References
1.	Digestate	25%	3.72%	6.72	20.606 mg/kg	1294 mg/kg	49.372 mg/kg	5536 mg/kg	(Uzinger et al., 2021)
		-	-	-	-	-	77.42 mg/L	0.08	(Buligon et al., 2023)
		-	-	-	4.16%	0.55%	6.46%	1.78	(Cristina et al., 2019)
		28.6%	3.4%	-	2.7%	0.7%	4.6%	0.9%	(Wang and Lee, 2021)
2.	Compost	19.1	2.19	8.72	11.582	4906	45.536	6387	(Uzinger et al., 2021)
		60.8%	-	-	17460 ppm	760 ppm	7630 ppm	1050 ppm	(Casado-Vela et al., 2006)
		-	13.9 g/kg	12.0	12.3 g/kg	6.0	19.4	5.2	(Silva et al., 2023)
		34.0%	4.1%	8.4	28.0	3.55 g/kg	54.50	7.2	(Malinska et al., 2016)
3.	Vermicompost	21.9	3.13	7.00	24.139	1719	56.587	6155	(Uzinger et al., 2021)
		-	-	-	29.5%	3.57	52.00	6.1	(Malinska et al., 2016)
		26.3%	2.7%	9.7	29.5	3.57	52.00	6.1 g/kg	(Malinska et al., 2016)
		-	-	-	46.7	4.9	47.6	24.5	(Suthar, 2009)
		-	-	-	1.22%	1.57%	-	241.4 mg/kg	(Banda et al., 2023)
		-	-	-	12.94	6.84	59.1	13.9%	(Amouei et al., 2017)
4.	Biochar	-	61,200 mg/kg	-	38800 mg/kg	7470 mg/kg	-	-	(Yuan et al., 2016)
		18.9	2.7	7.00	54.1	9.21	8.27	0.94	(Anna et al., 2015)
		21.5	5.4	3.98	42.6	2.1	8.1	8.2	(Lu et al., 2013)
		17.1	6.2	2.76	10.4	2.25	5.33	1.35	(Zhang et al., 2015)

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to ensure its safe and profitable agricultural use. The digestate contains a lot of organic matter in addition to nutrients. This ecosystem improves soil structure by increasing aggregation, improving drainage, and reducing soil erosion. Correspondingly increases the soil's facility to hold water, providing enough water for plants to absorb. In addition, organic matter in digestate serves as a food basis for favorable soil microorganisms, providing microbial activity that supports overall soil health and nutrient cycling (Slepetiene et al., 2020; Wang et al., 2023).

Compost gained from SS composting exhibits many beneficial properties. Firstly, it is richer in organic-matter, which increases soil-structure and improves moisture holding-capacity for better water retention and reduces soil erosion, compost also helps to provide macro and micro nutrients to agricultural soils, such by way of potassium, phosphorus, and nitrogen which are gradually released and acquired by plants over period, the slower discharge characteristic of nutrients reduces the risk of nutrient leaching and runoff, increases nutrient uptake efficiency is improved and environmental impact is reduced (Ahmad et al., 2023; Sayara et al., 2020). These microorganisms available in the compost show a significant part in improving soil health, nutrient cycling, better agricultural productivity and preventing plant diseases (Lucchetta et al., 2023).

Vermicomposting exhibits several desirable characteristics, in addition rich in organic matter, humus, and advantageous microbes, which support increased fertility and soil health. The nutrient content includes essential elements such as potassium, phosphorus, and nitrogen, in addition to this micro-nutrients, which are available in freely accessible arrangements for plant-uptake (Katiyar et al., 2023). First, it increases soil-structure, rises water-holding-capacity, and develops aeration. This decreases soil-erosion, improves root growth, and improves plant growth. Vermicompost increases nutrient availability and nutrient utilization efficiency, thereby improving agricultural crop yield, quality, and resilience to environmental stressors (Pathma and Sakthivel, 2012). Furthermore, Vermicompost enhances soil microbial activity and diversity. The existence of beneficial microbes such as actinomycetes, bacteria, and fungi subsidizes nutrient cycling, prevents plant diseases, and improves overall soil health.

Biochar obtained from SS is very useful for soil-fertility development and nutrient-cycling. It has a high carbon content and porous structure, making it great for nutrient retention and microbial colonization. The porosity of biochar rises the water holding-capacity and improves the water content of the soil. Additionally, the alkaline nature of biochar can help to modify soil pH, creating favorable conditions for plant-growth (Bolan et al., 2023; Gryta et al., 2024; Khan et al., 2024). The use of sewage sludge-derived biochar offers many agricultural and environmental benefits. First, biochar sequesters carbon, capturing CO_2 from the atmosphere and storing it more efficiently. This supports alleviate climate-change by decreasing greenhouse gas emissions (GHGs). It increases nutrient retention and reduces nutrient absorption, improves nutrient utilization, and reduces nutrient requirements (Bo et al., 2023; Li and Tasnady, 2023). Biochar also promotes soil health by supporting beneficial microbial activity and improves agricultural productivity.

8. Challenges and future prospects

Several challenges are besides being confronted with using sewage sludge. Abundance and availability of sewage sludge, the make-up of digestate, compost, vermicompost and biochar, and convenience of sewage sludge are the aspects that disturb the end product yield centered on the raw materials and its nutrients and heavy metal constituents. For the complete usage of the sewage sludge obtained from numerous industries, some of the challenges have to be met by some cutting-edge approaches (anaerobic digestion, composting, vermicomposting, and pyrolysis). For the proficient transformation of sewage sludge into (digestate, compost, vermicompost, and biochar), primary treatment of sewage sludge has to be accomplished with cutting-edge concoction approaches.

The proficient interruption of sewage sludge into diverse constituents is also an inspiring aspect to deliberate for enlightening (digestate, compost, vermicompost, and biochar) yield. The utilization of numerous new cradles of sludge waste from numerous industries stimulates value added end products productivity very effectively. It correspondingly diminishes the global concerns and negative impacts instigated by waste generation. Further, by using the approaches stated above, the global productivity and economic status of the world of value added products for agricultural application can remain upgraded.

Emerging economically feasible treatment approaches with progressive methods may benefit in the massive output in the near future. Microbial advancements at the genetic level might similarly elevate value-added end product productivity with the assistance of genetically modified microorganisms specifically for the practices such as anaerobic digestion, composting, vermicomposting. Progressive approaches with invention approaches, be able to diminish the budget and progress the productivity prominent to an advantage in the field of value added product making with environmentally friendly sludge recycling practices.

9. Conclusion

This inclusive review offers a detailed summary of the utilization of value added end products for agricultural applications made from sewage sludge waste in sludge and environmental management applications. The alteration of sewage sludge waste to value added end products by utilizing the practices (anaerobic digestion, composting, vermicomposting, and pyrolysis) deals a result for decreasing the waste capacity drastically and creation of possibly valued end products (digestate, compost, vermicomposting, and biochar) for various agricultural applications. The major objective of this comprehensive review was to offer an outline of the various production practices, value added end products, agricultural and soil amendment beneficiation with pros, cons and limitations were also discussed in detail. Finally, the manufacture of value added end products from sewage sludge waste is very possible from a cost-effective point of observation; since the feedstock is discarded industrial waste and, which is plentifully existing all over the domain; from this study, we diminish the industrial waste capacity then harvest the value addition end products and offer contamination free environment to the public. Lastly, the financial feasibility of manufacturing value added products from sludge waste on an industrial scale needs to remain assessed and evaluated further usually in the circumstance of sustainability trials.

Authors contributions

The authors confirm the review study design and conception: Abas, Tesfaye, Jayakumar, Workisa; data collection: Abas; analysis and interpretation of results: Tesfaye. The draft manuscript preparation and results were evaluated by all authors, and the final version of the manuscript was approved.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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