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REVIEW ARTICLE

Municipal sludge as soil amendment for flower crop growth: Insights into the current situation and potential challenges

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Abstract

The utilization of treated municipal sludge or biosolids, as an organic soil enhancer has garnered significant interest for its potential to enhance soil quality and plant growth. The use of treated sludge as an amendment is seen as a viable method for waste disposal and soil improvement. The impact of sludge applications on soil properties, microbiome and flower crop growth and yield depends on factors such as sludge composition, application rates and specific plant species. Safety concerns regarding contaminants such as heavy metals, pathogens and organic pollutants have raised questions about practical application, especially in flower crop cultivation. Despite its potential benefits, challenges like insufficient infrastructure, regulatory awareness and risks of improper handling hinder widespread adoption of municipal sludge as a flower crop soil amendment. Yet, ensuring proper treatment processes and adherence to regulatory guidelines is vital to mitigate potential risks. This review provides an overview of the current status and potential challenges related to the usage of municipal sludge as a soil amendment for flower crops. Addressing these challenges necessitates enhanced sludge management, infrastructure investment and sustainable integrated strategies. Continuous research is crucial to optimize treatment, create value-added products and understand long-term impacts of sludge on soil and environmental sustainability in flower crops.

Keywords: biosolids; environmental impacts; flower crops; municipal sludge; organic fertilizer

Introduction

Municipal sewage sludge refers to the residual, semi-solid material left over from industrial wastewater or sewage treatment processes (1). It is predominantly composed of organic matter, microorganisms that aid wastewater treatment and residual heavy metals or contaminants (2). Rapid global urbanization over the past century has concentrated the generation of domestic and industrial wastewater into centralized sewage collection channels, resulting in exponentially increasing volumes of biosolids or sewage sludge, which require sustainable handling (3). Over 70 % of the world's population is expected to reside in cities by 2050 due to expanding urbanization across the globe, imposing enormous pressure on centralized wastewater treatment systems to keep up with increasing rates of municipal waste generation (4). Historically, landfill disposal has been the primary strategy for municipalities to eliminate sewage sludge waste (3). However, when this sludge is treated, it becomes a source of potentially usable nutrients for crop production and helps reduce environmental hazards (5).

Since it has been shown in numerous peer-reviewed studies worldwide to have inherent soil-conditioning properties and to be a cost-effective way to improve physical, chemical and biological indicators of soil quality, the idea of recycling dried and treated organic matter from sewage sludge and spreading it onto farmland soils has persisted for decades (6). Sewage sludge contains all essential plant macronutrients-nitrogen (N), phosphorus (P) and potassium (K) required for growth (7). It also supplies valuable organic matter that enhances soil structure and water retention (6). When applied appropriately, municipal sludge can improve physiochemical properties of nutrient-deficient soils and provide necessary nutrients to meet crop demands (8). Beyond environmental advantages, municipal sludge fertilization reduces farmer expenditures on commercial inorganic fertilizers. Overall, with proper treatment and careful management, applying treated sewage sludge to agricultural land offers an economically and environmentally sound alternative to traditional sludge disposal practices (9). The sustainable recycling pathway of municipal sewage sludge from households to agricultural use is illustrated in Fig. 1.

Ornamental horticulture, encompassing the cultivation of plants for aesthetics, is a major agricultural industry globally. Key ornamental crop categories include cut flowers, potted flowering/foliage plants, bedding/garden plants and cut cultivated greens.

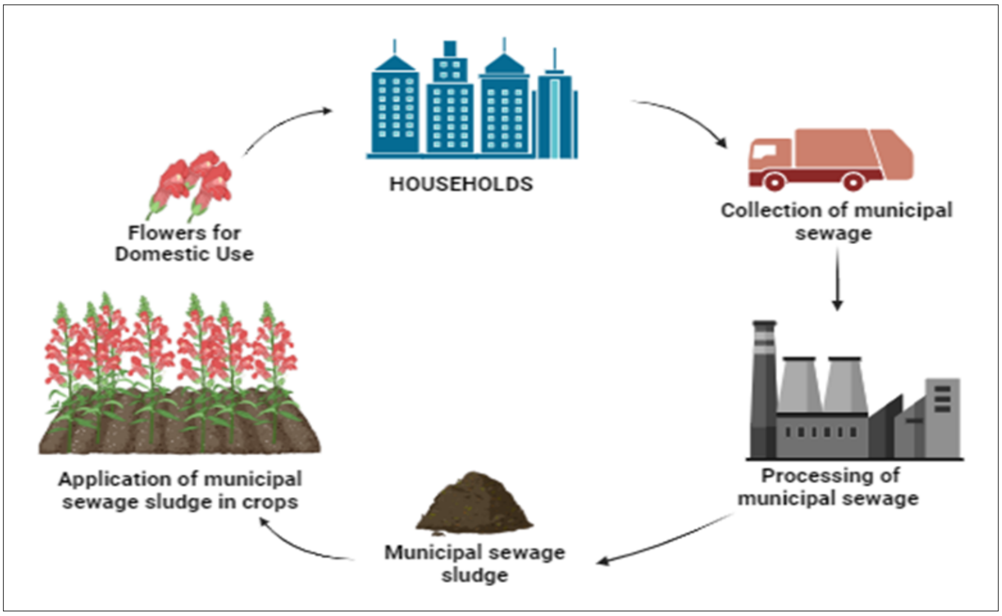

Fig. 1. Flushing to Flourishing cycle of municipal sewage sludge.

These high-value specialty crops require significant fertilizer inputs to achieve maximum yields and quality (10). The effects of organic waste fertilizers like municipal sludge on ornamental crop productivity are not as extensively studied as those on field crops. However, evidence suggests that municipal sludge can adequately meet nutritional requirements of ornamentals if nutrients are available for plant uptake when demand peaks (11). Flower crops, particularly cut flowers, are an important segment of the horticulture industry and ensuring their optimal growth and yield while maintaining environmental sustainability is crucial (12). More research continues to emerge on the efficacy of municipal sludge as an organic fertilizer for ornamental flower crops.

This paper reviews existing literature examining the impacts of treated municipal sludge fertilization on growth and yield parameters of key flower crops. Factors affecting crop response to municipal sludge fertilization are discussed, including differences in sludge treatment methods, application rates and nutrient bioavailability issues. When properly treated and applied, sludge amendments can improve the physical, chemical and biological properties of soils. Several studies have evaluated the effects of treated sludge applications on soil properties as well as crop growth and yield for food crops (13). This review summarizes current knowledge, trends and areas requiring further study on the use of recycled municipal sludge fertilizers in ornamental horticultural systems.

Trends in municipal sludge production and management

Global urban population growth demands sustainable management of sewage sludge volumes. Over seventy million tons of dry municipal sludge are anticipated to be generated annually worldwide by 2030, a 63 % increase from 2010 (14). According to the Central Pollution Control Board (CPCB), India generates approximately 39000 metric tons of dry sewage sludge per day from urban areas (15). The sludge generation rate is projected to increase to around 61000 metric tons per day by 2051 (16). Only about 19 % of the sewage treatment plants in India have dedicated sludge treatment facilities (15). Land application of treated sludge is considered a viable option for disposal and soil conditioning in India. The Ministry of Environment, Forest and Climate Change (MoEFCC) has issued guidelines for the utilization of sewage sludge on land (17). The Solid Waste Management Rules, 2016, provide guidelines for the management and disposal of sewage sludge in India (18).

Municipal sludge composition

Sewage sludge composition varies significantly depending on the source inputs to municipal wastewater treatment plants (Fig. 2). However, typical U.S. processed municipal sludge generally contain nutrients essential for plant growth (Table 1). On average, sludge consists of 40 %-60 % organic matter, supplying valuable soil amendments upon decomposition (19). Major plant nutrients-nitrogen, phosphorus and potassium-are present at average concentrations around 2 %-6 % for nitrogen and 0.5 %-1.5 % each for phosphorus and potassium (20). Micronutrients such as calcium, magnesium, iron and manganese are also supplied. Trace amounts of other elements may exist as contaminants depending on industrial inputs to the source wastewater (21).

Heavy metal contaminants are a key area of concern for land application of sewage sludge (22). Municipal and industrial discharges contribute metals such as zinc, copper, nickel, cadmium, lead and chromium to wastewater streams (23). Under the U.S. Environmental Protection Agency (EPA) 503 regulations, these heavy metals cannot accumulate above defined ceiling concentrations for sludge approved for land application (24). Still, repeated applications may gradually increase metal levels in agricultural soils to potentially phytotoxic levels that negatively impact crop growth (25). Careful soil monitoring is necessary with the long-term use of municipal sludge fertilizers. Organic compounds are another emerging sludge contaminant class garnering research attention (26). Although sewage sludge treatment significantly reduces pathogen loads, vigilant control of microbial contaminants is also required when applying sludge fertilizers in agriculture (27).

Overall, the exact nutritional value and contamination risk of any municipal sludge depend heavily on wastewater source inputs and treatment methods used at individual facilities (28). Understanding sludge properties is essential for developing appropriate management plans that match application rates to local crop and soil conditions (29). Testing of nutrient levels should be standard for optimizing municipal sludge application in agriculture.

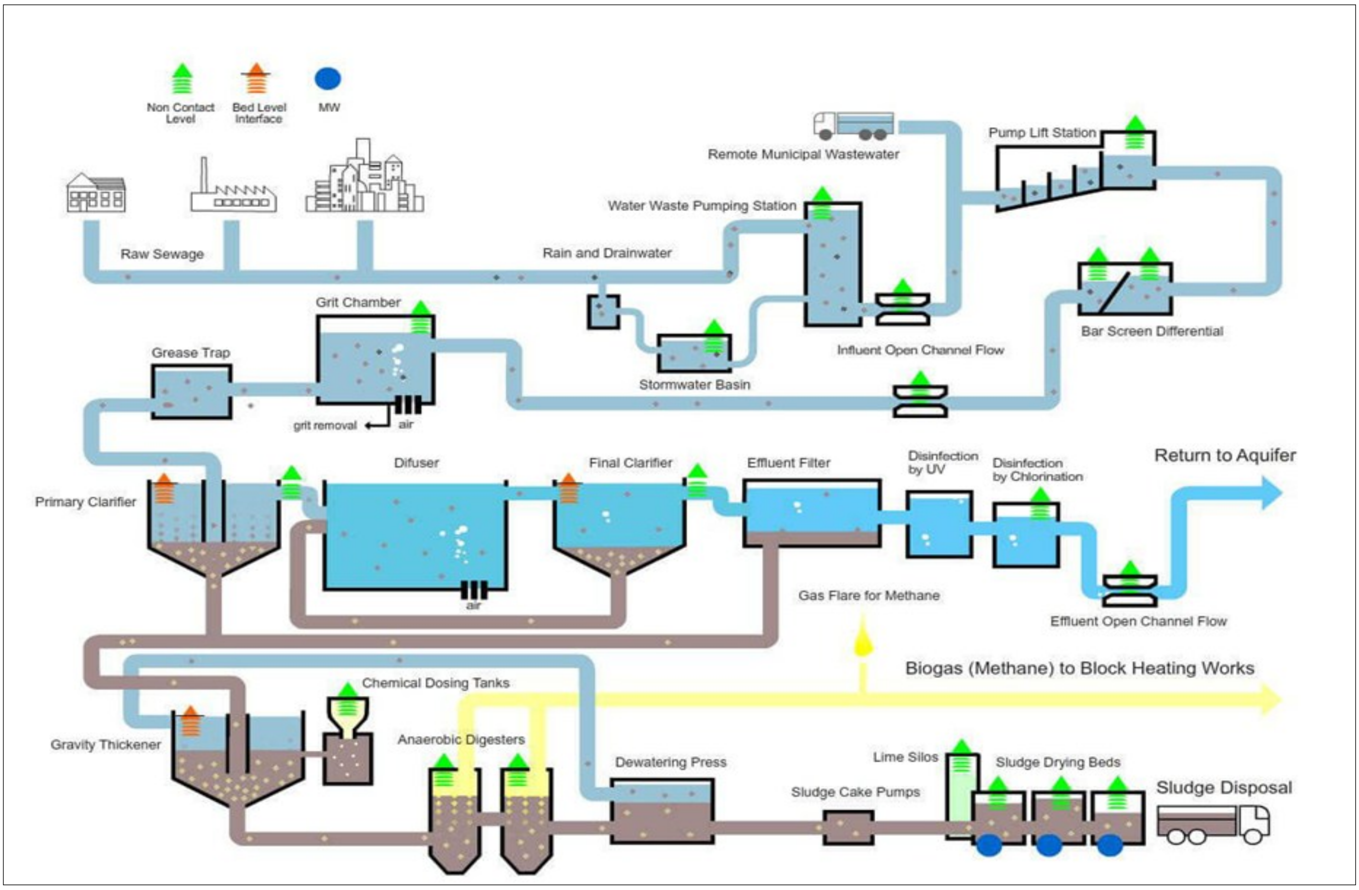

Fig. 2. Composting municipal sludge.

Table 1. Typical nutrient ranges in Indian municipal sludges from various sources (19)

Nutrient	Typical concentration range
Organic Matter	40-70 %
Nitrogen	2.35-4.2 %
Phosphorus	2.46-3.2 %
Potassium	0.83-1.24 %
Calcium	0.5-3.5 %
Magnesium	0.5-1 %
Sulfur	0.5-1 %
Iron	3000-15000 ppm
Manganese	75-750 ppm
Zinc	575-1732 ppm
Copper	9.3-524ppm
Lead	8.8-275.2 ppm
Chromium	7.5-170.0 ppm
Cadmium	0.6-9.5 ppm
Mercury	0-3.8 ppm

Municipal sludge treatment methods

Municipal sewage sludge requires treatment using standardized processes to reduce pathogens and pollutants to safe levels for land application. Common sludge stabilization methods include anaerobic digestion, aerobic digestion, composting, alkaline treatment and drying (30). These processes involve the use of high temperatures, microbial decomposition of organic compounds, pH adjustments and/or moisture reduction to dissolve, decompose or kill pathogens and reduce vector attraction (31). Treatment is tailored at individual facilities to meet contaminant reduction requirements based on intended sludge disposal strategies (32). The treatment method significantly impacts finished sludge fertilizer properties such as pH, organic matter breakdown rate and nutrient availability (33).

Composting accelerates organic matter stabilization, yielding a stabilized final product for immediate nutrient release. In contrast, applying dewatered but otherwise raw sludge may require months for organic compounds to fully decompose before nutrients like nitrogen become plant available. Anaerobically digesting sludge also enhances immediate nutrient availability for crops compared to undigested cake sludge (34). Considering the effects of stabilization processes helps optimize coordination of nutrient mineralization rates with crop demands (35). Beyond altering nutrient profiles, higher treatment intensities can also further reduce pathogen loads and contaminants in finished municipal sludge fertilizers (36). However, increased processing requires additional expenditure, which individual utilities weigh against contamination risks based on the characteristics of their wastewater sources (37). Table 2 provides information on the type of treated sludge used in each study, along with their advantages and disadvantages.

Overall, treatment processes adjust the degrees of municipal sludge stabilization and pathogen/pollutant reduction to create finished products suitable for different disposal options (43). All recycling of sewage sludge for land application as fertilizer requires some form of treatment to satisfy health and environmental regulations (44). Managing application rates and timing based on chosen sludge stabilization methods allows for matching nutrient availability from these organic fertilizers with crop growth stage needs (45). Further advances improving stabilization or contaminant removal may support expanding agricultural uses for municipal sludge fertilizers.

Table 2. Type of treated sludge and their advantages and disadvantages

Method	Advantages	Disadvantages	References
Anaerobic digestion	Produces biogas (methane) as a renewable energy source Reduces sludge volume and pathogen content Low energy consumption	Long retention times Requires strict environmental conditions (pH, temperature, etc.) Potential odor issues	(38)
Aerobic digestion	Faster stabilization process Produces a well-stabilized sludge product Lower odor potential	Higher energy consumption Larger reactor volumes required Potential for excessive foaming	(39)
Composting	Produces a useful soil amendment Reduces sludge volume Relatively simple process	Potential odor issues Requires bulking agents Potential for pathogen regrowth if not managed properly	(40)
Thermal drying	Significant volume reduction Produces a dry, easily transportable product Pathogen destruction	High energy consumption Potential for air emissions Capital-intensive process	(41)
Land application	Recycles nutrients to soil Low-cost option Relatively simple process	Potential for groundwater contamination Odor issues Public perception concerns	(42)

Effect of treated municipal sludge on soil amendments

Treated municipal sludge, as a soil amendment, can positively impact soil properties and microbiome. Its organic matter content improves soil structure, enhancing water retention and nutrient availability. The sludge's nutrients, such as nitrogen, phosphorus and potassium, benefit plant growth. Furthermore, it fosters microbial activity, which is crucial for nutrient cycling and soil health. However, improper application may lead to the accumulation of heavy metals or pathogens, negatively affecting soil and plant health. Therefore, it is essential to follow guidelines for safe application.

Influence on soil properties

When applied appropriately, municipal sludge amendments can significantly improve soil physical, chemical and biological properties. However, excessive loading rates pose contamination and phytotoxicity risks, warranting close monitoring (46). Understanding the impacts on soil quality indicators is key to sustainable land application programs. Organic matter additions from sludge facilitate binding between soil particles, enhancing aggregation, moisture retention and permeability (6). Favorable changes in pore sizes and volumes have been measured in amended soils. However, high application levels can increase compaction risks over time (47). The application of biosolids has been shown to increase soil pH in acidic soils and decreased pH in alkaline soils, bringing the soil pH closer to neutral levels (13). Treated municipal sludge is rich in organic matter, which can improve soil structure, water-holding capacity and nutrient availability. The application of biosolids has been reported to increase soil organic carbon content by up to 40 % compared to control soils (26). Biosolids contain essential plant nutrients such as nitrogen, phosphorus and potassium, as well as micronutrients like zinc, copper and iron. The application of biosolids also increased soil nutrient levels, resulting in higher crop yields (48). Untreated or improperly treated sludge may contain heavy metals like lead, cadmium and mercury, which can accumulate in the soil and potentially pose risks to human health and the environment (49). Table 3 provides details on the impact of soil amendments on growth of flower crops.

Effects on soil microbiome

With extremely high densities and diversity of both non-pathogenic and pathogenic microorganisms, municipal sewage sludge carries implications for indigenous soil microbial communities upon amendment. Elucidating the persistence, activity and intricate food web interactions of introduced sludge bacteria and fungi continues to be an active research area with important biosecurity implications.

Table 3. Impact of soil amendments on yield and quality of flower crops

Soil property	Effect on soil property	Impact on flower crop growth	Reference
Nutrient content	Increased availability of nutrients like nitrogen, phosphorus and potassium	Improved plant growth, biomass accumulation, flower yield and quality in roses and chrysanthemums	(50, 51)
Organic matter	Improved soil structure, water-holding capacity and cation exchange capacity	Enhanced root growth, nutrient uptake and yield in cut-flower roses and petunia	(52)
Soil ph	Slightly alkaline pH from sludge may affect nutrient availability and microbial activity	Potential impact on nutrient uptake and plant growth, depending on the crop species and soil conditions	(53)
Electrical conductivity (ec)	Increased EC due to salt content in sludge	Reduced plant growth and yield in sensitive flower crops like carnations and gerbera at high EC levels	(54)
Heavy metal accumulation	Accumulation of heavy metals like cadmium, lead and mercury in soil and plant tissues	Phytotoxicity, reduced growth and potential entry into the food chain for edible flowers	(55)
Soil microbial community	Changes in diversity and composition of bacteria, fungi and other microorganisms	Potential impacts on nutrient cycling, disease suppression and plant growth promotion processes	(56)
Soil physical properties	Improved soil structure, aggregation and water-holding capacity	Better root growth, nutrient uptake and water availability for flower crops	(57)

Shifts in microbial community structure

Culture-independent DNA sequencing has revealed significant but transient impacts of sewage sludge amendment on the taxonomic structure of native soil microbiomes (58). The magnitude of the observed community shifts tends to scale with the loading rate but also depends on soil type, climate and land use history. Key bacterial phyla enriched post-amendment include Actinobacteria, Proteobacteria, Firmicutes and Bacteroidetes, while Ascomycota fungi frequently increase under nutrient-rich conditions created by sludge incorporation (59).

Functional diversity and ecosystem services

While species identities fluctuate, meta-analysis results indicate that microbial functional diversity in sludge-amended soils changes minimally over multiple growing seasons (59). Core ecosystem services like carbon cycling and contaminant degradation are largely unaffected in the long-term, given the functional redundancy inherent to most soils (58). However, examining broad phylogenetic marker genes likely overlooks dynamics among rare biota responsible for specialized processes that are undetectable through bulk community analysis.

Persistence of potential pathogens

Disease-causing bacteria, viruses, protozoa and helminths originating in untreated human and industrial wastes can survive conventional municipal sludge treatment processes, raising biosecurity concerns for agricultural land use (60). Typical regulatory approaches focus on monitoring model faecal-indicator microbes and regulating application timing to minimize food crop contamination. However, our understanding of the environmental fate and transport mechanisms for emerging water- and vector-borne pathogens remains limited (61). Treated sludge residuals frequently harbour antibiotic resistance genes, which could spread via microbial horizontal transfer mechanisms as well (62).

Factors impacting crop response on application of treated municipal sludge

Many variables interact to determine crop growth and yield responses when substituting standard inorganic fertilizers with treated municipal sludge products. These factors range from sludge properties based on processing methods to local environmental and soil characteristics. Matching application rates and timing to specific crop demands is also essential for positive yield impacts (63). Understanding variables that impact sludge fertilizer efficacy aids designing optimal management plans.

Application rates significantly influence crop responses to municipal sludge fertilization. Under-fertilization risks nutrient deficiencies that reduce growth, while over-application may burn plants or leach nutrients, causing environmental damage (47). Accurately estimating plant available nutrients in sludge is challenging since mineralization from organics occurs gradually and depends on environment conditions (64). Most states provide guidelines for maximum annual or cumulative loading rates based on typical sludge nutrient composition to avoid toxicity (65). Controlled environment studies often test a wide dosage range to delineate rate effects. Overall, characterizing and adjusting application levels based on local sludge nutrient profiles is necessary to ensure sufficient availability without negative impacts from excess loading (66).

Single high rate sludge applications may supply adequate nutrition for a full cropping cycle or longer for some slow-release products (67). However, split applications can better synchronize nutrient availability with periods of peak demand, especially for highly stabilized sludge (68). Applying municipal sludge too early risks deficiencies during flowering or fruiting if nutrients become immobilize or leach before uptake (69). Research on optimizing application schedules for common municipal sludge stabilization processes would support more efficient use that meets ornamental crop requirements. Beyond rate and timing considerations, the choice of application method also impacts some specialty crops. Overall, many interacting agronomic factors must be strategically aligned based on municipal sludge properties and crop growth habits to achieve positive yield benefits from organic waste fertilization.

Soil characteristics constitute additional variables that modulate crop growth response to sludge fertilizers. Soil texture impacts sludge binding and permeability, affecting nutrient retention and loss pathways (70). Understanding local soil profile attributes provides necessary context for maximizing benefits and minimizing risks when applying municipal sludge as an organic nutrient source. Table 4 summarizes the factors impacting crop response to the application of treated municipal sludge

Finally, ambient environmental conditions interact with sludge fertilization impacts on ornamental crop yield. Climatic variables like precipitation, temperature, light intensity and wind speed affect plant growth directly, while also influencing soil moisture, aeration and inorganic nitrogen levels that mediate nutrient release rates from organic sludge fertilizers (75). Unusual weather patterns may create a typical responses to standard sludge management practices established from regional trials (76). Moreover, climate change shifts in environmental patterns could alter long term crop-sludge dynamics. There also exist potential ecosystem impacts of shifting nutrient cycling flows by recycling human biosolids through plants (77). Broad environmental interactions beyond simply supplementing crop fertility warrant continued holistic analysis for the sustainable application processed of processed municipal sludge organics as regenerative fertilizer inputs.

Table 4. The factors impacting crop response in the application of treated municipal sludge

Factor	Impact on flower crops	References
Nutrient content and availability	Biosolids provide essential nutrients like nitrogen,	(9)
Organic matter content	The organic matter in biosolids can improve soil	(12)
Heavy metal content	Flower crops can accumulate heavy metals	(71)
Pathogen content	Untreated or improperly treated biosolids may	(31)
Soil characteristics	Soil properties like pH, texture and cation	(72)
Crop type and growth stage	Different flower crop species and growth stages	(73)
Application rate and method	The rate and method of biosolids application can	(42, 74)
Environmental conditions	Temperature, rainfall and soil moisture can influence	(74)

Ornamental crop responses of treated municipal sludge application

Crop-specific controlled trials are necessary to validate the impacts on key productivity outcomes relative to standard practices before advising the broad sludge adoption. Ornamental crops encompass diverse varieties with unique growth habits, produced for aesthetic purposes rather than human consumption (78). Sludge fertilization consistently increases shoot heights, diameters, leaf areas and flowering in common annual and perennial bedding plants, potted ornamentals, cut flowers and greenery foliage (79). However, variability among species sensitivity to loading rates highlights the need for crop-specific calibration to avoid toxicity symptoms that negate growth gains (80). Phytotoxic accumulations of salts, ammonium or heavy metals manifest at different thresholds based on crop tolerance ranges (81). Strategies like alternating sludge with commercial fertilizers help dilute exposures while still reducing input costs (82). Further optimizing application rates and frequencies for key ornamental varieties would support the integration sludge into horticultural fertility programs. Table 5. provides the effects of municipal sludge fertilizers on ornamental crops.

Beyond direct yield indices like biomass and flower numbers, research also demonstrates that municipal sludge fertilization improves the efficiency of water and nutrient use (83). Water loss via transpiration and evaporation decreases per unit ornamental tissue growth or area, conserving irrigation resources (84). However, quantifying the exact economic or environmental sustainability gains from a municipal sludge fertilizer switch requires complete life-cycle assessments tracking costs, resource uses and emissions across the entire ornamental production chain (85). Integrating circular economy principles through recovering and recycling bio-waste nutrient sources like processed municipal sludge could provide meaningful progress towards the ecological intensification of specialty crop systems. Further research should analyse the full costs and benefits for nursery growers and the surrounding community.

Municipal sludge derived from human waste sources carries negative public perceptions regarding contaminants that require careful education and management to overcome (86). Approving usage on human food crops often requires higher treatment intensities and regulatory oversight compared to non-consumptive ornamental horticulture (87). However, observable tissue damage, chlorosis, stunted growth or leaf necrosis from inappropriate sludge applications or rates can devalue marketability similarly for both edible and ornamental crops, even if not directly hazardous to consumers (88). With proper treatment and control of application levels, municipal sludge products can serve as effective components of fertility programs for sustainable ornamental crop production.

Environmental considerations in application of treated municipal sludge

Soil contamination and odour issues

Municipal sludge may contain heavy metals (e.g. lead, cadmium and mercury), pathogens and organic contaminants (e.g. pharmaceuticals and personal care products) that can accumulate in the soil and potentially contaminate groundwater and surface water (13, 89). Despite secondary treatment, anaerobic digestion, composting and disinfection, municipal sludge retains higher contaminant levels than commercial inorganic fertilizers, which require control and monitoring during land application (32). Proper treatment and regulation of sludge quality are essential to minimize these risks. Untreated or improperly stabilized sludge may release offensive odors during land application, causing a nuisance to nearby communities (90).

Greenhouse gas emissions and nutrient loading

The decomposition of organic matter in sludge can release greenhouse gases like methane and carbon dioxide, contributing to climate change (91). Life-cycle assessments estimate that each metric ton of sludge applied to land preserves approximately 0.5 metric tons of carbon dioxide-equivalent emissions relative to traditional disposal methods and commercial nutrient replacements (92). Land application also constitutes a lower carbon strategy for municipalities compared to incineration and landfilling, depending on waste transportation distances (93).

Excessive application of sludge can lead to nutrient loading (e.g. nitrogen and phosphorus) in water bodies, causing eutrophication and algal blooms (94). Utilizing residual biosolids for crop fertility can substitutes for a portion of commercial inorganic fertilizers, reducing environmental impacts from manufacturing and transporting these synthetic inputs (95). Adhering to loading rate ceilings, soil concentration thresholds, crop restrictions, management practices and other safeguards helps mitigate health and ecological risks - which require continued vigilance with long term municipal sludge fertilizer usage (28).

Table 5. Effects of municipal sludge fertilizers on ornamental crops (50-52, 54)

Ornamental crop	Sludge treatment	Key effects on crop
Bedding plants	Composted	Increased growth indices; toxicity symptoms at high application rates
Potted ornamentals (*Spathiphyllum, Anthurium*)	Anaerobically digested	Enhanced flowering and biomass; optimal at moderate fertilization rates
Cut flowers (roses, gerbera, lilium)	Dried	Improved yield components; potential accumulation of Na, Cl, heavy metals
Landscape plants (trees, shrubs)	Composted with dairy manure	Increased growth indices; effective peat substitute in potting media
Orchids	Dewatered cake	Increased plant height, leaves, roots; higher spike counts
Chrysanthemums	Anaerobically digested	Increased yield, flower size and stem strength
Carnation	Pelletized	Enhanced productivity and postharvest quality
Gladiolus	Composted spikes	Augmented corms size, spikes
Tuberose	Raw sludge	Increased flowering traits
China aster	Vermicompost	Higher growth, yield parameters
Gerbera	Thermally dried	Improved vase life of cut flowers

Economic considerations in application of treated municipal sludge

Farmers also save costs compared to directly purchasing and applying comparable amounts of other organic amendments like animal manures. Municipal utilities can also reduce operational costs for wastewater treatment by hundreds of thousands to millions of dollars annually by recycling sludge as fertilizer instead of using landfills or incinerators (96). Indirect benefits like soil quality enhancement leading to higher crop productivity over subsequent seasons also accrue with municipal sludge land application (97). Overall, the reuse of human waste streams like treated municipal sludge to grow agricultural crops supports multiple sustainability goals if properly managed.

Transporting sludge from treatment facilities to application sites, along with the associated labor and equipment costs, can be significant, especially for long distances. Acquiring and managing land for sludge application, including site preparation, monitoring and maintenance, can be costly (98). Properly treated and processed biosolids can be sold or used as a soil amendment or fertilizer, generating revenue and offsetting some costs (99). Land application of biosolids can be more cost-effective than disposal methods like landfilling or incineration, depending on local regulations and transportation distances.

Proper treatment and stabilization of municipal sludge to meet regulatory standards can be costly, involving processes like anaerobic digestion, composting or thermal drying. Overall, the reuse of human waste streams like treated municipal sludge to grow agricultural crops supports multiple sustainability goals if properly managed.

Future outlook

Increased urbanization and global population growth will drive the demand for sustainable biosolids management solutions worldwide, fostering international collaboration and knowledge sharing (100). Strategic partnerships between municipal wastewater authorities and agricultural producers/retailers could promote the development of more extensive collection and distribution networks to increase accessibility to these organic fertility sources. Advances in treatment technologies may also further expand future reliance on municipal sludge fertilizers by reducing contaminants or improving stabilization. Emerging techniques like pyrolysis, wet oxidation and microwave irradiation offer the potential to reprocess residual sludge from initial treatments into safer biochar or activated carbon fertilizers. Combining composting with anaerobic digestion or chemical amendments may accelerate stabilization pathways as well.

Understanding public perceptions and developing educational communications is another avenue for facilitating adoption of municipal sludge fertilizers in agriculture. Strategic social marketing framed around resource efficiency and soil health may help overcome initial aversions. Demonstration sites displaying vigorous plant growth can also convince skeptics on performance when scientific testimonials fail.

Continuing research on maximizing agronomic efficiency and minimizing trade-offs will determine future roles for processed organic waste amendments in regenerative agriculture. Ornamental horticulture can provide initial niche markets for scaling reuse systems before expanding into crops directly supporting human nutrition. Scientifically aligning technological, environmental and social spheres will enable sustainable transitions for municipal sludge from discharged effluent back into living soils.

Conclusion

The application of treated municipal sludge, or biosolids, as an organic amendment in flower crop production offers both benefits and potential risks. On the positive side, biosolids are rich in essential nutrients like nitrogen, phosphorus and potassium, which can enhance the growth, flowering and yield of flower crops. Additionally, the organic matter content in biosolids can improve soil structure, water-holding capacity and cation exchange capacity, creating a favourable growing environment. However, the presence of heavy metals, pathogens and other contaminants in biosolids poses potential risks to flower crop quality, human health and the environment. To mitigate these risks and maximize the benefits, strict regulations, proper treatment processes and careful monitoring are crucial. Factors such as crop type, growth stage, application rate, method and environmental conditions also influence the effectiveness and the potential risks of biosolids application. Ultimately, while biosolids can be a valuable organic amendment for flower crop production, their use requires careful consideration, adherence to best management practices and a thorough understanding of the specific requirements and sensitivities of the flower crops being cultivated.

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Authors' contributions

ABA conducted literature search, analysed and interpreted the compiled information. RS conceptualized the review topic, provided guidance on the review process and approved the final manuscript. MG and SS critically reviewed the manuscript and approved the final manuscript. EP contributed to manuscript editing, summarization and revision and PM contributed to manuscript editing, summarization and revision. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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References

1. Tyagi VK, Lo S-L. Sludge: A waste or renewable source for energy and resources recovery? Renew Sustain Energy Rev. 2013;25:708–28. https://doi.org/10.1016/j.rser.2013.05.029

2. Kelessidis A, Stasinakis AS. Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries. Waste Manag. 2012;32(6):1186–95. https://doi.org/10.1016/j.wasman.2012.01.012

3. United Nations DESA. World urbanization prospects 2018: Highlights (ST/ESA/SER.A/421). New York: Department of Economic and Social Affairs, Population Division; 2019. https://population.un.org/wup/assets/WUP2018-Report.pdf

4. Di Costanzo N, Cesaro A, Di Capua F, Esposito G. Exploiting the nutrient potential of anaerobically digested sewage sludge: A review. Energies. 2021;14(23):8149. https://doi.org/10.3390/en14238149

5. Weber J, Karczewska A, Drozd J, Licznar M, Licznar S, Jamroz E, et al. Agricultural and ecological aspects of a sandy soil as affected by the application of municipal solid waste composts. Soil Biol Biochem. 2007;39(6):1294–302. https://doi.org/10.1016/j.soilbio.2006.12.005

6. Lamastra L, Suciu NA, Trevisan M. Sewage sludge for sustainable agriculture: Contaminants' contents and potential use as fertilizer. Chem Biol Technol Agric. 2018;5(1):1–6. https://doi.org/10.1186/s40538-018-0122-3

7. Antille DL, Sakrabani R, Tyrrel SF, Le MS, Godwin RJ. Characterization of organomineral fertilizers derived from nutrient-enriched biosolids granules. Appl Environ Soil Sci. 2013;2013:694597. https://doi.org/10.1155/2013/694597

8. Rigby H, Smith S. Nitrogen availability and indirect measurements of greenhouse gas emissions from aerobic and anaerobic biowaste digestates applied to agricultural soils. Waste Manag. 2013;33(12):2641–52. https://doi.org/10.1016/j.wasman.2013.08.005

9. Majsztrik J, Owen JS. Improving nutrient management in the cultivation of ornamental plants in greenhouse, container and field production. In: Achieving sustainable cultivation of ornamental plants. Burleigh Dodds Sci Publ; 2020. p. 279–302. https://doi.org/10.1201/9781003047766

10. Succop CE, Newman SE. Organic fertilization of fresh market sweet basil in a greenhouse. Hort Technology. 2004;14(2):235–9. https://doi.org/10.21273/HORTTECH.14.2.0235

11. Byczynski L. The flower farmer: An organic grower's guide to raising and selling cut flowers. Chelsea Green Publ; 2008.

12. Singh R, Agrawal M. Potential benefits and risks of land application of sewage sludge. Waste Manag. 2008;28(2):347–58. https://doi.org/10.1016/j.wasman.2006.12.010

13. UN Water. Wastewater management: a UN-water analytical brief. New York; 2015.

14. CPCB. Inventorization of sewage treatment plants. Central Pollution Control Board, New Delhi; 2015.

15. Kamyotra J, Bhardwaj R. Municipal wastewater management in India. India Infrastructure Report. 2011;299.

16. Shende A, Pophali G. Sewage and faecal sludge management: revisiting discharge standards in India. Int J Environ Sci Technol. 2023;20(11):12793–806. https://doi.org/10.1007/s13762-022-04688-6

17. Bhave P, Sadhwani K. Solid waste management legislation: A review. Envtl Pol'y & L. 2016;46:168.

18. Hung Y-T, Wang LK, Shammas NK. Handbook of environment and waste management: air and water pollution control. World Scientific; 2012.

19. Singh V, Phuleria HC, Chandel MK. Unlocking the nutrient value of sewage sludge. Water Environ J. 2022;36(2):321–31. https://doi.org/10.1111/wej.12739

20. Jamali M, Kazi T, Arain M, Afridi H, Jalbani N, Memon A. Heavy metal contents of vegetables grown in soil irrigated with mixtures of wastewater and sewage sludge in Pakistan using ultrasonic-assisted pseudo-digestion. J Agron Crop Sci. 2007;193(3):218–28. https://doi.org/10.1111/j.1439-037X.2007.00261.x

21. Zielińska A, Oleszczuk P, Charmas B, Skubiszewska-Zięba J, Pasieczna-Patkowska S. Effect of sewage sludge properties on the biochar characteristic. J Anal Appl Pyrolysis. 2015;112:201–13. https://doi.org/10.1016/j.jaap.2015.01.025

22. Sharma B, Sarkar A, Singh P, Singh RP. Agricultural utilization of biosolids: a review on potential effects on soil and plant growth. Waste Manag. 2017;64:117–32. https://doi.org/10.1016/j.wasman.2017.03.002

23. Smith SR. A critical review of the bioavailability and impacts of heavy metals in municipal solid waste composts compared to sewage sludge. Environ Int. 2009;35(1):142–56. https://doi.org/10.1016/j.envint.2008.06.009

24. Mantovi P, Baldoni G, Toderi G. Reuse of liquid, dewatered and composted sewage sludge on agricultural land: Effects of long-term application on soil and crop. Water Res. 2005;39(2–3):289–96. https://doi.org/10.1016/j.watres.2004.10.003

25. Zhang Y, Banks CJ, Heaven S. Co-digestion of source segregated domestic food waste to improve process stability. Bioresour Technol. 2012;114:168–78. https://doi.org/10.1016/j.biortech.2012.03.040

26. U.S. Environmental Protection Agency. Environmental regulations and technology: Control of pathogens and vector attraction in sewage sludge. Cincinnati (OH): USEPA; 2003.

27. Nkoa R. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: A review. Agron Sustain Dev. 2014;34:473–92. https://doi.org/10.1007/s13593-013-0196-z

28. Guo L, Wu G, Li Y, Li C, Liu W, Meng J, et al. Effects of cattle manure compost combined with chemical fertilizer on topsoil organic matter, bulk density and earthworm activity in a wheat–maize rotation system in eastern China. Soil Tillage Res. 2016;158:1–9. https://doi.org/10.1016/j.still.2015.10.010

29. Subramanian S, Kumar N, Murthy S, Novak JT. Effect of anaerobic digestion and anaerobic/aerobic digestion processes on sludge dewatering. J Residuals Sci Technol. 2007;4:17–23.

30. Cheraghi M, Motesharezadeh B, Alikhani HA, Mousavi SM. Optimal management of plant nutrition in tomato (Lycopersicon esculentum Mill.) by using biologic, organic and inorganic fertilizers. J Plant Nutr. 2023;46(8):1560–79. https://doi.org/10.1080/01904167.2022.2092511

31. Lang NL, Smith SR. Influence of soil type, moisture content and biosolids application on the fate of Escherichia coli in agricultural soil under controlled laboratory conditions. J Appl Microbiol. 2007;103(6):2122–31. https://doi.org/10.1111/j.1365-2672.2007.03490.x

32. Moldes A, Cendon Y, Barral MT. Evaluation of municipal solid waste compost as a plant growing media component by applying mixture design. Bioresour Technol. 2007;98(16):3069–75. https://doi.org/10.1016/j.biortech.2006.10.021

33. Hong J, Hong J, Otaki M, Jolliet O. Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan. Waste Manag. 2009;29(2):696–703. https://doi.org/10.1016/j.wasman.2008.03.026

34. Lowman A, McDonald MA, Wing S, Muhammad N. Land application of treated sewage sludge: community health and environmental justice. Environ Health Perspect. 2013;121(5):537–42. https://doi.org/10.1289/ehp.1205470

35. Liang Y, Si J, Nikolic M, Peng Y, Chen W, Jiang Y. Organic manure stimulates biological activity and barley growth in soil subject to secondary salinization. Soil Biol Biochem. 2005;37(6):1185–95. https://doi.org/10.1016/j.soilbio.2004.11.017

36. Mabrouk O, Hamdi H, Sayadi S, Al-Ghouti MA, Abu-Dieyeh MH, Zouari N. Reuse of sludge as organic soil amendment: insights into the current situation and potential challenges. Sustainability. 2023;15(8):6773. https://doi.org/10.3390/su15086773

37. Tsadilas C, Mitsios I, Golia E. Influence of biosolids application on some soil physical properties. Commun Soil Sci Plant Anal. 2005;36(4–6):709–16. https://doi.org/10.1081/CSS-200043350

38. Appels L, Baeyens J, Degrève J, Dewil R. Principles and potential of the anaerobic digestion of waste-activated sludge. Prog Energy

Combust Sci. 2008;34(6):755–81. https://doi.org/10.1016/j.pecs.2008.06.002

39. Tchobanoglous G, Burton F, Stensel HD. Wastewater engineering: Treatment and reuse. Am Water Works Assoc J. 2003;95(5):201.

40. Haug RT. The practical handbook of compost engineering. Routledge; 2018. https://doi.org/10.1201/9780203736234

41. Bennamoun L, Arlabosse P, Léonard A. Review on fundamental aspects of the application of drying process to wastewater sludge. Renew Sustain Energy Rev. 2013;28:29–43. https://doi.org/10.1016/j.rser.2013.07.043

42. Lu Q, He ZL, Stoffella PJ. Land application of biosolids in the USA: A review. Appl Environ Soil Sci. 2012;2012:201462. https://doi.org/10.1155/2012/201462

43. Pan M, Yau PC, Lee KC, Zhang H, Lee V, Lai CY, et al. Nutrient accumulation and environmental risks of biosolids and different fertilizers on horticultural plants. Water Air Soil Pollut. 2021;232(12):480. https://doi.org/10.1007/s11270-021-05424-5

44. Chaudri AM, Allain CM, Badawy SH, Adams ML, McGrath SP, Chambers BJ. Cadmium content of wheat grain from a long-term field experiment with sewage sludge. J Environ Qual. 2001;30(5):1575–80. https://doi.org/10.2134/jeq2001.3051575x

45. Gómez-Silván C, Andersen GL, Calvo C, Aranda E. Assessment of bacterial and fungal communities in a full-scale thermophilic sewage sludge composting pile under a semipermeable cover. Bioresour Technol. 2020;298:122550. https://doi.org/10.1016/j.biortech.2019.122550

46. Major N, Schierstaedt J, Jechalke S, Nesme J, Ban SG, Černe M, et al. Composted sewage sludge influences the microbiome and persistence of human pathogens in soil. Microorganisms. 2020;8(7):1020. https://doi.org/10.3390/microorganisms8071020

47. Viau E, Peccia J. Survey of wastewater indicators and human pathogen genomes in biosolids produced by class A and class B stabilization treatments. Appl Environ Microbiol. 2009;75(1):164–74. https://doi.org/10.1128/AEM.01331-08

48. Oun A, Kumar A, Harrigan T, Angelakis A, Xagoraraki I. Effects of biosolids and manure application on microbial water quality in rural areas in the US. Water. 2014;6(12):3701–23. https://doi.org/10.3390/w6123701

49. Zhang W, Yang P, Yang X, Chen Z, Wang D. Insights into the respective role of acidification and oxidation for enhancing anaerobic digested sludge dewatering performance with Fenton process. Bioresour Technol. 2015;181:247–53. https://doi.org/10.1016/j.biortech.2015.01.003

50. G El-Alsayed S, M Ismail S. Impact of soil amendments and irrigation water on growth and flowering of Rosa plant grown in sandy soil Rosa hybrida. Alexandria Sci Ex J. 2017;38:626–41. https://doi.org/10.21608/asejaiqjsae.2017.4058

51. AL-Huqail AA, Kumar P, Abou Fayssal S, Adelodun B, Širić I, Goala M, et al. Sustainable use of sewage sludge for marigold (*Tagetes erecta* L.) cultivation: Experimental and predictive modeling studies on heavy metal accumulation. Horticulturae. 2023;9(4):447. https://doi.org/10.3390/horticulturae9040447

52. Dubey R, Simrat-Singh, Kukal S, Kalsi H. Evaluation of different organic growing media for growth and flowering of petunia. Comm Soil Sci Plant Anal. 2013;44(12):1777–85. https://doi.org/10.1080/00103624.2013.790398

53. Oleszczuk P. Phytotoxicity of municipal sewage sludge composts related to physico-chemical properties, PAHs and heavy metals. Ecotoxicology and Environmental Safety. 2008;69(3):496–505. https://doi.org/10.1016/j.ecoenv.2007.04.006

54. Ali IA, Hassan SE, Abdelhafez AA, Hewidy M, Nasser MA, Saudy HS, et al. Modifying the growing media and biostimulants supply for healthy gerbera (*Gerbera jamesonii*) flowers. Gesunde Pflanzen. 2023:1–9. https://doi.org/10.1007/s10343-023-00943-z

55. Leoni B, Loconsole D, Cristiano G, De Lucia B. Comparison between chemical fertilization and integrated nutrient management: Yield, quality, N, and P contents in Dendranthema grandiflorum (Ramat.) Kitam. cultivars. Agronomy. 2019;9(4):202. https://doi.org/10.3390/agronomy9040202

56. Nair A, Ngouajio M. Soil microbial biomass, functional microbial diversity, and nematode community structure as affected by cover crops and compost in an organic vegetable production system. Appl Soil Ecol. 2012;58:45–55. https://doi.org/10.1016/j.apsoil.2012.03.008

57. Hossain MK, Strezov V, Chan KY, Nelson PF. Agronomic properties of wastewater sludge biochar and bioavailability of metals in production of cherry tomato (*Lycopersicon esculentum*). Chemosphere. 2010;78(9):1167–71. https://doi.org/10.1016/j.chemosphere.2010.01.009

58. Singh R, Agrawal M. Variations in heavy metal accumulation, growth and yield of rice plants grown at different sewage sludge amendment rates. Ecotoxic Environ Safety. 2010;73(4):632–41. https://doi.org/10.1016/j.ecoenv.2010.01.020

59. Cieślik BM, Namieśnik J, Konieczka P. Review of sewage sludge management: Standards, regulations and analytical methods. J Cleaner Prod. 2015;90:1–15. https://doi.org/10.1016/j.jclepro.2014.11.031

60. Sullivan D, Bary A, Nartea T, Myrhe E, Cogger C, Fransen S. Nitrogen availability seven years after a high-rate food waste compost application. Compost Sci Utiliz. 2003;11(3):265–75. https://doi.org/10.1080/1065657X.2003.10702133

61. Valdez-Perez M, Fernandez-Luqueno F, Franco-Hernandez O, Cotera LF, Dendooven L. Cultivation of beans (*Phaseolus vulgaris* L.) in limed or unlimed wastewater sludge, vermicompost or inorganic amended soil. Sci Horti. 2011;128(4):380–7. https://doi.org/10.1016/j.scienta.2011.01.016

62. Ahmed HK, Fawy HA, Abdel-Hady E. Study of sewage sludge use in agriculture and its effect on plant and soil. Agric Biol J North Am. 2010;1(5):1044–9. https://doi.org/10.5251/abjna.2010.1.5.1044.1049

63. Naderi R, Ghadiri H. Urban waste compost, manure and nitrogen fertilizer effects on the initial growth of corn (*Zea mays* L.). 2010;15:159-65.

64. Hargreaves J, Adl M, Warman P. A review of the use of composted municipal solid waste in agriculture. Agric Ecosyst Environ. 2008;123(1–3):1–14. https://doi.org/10.1016/j.agee.2007.07.004

65. Larney FJ, Angers DA. The role of organic amendments in soil reclamation: A review. Can J Soil Sci. 2012;92(1):19–38. https://doi.org/10.4141/cjss2010-064

66. Rusan MJM, Hinnawi S, Rousan L. Long term effect of wastewater irrigation of forage crops on soil and plant quality parameters. Desalination. 2007;215(1–3):143–52. https://doi.org/10.1016/j.desal.2006.10.032

67. Johnston A, Poulton P. The importance of long‐term experiments in agriculture: Their management to ensure continued crop production and soil fertility; The Rothamsted experience. Eur J Soil Sci. 2018;69(1):113–25. https://doi.org/10.1111/ejss.12521

68. Lou Y, Davis AS, Yannarell AC. Interactions between allelochemicals and the microbial community affect weed suppression following cover crop residue incorporation into soil. Plant Soil. 2016;399:357–71. https://doi.org/10.1007/s11104-015-2698-8

69. Hargreaves J, Adl MS, Warman PR, Rupasinghe HV. The effects of organic amendments on mineral element uptake and fruit quality of raspberries. Plant Soil. 2008;308:213–26. https://doi.org/10.1007/s11104-008-9621-5

70. Zmora-Nahum S, Hadar Y, Chen Y. Physico-chemical properties of commercial composts varying in their source materials and country of origin. Soil Biol Biochem. 2007;39(6):1263–76. https://doi.org/10.1016/j.soilbio.2006.12.017

71. Cuypers A, Remans T, Weyens N, Colpaert J, Vassilev A, Vangronsveld J. Soil-plant relationships of heavy metals and

metalloids. Heavy Metals in Soils: Trace Metals and Metalloids in Soils and Their Bioavailability. Springer: Dordrecht; 2013. p. 161-93. https://doi.org/10.1007/978-94-007-4470-7_6

72. Korboulewsky N, Dupouyet S, Bonin G. Environmental risks of applying sewage sludge compost to vineyards: Carbon, heavy metals, nitrogen, and phosphorus accumulation. J Envrion Qual. 2002;31(5):1522–7. https://doi.org/10.2134/jeq2002.1522
73. Cheng H, Xu W, Liu J, Zhao Q, He Y, Chen G. Application of composted sewage sludge (CSS) as a soil amendment for turfgrass growth. Ecol Engin. 2007;29(1):96–104. https://doi.org/10.1016/j.ecoleng.2006.08.005
74. Butterbach-Bahl K, Baggs EM, Dannenmann M, Kiese R, Zechmeister-Boltenstern S. Nitrous oxide emissions from soils: How well do we understand the processes and their controls? Philosph Trans Royal Soc B: Biol Sci. 2013;368(1621):20130122. https://doi.org/10.1098/rstb.2013.0122
75. Antoniadis V, Levizou E, Shaheen SM, Ok YS, Sebastian A, Baum C, et al. Trace elements in the soil-plant interface: Phytoavailability, translocation and phytoremediation - A review. Earth-Sci Rev. 2017;171:621–45. https://doi.org/10.1016/j.earscirev.2017.06.005
76. Agegnehu G, Bass AM, Nelson PN, Bird MI. Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. Sci Total Environ. 2016;543:295–306. https://doi.org/10.1016/j.scitotenv.2015.11.054
77. Montemurro F, Ferri D, Tittarelli F, Canali S, Vitti C. Anaerobic digestate and on-farm compost application: Effects on lettuce (*Lactuca sativa* L.) crop production and soil properties. Sci Utiliz. 2010;18(3):138–93. https://doi.org/10.1080/1065657X.2010.10736954
78. Siebielec G, Siebielec S, Lipski D. Long-term impact of sewage sludge, digestate and mineral fertilizers on plant yield and soil biological activity. J Cleaner Prod. 2018;187:372–9. https://doi.org/10.1016/j.jclepro.2018.03.245
79. Gheewala SH. Life cycle assessment (LCA) to evaluate environmental impacts of bioenergy projects. J Sustain Energy Environ. 2011;35(1):35–8.
80. Yadav A, Gupta R, Garg VK. Organic manure production from cow dung and biogas plant slurry by vermicomposting under field conditions. Int J Recycl Otrg Waste Agric. 2013;2:1–7. https://doi.org/10.1186/2251-7715-2-21
81. Carbonell G, de Imperial RM, Torrijos M, Delgado M, Rodriguez JA. Effects of municipal solid waste compost and mineral fertilizer amendments on soil properties and heavy metals distribution in maize plants (*Zea mays* L.). Chemosphere. 2011;85(10):1614–23. https://doi.org/10.1016/j.chemosphere.2011.08.025
82. Fetene Y, Addis T, Beyene A, Kloos H. Valorisation of solid waste as key opportunity for green city development in the growing urban areas of the developing world. J Envrion Chem Engin. 2018;6(6):7144–51. https://doi.org/10.1016/j.jece.2018.11.023
83. Vaithyanathan VK, Cabana H. Integrated biotechnology management of biosolids: Sustainable ways to produce value-added products. Front Water. 2021;3:729679. https://doi.org/10.3389/frwa.2021.729679
84. Capizzi-Banas S, Deloge M, Remy M, Schwartzbrod J. Liming as an advanced treatment for sludge sanitisation: Helminth eggs elimination-Ascaris eggs as model. Water Res. 2004;38(14–15):3251–8. https://doi.org/10.1016/j.watres.2004.04.015
85. Brown S, Kruger C, Subler S. Greenhouse gas balance for composting operations. J Environ Qual. 2008;37(4):1396–410. https://doi.org/10.2134/jeq2007.0453
86. Banks CJ, Zhang Y, Jiang Y, Heaven S. Trace element requirements for stable food waste digestion at elevated ammonia concentrations. Bioresource Technol. 2012;104:127–35. https://doi.org/10.1016/j.biortech.2011.10.068
87. Foley J, De Haas D, Hartley K, Lant P. Comprehensive life cycle inventories of alternative wastewater treatment systems. Water Res. 2010;44(5):1654–66. https://doi.org/10.1016/j.watres.2009.11.031
88. Shober AL, Sims JT. Phosphorus restrictions for land application of biosolids: Current status and future trends. J Environ Qual. 2003;32(6):1955–64. https://doi.org/10.2134/jeq2003.1955
89. Raj D, Antil R. Evaluation of maturity and stability parameters of composts prepared from agro-industrial wastes. Bioresource Technol. 2011;102(3):2868–73. https://doi.org/10.1016/j.biortech.2010.10.077
90. Wasay S, Barrington S, Tokunaga S. Organic acids for the in situ remediation of soils polluted by heavy metals: Soil flushing in columns. Water Air Soil Poll. 2001;127:301–14. https://doi.org/10.1023/A:100525191516
91. Stoorvogel JJ, Bakkenes M, Temme AJ, Batjes NH, ten Brink BJ. S-World: A global soil map for environmental modelling. Degrad Dev. 2017;28(1):22–33. https://doi.org/10.1002/ldr.2656
92. Seshadri B, Bolan NS, Naidu R, Wang H, Sajwan K. Clean coal technology combustion products: Properties, agricultural and environmental applications, and risk management. Adv Agron. 2013;119:309–70. https://doi.org/10.1016/B978-0-12-407247-3.00006-8
93. Wang H, Brown SL, Magesan GN, Slade AH, Quintern M, Clinton PW, et al. Technological options for the management of biosolids. Environ Sci Poll Res Int. 2008;15:308–17. https://doi.org/10.1007/s11356-008-0012-5
94. Kalogo Y, Monteith H, Eng P. State of Science Report: Energy and Resource Recovery from Sludge. 2012.
95. Awasthi MK, Sarsaiya S, Patel A, Juneja A, Singh RP, Yan B, et al. Refining biomass residues for sustainable energy and bio-products: An assessment of technology, its importance, and strategic applications in circular bio-economy. Renew Sustain Energy Rev. 2020;127:109876. https://doi.org/10.1016/j.rser.2020.109876
96. Zaker A, Chen Z, Wang X, Zhang Q. Microwave-assisted pyrolysis of sewage sludge: A review. Process Technol. 2019;187:38–104. https://doi.org/10.1016/j.fuproc.2018.12.011
97. Antil RS, Raj D. Integrated nutrient management for sustainable crop production and improving soil health. Nutrient Dynamics for Sustainable Crop Production. Springer: Singapore; 2020. p. 67-101. https://doi.org/10.1007/978-981-13-8660-2_3
98. Radics RI, Dasmohapatra S, Kelley SS. Public perception of bioenergy in North Carolina and Tennessee. Energy Sustain Soc. 2016;6(1):1–11. https://doi.org/10.1186/s13705-016-0081-0
99. Charron DF. Ecosystem approaches to health for a global sustainability agenda. EcoHealth. 2012;9:256–66. https://doi.org/10.1007/s10393-012-0791-5
100. Zolfaghary P, Zakerinia M, Kazemi H. A model for the use of urban treated wastewater in agriculture using multiple criteria decision making (MCDM) and geographic information system (GIS). Agric Water Manag. 2021;243:106490. https://doi.org/10.1016/j.agwat.2020.106490

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