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AGRICULTURAL RESOURCE RECOVERY FROM MUNICIPAL BIOWASTE AND WASTEWATER STREAMS FOR SOIL HEALTH, WATER REUSE, AND RESILIENT FOOD PRODUCTION

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ABSTRACT

Municipal biowaste and wastewater contain recoverable water, organic matter, carbon, nutrients, and energy that can support agriculture while reducing disposal pressures. This review examines the pathways through which these streams can improve soil health, enable water reuse, and strengthen resilient food production. Literature published between 2016 and 2025 was identified through major scientific databases and synthesized thematically across recovery technologies, agronomic effects, environmental risks, economic feasibility, and governance. Composting, vermicomposting, anaerobic digestion, pyrolysis, hydrothermal carbonization, nutrient precipitation, ammonia capture, and advanced wastewater treatment produce compost, digestate, biosolids, biochar, hydrochar, struvite, concentrated nitrogen products, reclaimed water, and energy. These resources can increase soil organic matter, nutrient availability, aggregation, microbial activity, and water-holding capacity while reducing dependence on freshwater and synthetic fertilizers. Reclaimed wastewater may stabilize irrigation supplies during drought, and recovered nutrients can support urban, peri-urban, and resource-constrained farming. Benefits are conditional on feedstock quality, treatment performance, local soil and crop requirements, and appropriate application rates. Pathogens, salinity, heavy metals, pharmaceuticals, per- and polyfluoroalkyl substances (PFAS), microplastics, antimicrobial-resistance determinants, nutrient losses, and greenhouse-gas emissions remain important concerns. Safe implementation requires source segregation, effective treatment, product certification, traceability, long-term monitoring, and harmonized regulation. Integrated life-cycle, economic, and region-specific assessments are needed to select recovery pathways that balance agricultural value, public health, environmental protection, and market viability.

KEYWORDS: Municipal biowaste; wastewater reclamation; nutrient recovery; soil health; circular agriculture; resilient food production

1. INTRODUCTION

The amount of organic solid waste and wastewater generated has significantly increased due to rapid urbanization, population growth, shifting consumption habits and the growth of service provision by cities. Municipal biowaste is comprised of food waste, kitchen waste, garden waste and other organic wastes that are easily degraded and have high levels of organic carbon and plant nutrients. As urban populations and domestic consumption continue to grow, the amount of MSW generated is projected to grow significantly in the near future, adding to the already limited waste-management capacity (Kaza et al., 2018). The interest in municipal and agricultural biowaste is increasing and has become a scientific priority due to the growing awareness of the possibility of converting biodegradable waste into useful products rather than landfilling or incinerating it without material recovery (Giacomello et al., 2025).

This is a similar challenge for municipal wastewater. A significant portion of these are not adequately treated, or discharged without the extraction of the water, nutrients, organic matter and embedded energy. Treated wastewater can be a fairly reliable water source if treated properly, especially in areas with fluctuating rainfall and diminishing supply of conventional water. It also includes other nutrients such as nitrogen and phosphorus which can be beneficial for crop production if their concentrations and risks are managed appropriately. A shift towards treating wastewater as a recoverable resource can thus help to minimize environmental pollution and promote water and nutrient security (UNESCO World Water Assessment Programme, 2017). However, if poorly treated wastewater and unregulated agricultural reuse enter the soil, surface water, groundwater and food chain, it can lead to high nutrient, salt, pathogen, heavy metal and organic contaminant levels in soil, surface water, groundwater and food chain, respectively (Javier Mateo-Sagasta (IWMI), 2017).

Soil degradation, scarcity of fresh water, and reliance on synthetic fertilizers are particularly critical in agriculture and are becoming a growing challenge to sustaining a stable production environment. Soils can lose their water-holding ability, nutrient cycling, and biological activity due to continuous removal of nutrients, erosion, loss of soil organic matter, salinization, and inappropriate use of inputs. A different approach to agriculture is to recycle the recovered organic matter and nutrients to productive land in circular agricultural systems. AgroCycle approach illustrates that residues from various food and agricultural value chains can be used as inputs for new production chains, thus minimizing waste and increasing the use efficiency of resources (Toop et al., 2017). This would link up municipal solid waste management to soil rehabilitation, water security in irrigation and agricultural productivity.

Recovery options include (but are not limited to) composting, anaerobic digestion, digestate processing, biochar production, nutrient precipitation, ammonia capture and wastewater reclamation. The biological processes can transform the constituents of wastewater into energy carriers, fertilisers, and other beneficial products, but only under certain conditions. These outcomes depend on feedstock quality, process configuration, and the intended application of the recovered products (Puyol et al., 2017). Municipal wastewater treatment plants can then become resource-recovery facilities, although the commercial viability of the recovery, the quality of the recovered product, the infrastructure needed for the recovery and the uncertain markets remain limiting factors (Kehrein et al., 2020). Circularity must be coordinated between the collection, treatment, certification, distribution and application in agriculture and not be limited to an isolated recovery technology.

Past scholarship often deals with the treatment of biowaste, reuse of wastewater, amendments to soil, or recovery of nutrients individually. The fragmentation leaves gaps in knowledge regarding a combination of soil functions, irrigation availability, crop performance, food safety and long-term resilience that is recovered from the resources. Technological innovation is needed to incorporate environmental assessment, economic viability, regulation and stakeholder involvement into circular water-sector models (Smol et al., 2020). Inconsistent standards, inadequate monitoring, contaminant issues, insufficient institutional coordination, and low demand for recovered products can otherwise limit implementation (Guerra-Rodríguez et al., 2020).

This review integrates municipal biowaste and wastewater recovery with soil health, agricultural water reuse, food-production resilience, environmental and health risks, and enabling governance. The review has the following objectives:

- To examine technologies for recovering water, nutrients, organic matter, and carbon from municipal biowaste and wastewater.
- To evaluate the effects of recovered resources on soil health, irrigation security, crop productivity, and food-system resilience.
- To identify environmental, health, economic, and governance barriers and propose priorities for safe and scalable agricultural application.

2. REVIEW METHODOLOGY

A structured narrative review was conducted to examine agricultural resource recovery from municipal biowaste and wastewater. Literature published between 2016 and 2025 was searched through Scopus, Web of Science, ScienceDirect, SpringerLink, PubMed, and Google Scholar. Search combinations included terms such as “municipal biowaste,” “municipal wastewater,” “resource recovery,” “compost,” “digestate,” “biosolids,” “biochar,” “nutrient recovery,” “reclaimed wastewater,” “soil health,” “agricultural irrigation,” “crop productivity,” and “resilient food production.” Boolean operators were used to combine waste-stream, recovery-technology, agricultural-application, and outcome-related terms.

Studies were considered when they examined municipal organic waste or wastewater as a source of recoverable water, nutrients, organic matter, carbon, or agricultural amendments. Eligible literature addressed recovery technologies, soil properties, irrigation reuse, crop responses, environmental and health risks, life-cycle performance, economic feasibility, regulation, or stakeholder acceptance. Studies unrelated to agricultural applications, publications outside the selected period, duplicate records, non-English documents, and sources lacking sufficient methodological or technical information were excluded.

Titles and abstracts were initially examined for relevance, followed by an assessment of the complete text. Information was extracted on waste-stream characteristics, treatment processes, recovered products, application conditions, soil and crop responses, water-quality effects, contaminants, risk-control measures, and implementation barriers. Source quality was evaluated according to the clarity of objectives, appropriateness of methods, transparency of data, relevance of outcomes, and consistency between results and conclusions.

The selected evidence was organized through thematic synthesis. Findings were compared across resource streams, technologies, soils, crops, climates, and application conditions. Areas of agreement, conflicting results, practical limitations, and knowledge gaps were identified. The resulting synthesis connected technological recovery pathways with soil health, agricultural water reuse, food-production resilience, risk management, sustainability, and governance.

3. Municipal Biowaste and Wastewater Resource-Recovery Pathways

3.1 Municipal Resource Streams and Recoverable Components

The municipal biowaste consists of all biodegradable waste, including food waste, kitchen waste, garden waste and other organic waste collected from households, markets and restaurants and public areas. They include a variety of organic carbon, nitrogen, phosphorus, potassium and micronutrients that are capable of being returned to agricultural systems once they have been treated appropriately. The importance of source segregation is that contamination with plastics or metals, glass or hazardous substances can damage the quality and safety of products recovered. The organic fraction of municipal solid waste can be converted to biogas by anaerobic digestion, leaving behind digestate, which contains a high concentration of nutrients, but may need additional digestion or filtration prior to use in agriculture (Peng & Pivato, 2019). Sewage sludge and biosolids are produced by the municipal wastewater treatment process and include organic matter and plant nutrients, including nitrogen and phosphorus. Treated effluent is also a potential nutrient source and carrier of water. The value of these materials is dependent on constituent makeup, treatment history, stability and contaminant concentrations. The management of the digestate and its combination with municipal solid-waste (MSW) compost may provide the possibility to obtain soil amendments with characteristics appropriate to agricultural uses (Pecorini et al., 2020).

3.2 Biological and Thermochemical Recovery Technologies

The biological stabilization of organic wastes by composting requires aerobic conditions and yields a humified amendment which can enhance soil organic matter and nutrient availability. Vermicomposting is a microbial decomposition process along with earthworm activity, which can yield a fine, biologically fertile product. Product quality is dependent on feedstock cleanliness, maturity, C:N ratio, aeration and temperature, though.

The process of anaerobic digestion produces a methane rich biogas by treating biodegradable material without the presence of oxygen. The remaining digestate is rich in the nutrients originally supplied and can be separated to a solid and a liquid fraction, concentrated, composted, dried or used for the production of fertilizer products. To control nutrient losses, odour, pathogens and transportation costs, appropriate management is required (Kovačić et al., 2022).

There are other thermochemical processes that can also stabilize carbon and concentrate nutrients. Municipal digestate can be pyrolyzed to obtain char, which can have adsorption and soil improving characteristics (Nisticò et al., 2019). The food waste that is anaerobically digested can also be transformed to biochar, which could also be used to sequester phosphorus and allow its recovery and reapplication in agriculture (Alghashm et al., 2018). Hydrothermal carbonization is especially beneficial for wet feedstocks, since drying is not required, and has the potential to yield a hydrochar and liquid rich in nutrients.

3.3 Nutrient and Water-Recovery Technologies

Phosphorus can be sequestered out of wastewater as struvite, which is a crystalline magnesium ammonium phosphate compound that can be applied as a slow-release fertilizer. The relatively small municipal treatment plants can supply adequate phosphorus rich streams for struvite production (Hallas et al., 2019). The efficiency of the recovery is influenced by pH, availability of magnesium, nutrient concentration, mixing, and crystal-settling behaviour. A fluidized-bed configuration can enhance crystal growth and settleability to recover phosphate (Fang et al., 2016). Chemical and bioelectrochemical methods also allow for the recovery of both nitrogen and phosphorus in the form of struvite (Sreelakshmi et al., 2022).

There are several methods for recovering nitrogen, such as ammonia stripping, membrane separation, adsorption, ion exchange, and biological concentration. The process of treating of effluents from the biogas sector can lead to the generation of more concentrated nutrient products and to the minimisation of uncontrolled discharges (Zielińska & Bułkowska, 2024). The biological treatment, filtration, membrane treatment, disinfection, and other advanced treatment technologies are used to produce reusable water for specific agricultural applications of wastewater reclamation. Integrated systems can recover energy, carbon, nutrients and water in sequence to enhance the overall resource efficiency (Dereszewska & Cytawa, 2023).

Table 1 summarizes municipal resource streams, recovery pathways, products, and agricultural uses.

Table 1. Municipal resource streams, recovery pathways, and agricultural products

Municipal stream	Recovery pathway	Recovered product	Agricultural value and key controls	References
Food, kitchen, and green waste	Composting, vermicomposting, anaerobic digestion	Compost, vermicompost, digestate, biogas	Soil conditioning, fertilization, and energy; control maturity, pathogens, plastics, and salinity	(Kovačić et al., 2022; Peng & Pivato, 2019)
Organic fraction of municipal solid waste	Composting and digestate blending	Compost–digestate blends	Balanced nutrient and carbon supply; verify maturity, composition, and application rate	(Pecorini et al., 2020)
Municipal biowaste and food-waste digestate	Pyrolysis	Char and biochar	Carbon addition, nutrient retention, and phosphorus recovery; assess pyrolysis conditions and contaminants	(Alghashm et al., 2018; Nisticò et al., 2019)
Sewage sludge and biosolids	Stabilization, digestion, composting, thermochemical	Biosolids, compost, digestate, biochar	Nutrient supply and soil restoration; monitor pathogens, metals, PFAS, pharmaceuticals,	(Börjesson & Kätterer, 2018; Habimana & Sauvé, 2025)

	conversion		and microplastics	
Municipal wastewater and treated effluent	Biological treatment, filtration, disinfection, advanced treatment	Reclaimed water	Irrigation and fertigation; manage salinity, sodicity, pathogens, trace elements, and emerging contaminants	(Hashem & Qi, 2021; Ofori et al., 2024)
Phosphorus-rich wastewater sidestreams	Struvite precipitation and crystallization	Struvite	Slow-release phosphorus and nitrogen; control pH, magnesium supply, purity, and crystallization	(Fang et al., 2016; Hallas et al., 2019)
Nitrogen-rich liquid streams	Ammonia stripping, membranes, adsorption, ion exchange	Concentrated nitrogen products	Nitrogen fertilization; consider recovery efficiency, purity, energy demand, and ammonia loss	(Zielińska & Bułkowska, 2024)
Integrated municipal streams	Cascading biological, chemical, and thermochemical treatment	Water, nutrients, carbon products, energy	Combined irrigation, fertilization, soil improvement, and energy recovery; requires certification and economic viability	(Dereszewska & Cytawa, 2023)

4. Effects of Recovered Resources on Soil Health

Figure 1 illustrates how recovered resources influence soil health and crop outcomes.

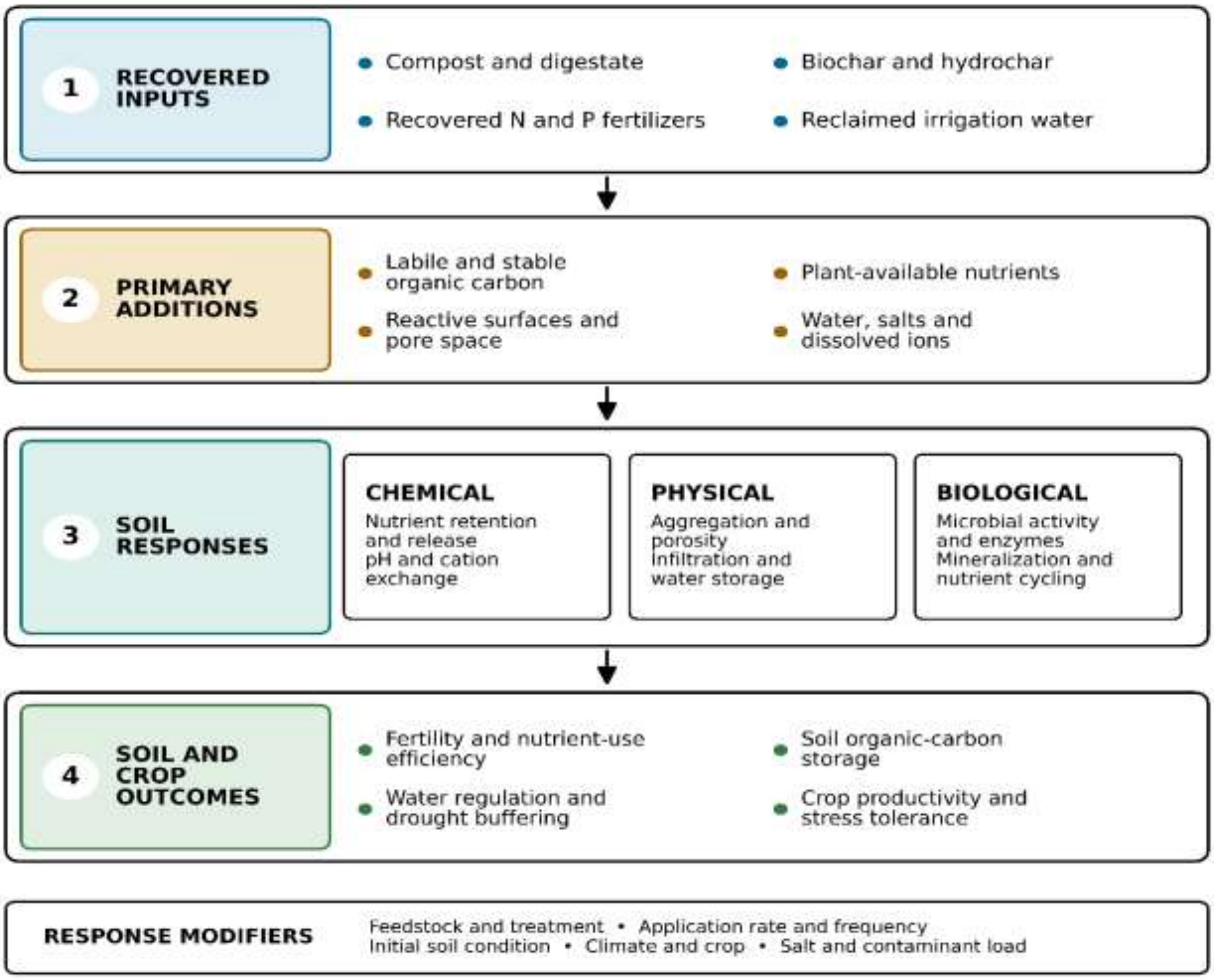

Figure 1. Mechanistic Cascade Linking Recovered Municipal Resources to Soil Health and Crop Outcomes

4.1 Soil Fertility and Nutrient Cycling

Recovered materials such as compost, digestate, biosolids, biochar and others can be added back to soils in agriculture to replenish organic material and nutrients. They are comprised of various nutrients depending on the raw feedstock and processing method. In general, digestate is able to release readily available ammonium nitrogen, while compost releases nutrients over a longer period as organic matter is being broken down. Biosolids can be used to add N, P, S, and micronutrients and biochar can help to limit the release of nutrients from the root zone. The mixture of compost, biochar and digestate may provide a sustainable solution for supplying immediate nutrients, conditioning soils and promoting maize growth while minimizing reliance on conventional fertilizers (Ortiz-Liébana et al., 2023).

Availability of nutrients, not just nutrient contents is the decisive factor in the potential for substitution of fertilizers with recovered materials. Using only the crop need for nitrogen can cause over-accumulation of phosphorus, especially with composts having a low N/P ratio. Results on urban agriculture using compost suggest that the recovery efficiency can be enhanced, if the nutrient recycling is synchronized with the nutrient demand of crops, to avoid runoff or leaching losses (Shrestha et al., 2020). For balanced nutrient management, therefore, soil testing, product characterization and incorporation into mineral fertilizers are needed.

4.2 Soil Physical and Biological Quality

Organic amendments may decrease bulk density and enhance the soil aggregation, porosity, aeration, infiltration and water-holding capacity. These changes are especially beneficial in sandy, compacted, or poor soils that have little organic matter. Sewage-sludge application has been linked with increased soil carbon and better soil structure, but it can also lead to reduced nitrogen-use efficiency, and the accumulation of phosphorus or metals needs to be monitored (Börjesson & Kätterer, 2018). Biochar can also supply stable carbon and create porous microsites to hold water, nutrients and microorganisms.

Recovered organic materials also affect microbial biomass, microbial community structure, enzyme activity and the transformation of nutrients. Repeated addition of MSW compost can impact soil microbial metabolic pathways and enhance soil properties and productivity (Abbey et al., 2022). Digestate can provide readily available compounds that can promote microbial activity while biochar can change the microbial habitat or nutrient availability. However, these responses are not uniformly beneficial. Results from a mesocosm experiment demonstrated that effects of digestate and biochar depended on digestate composition and dose, as well as the presence of different microbial communities and GHGs emissions (Pastorelli et al., 2024).

4.3 Long-Term Soil Responses

Repeated applications of appropriately treated recovered amendments can restore organic matter and productive capacity in low-fertility or organic-matter-depleted soils. The use of biosolids for long periods of time in overgrazed rangelands showed improvements in biological and overall soil-health indicators, but not necessarily at a higher rate of application (Buchanan & Ippolito, 2021). The appropriate rates are thus necessary to exclude salinity, nutrient imbalance, contamination or soil degradation.

Performance can be enhanced with digestate amendments (e.g., biochar, sulphur), and short and long-term effects can differ due to nutrient mineralisation and microbial communities adapting (Holatko et al., 2023). The same can be suggested from the field evidence, which shows that the repeated application of digestate in combination with compost, manure, or sewage sludge results in treatment-specific changes in bacterial and fungal communities (Mora-Salguero et al., 2025). Therefore, the response of the soil is dependent on the texture, climate, needs of the crop, source of the feedstock, intensity of treatment, degree of maturity of the amendments, amount and length of application. It is essential to monitor long-term to identify temporary gains of fertility versus sustained enhancement of soil functioning.

5. Reclaimed Wastewater for Agricultural Irrigation

5.1 Water-Reuse Potential

In drought-stressed regions where freshwater supplies are limited and urban and agricultural users compete for the same sources, reclaimed wastewater provides a viable alternative for irrigation. Treated municipal effluent (TME) has a steady supply and can be used for irrigation even if it is not raining. It can reduce freshwater withdrawals, limit discharges of untreated wastewater to natural water bodies, and improve water security in arid and semi-arid regions. However, it is dependent on treatment levels, crop, soil, irrigation, and the use of the harvested product. When the health risks, salinity, and toxicity can be managed, treated wastewater can be used for agricultural production (Hashem & Qi, 2021).

5.2 Agronomic Benefits and Management Requirements

Nitrogen, phosphorus, potassium and micronutrients are often present in reclaimed wastewater and can be used to provide a supplement to crop fertilization. This fertigation effect can help to decrease the use of mineral-fertilisers and the cost of their production. Evaluations of treated wastewater used for crop irrigation have shown that fertilizer requirements and effects on soil properties depend on water quality and the treatment applied before reuse (Ofori et al., 2024). For this reason, the irrigation schedule should be designed to balance crop water needs with the nutrients applied with wastewater. Crop and site suitability will need to be established prior to implementation. Drip and subsurface irrigation can limit direct contact between the reclaimed water and edible parts of plants, and also minimize evaporation and uncontrolled exposure. The soil conditions also need to be taken into account as the texture of the soil and its drainage, initial salinity, and groundwater depth can affect the movement and accumulation of salts and nutrients. Technical guidance, farmer involvement, regulatory support, and local environmental and socioeconomic adaptation are therefore essential for sustainable reuse (Ghanbari et al., 2024).

5.3 Soil and Water-Quality Considerations

Long-term irrigation with reclaimed water can alter soil pH, electrical conductivity, organic matter, nutrient availability, and microbial activity. Some benefits have been observed on soil fertility, but they vary depending on the soil depth and irrigation systems (Sdiri et al., 2023). Over-application will also lead to a rise in salinity and sodicity, especially in areas with high evapotranspiration, low rainfall, and poor drainage. Therefore, salinity of recycled water needs to be controlled by blending, leaching, drainage improvement and salt-tolerant crops (Rahman et al., 2022). If the concentration of PTEs in the irrigation water is relatively low, but the concentration is present over time, PTEs can build up. They have been shown to be important for monitoring in the soil profile over time (Gu et al., 2019). If treatment and management are inadequate, uncontrolled wastewater irrigation can also lead to soil degradation and pollution (Alnaimy et al., 2021). For safe reuse, regular salinity, sodicity, nutrient, pathogen, trace element and emerging contaminant evaluations are needed, along with treatments that follow standards and long-term monitoring of soil and groundwater.

6. Contributions to Resilient Food Production

6.1 Crop Productivity and Resource Efficiency

The resources of municipal biowaste and wastewater can be utilized for the production of crops, providing water, organic matter and nutrients. They are effective based on the nutrient availability, rate of application, crop requirement and environmental conditions. Biowastes produced by municipalities have been shown to enhance plant growth, NUE and allow for partial replacement of mineral fertilizers, reducing the amount of nitrification losses from the plant–soil system (Fragalà et al., 2023). These products can be used in combination with conventional fertilizers if their composition and nutrient-release ability have been appropriately defined.

Liquid anaerobic digestate can be directly applied to growing crops as a source of easily released nitrogen and other nutrients. It may be used as a key nutrient source in soilless horticulture, but with supplementation to correct nutrient imbalances and optimize plant growth as may be required (Weimers et al., 2022). Struvite (MgNH4PO4.6H2O) is another recovered phosphorus source. It has a slow release property that can provide a prolonged supply of P to the plant while reducing the potential for rapid P loss. However, the response of the different crops varies depending on the species and soil, such as differences in biomass, phosphorus availability and uptake between Chinese cabbage, cowpea and maize (Sun et al., 2024). The evaluation of wastewater-derived struvite has also shown that it can be a safe fertilizer if the quality of the product and soil-specific behaviour are evaluated before application (Mancho et al., 2023).

Reclaimed water supplies both irrigation water and dissolved nutrients. It can reduce freshwater withdrawals and fertilizer demand; however, even well-treated water can alter soil salinity, nutrient balances, microbial activity, and crop responses. Outcomes therefore depend on water quality, soil properties, crop type, irrigation method, and long-term management. The use of treated wastewater has been demonstrated in experiments with potato and maize to affect the soil properties and plant growth, emphasizing the importance of crop-specific reuse strategies (Abou Jaoude et al., 2025). Additionally, continuous sub-irrigation will increase water delivery efficiency by providing water directly under the soil surface. This has allowed for the productive use of treated municipal wastewater in rice cultivation and reduction of methane and nitrous oxide emissions in rice production (Phung et al., 2020).

6.2 Climate and Food-System Resilience

Reclaimed water can sustain irrigation during drought and irregular rainfall, while compost, digestate, and recovered nutrients improve water retention and reduce dependence on external fertilizers. Together, these resources diversify agricultural inputs and buffer farms against water, fertilizer, and energy disruptions. Urban and peri-urban agriculture is an especially appropriate way of resource recovery in that waste generation, wastewater treatment and food demand takes place within relatively short distances. Municipal compost can be used to return nutrients to the surrounding agricultural land, but must be used in line with the nutrient status of the soils and crop requirements and avoid the build-up of phosphates (Arosemena Polo et al., 2024). In addition, struvite can find application in urban hydroponic systems, as recovered phosphorus can be fed as a part of the mineral nutrient supply and support more resilient production (Arcas-Pilz et al., 2021).

Locally sourced inputs can lower smallholder and resource-limited farmers' cost of water, fertilizer, and other inputs. However, their role in food security relies on cost effectiveness of treatment, availability of the product, technical guidance, reduction in contaminants, and farmer acceptance. Resource recovery is part of a food system that is resilient, provided that the agronomic benefits are supported by a consistent quality of product, safe application, and locally appropriate governance.

Table 2 compares the agronomic benefits and limitations of recovered resources.

Table 2. Contributions of recovered resources to soil health and resilient food production

Recovered resource	Principal agronomic and soil-health benefits	Resilience contribution	Main limitation	References
Compost	Increases organic matter, aggregation, microbial activity, and gradual nutrient release	Restores degraded soils and improves water retention	Slow nutrient release and possible phosphorus accumulation	(Abbey et al., 2022; Shrestha et al., 2020)
Digestate	Supplies plant-available nutrients and organic matter	Reduces mineral-fertilizer demand and supports short-term growth	Ammonia loss, salinity, odour, and variable composition	(Holatko et al., 2023; Weimers et al., 2022)

Biosolids	Adds carbon, macronutrients, and micronutrients	Improves fertility in nutrient-deficient or degraded land	Metals and emerging contaminants may accumulate	(Börjesson & Kätterer, 2018; Buchanan & Ippolito, 2021)
Biochar and other thermochemical chars	Improve carbon storage, porosity, nutrient retention, and microbial habitat	May increase water retention and drought tolerance	Performance varies with feedstock, process, soil, and dose	(Alghashm et al., 2018; Pastorelli et al., 2024)
Compost–biochar–digestate blends	Combine readily available nutrients with longer-term soil conditioning	Support crop growth and partial fertilizer substitution	Require component characterization and precise blending	(Ortiz-Liébana et al., 2023)
Struvite	Provides slowly available phosphorus and nitrogen	Reduces reliance on mined phosphate and supports hydroponics	Solubility, purity, and crop responses vary	(Arcas-Pilz et al., 2021; Sun et al., 2024)
Reclaimed wastewater	Supplies irrigation water and dissolved nutrients	Improves dry-season water security and reduces freshwater demand	Salinity, pathogens, trace elements, and emerging contaminants	(Abou Jaoude et al., 2025; Ofori et al., 2024)
Biowaste-derived biostimulants	Improve plant nitrogen metabolism and nutrient-use efficiency	Support crop growth with lower mineral-fertilizer inputs	Effectiveness depends on crop, dose, and composition	(Fragalà et al., 2023)
Integrated urban nutrient recovery	Returns locally generated nutrients to urban and peri-urban farming	Diversifies inputs and strengthens circular food systems	Transport, nutrient-demand mismatch, regulation, and acceptance	(Arosemena Polo et al., 2024)

7. Environmental, Agronomic, and Public-Health Risks

7.1 Biological and Chemical Hazards

If source control and treatment are inadequate, biological and chemical hazards can be introduced into the agricultural environment when municipal biowaste products and reclaimed wastewater are used. Inadequate treatment can allow pathogenic bacteria, viruses, protozoa, and helminths to survive, contaminate soils, irrigation systems, and crops, and expose farmers and consumers to infection. Exposure can happen during direct contact, via aerosols, accidental ingestion or by eating contaminated produce. The agricultural application of partially treated or untreated wastewater has been shown to be a measurable threat to health based on epidemiological evidence, especially when the wastewater is not adequately protected for those applying it and crops are eaten raw (Adegoke et al., 2018).

Chemical hazards include heavy metals, pharmaceutical residues, personal-care products, persistent organic pollutants, and per- and polyfluoroalkyl substances. A few compounds may not be completely eliminated from the wastewater and may be concentrated in the sewage sludge. Environmental conditions and chemical properties can affect the bioavailabilities of pharmaceuticals and their metabolites, which can either persist in the environment or be absorbed by sludge and amended soil (Martín et al., 2021). Human exposure through crops is plausible: a controlled trial detected carbamazepine exposure after participants consumed produce irrigated with treated wastewater (Paltiel et al., 2016). PFAS contamination has specific concerns due to its environmental persistence, mobility and fluctuating regulation by jurisdiction (Saliu & Sauvé, 2024).

Wastewater treatment residues may also contain microplastics, antibiotic-resistant bacteria and genes for antimicrobial-resistance. Microplastics can provide surfaces for microbial biofilms and may facilitate the persistence and dissemination of antibiotic-resistance genes in wastewater-treatment systems (Zhao et al., 2024). This means that meeting conventional nutrient and pathogen limits is not necessarily sufficient to address all emerging hazards.

7.2 Agricultural and Environmental Risks

The re-use of recovered products can lead to salinisation, sodicity, nutrient imbalance or contamination. Excess nitrogen can leach as nitrate, whereas surplus phosphorus can be transported through runoff and contribute to eutrophication. If the digestate, containing ammonium, is applied at inappropriate rates, or left on the soil surface, ammonia volatilization and nitrous oxide emissions can also result.

The potential exists for contaminants to be transferred to the livestock and human food chain via crop uptake. The degree of transfer will depend on the properties of the contaminant, soil pH, soil organic matter, crop species, irrigation system, and the amount of time the crop is exposed. Biosolids and soils contain emerging contaminants, and while the concentrations of these contaminants in recovered products are crucial, they may not be the only variable to consider when assessing their movement and persistence (Habimana & Sauvé, 2025).

Microplastics can be added to compost and digestate by contaminated feedstocks and be incorporated in agricultural soils via the application of organic fertilizers (Weithmann et al., 2018). Sewage-sludge application also causes accumulation in the field, which points to persistent soil reservoirs when applications are repeated (Corradini et al., 2019). The long-term impacts on aggregation, water movement, soil organisms, contaminant transport and crop performance remain poorly understood.

7.3 Risk Mitigation

The first step to risk reduction is to manage industrial, home and commercial food and water inputs into municipal collection and wastewater systems through source segregation and control. Treatment should be a combination of product quality testing, sanitizing, contaminant reduction and stabilization. Pathogen inactivation is needed during composting and depending on crop use and exposure risk reclaimed wastewater may need filtration, disinfection or advanced treatment.

Figure 2 presents a risk-based pathway for safe agricultural resource reuse.

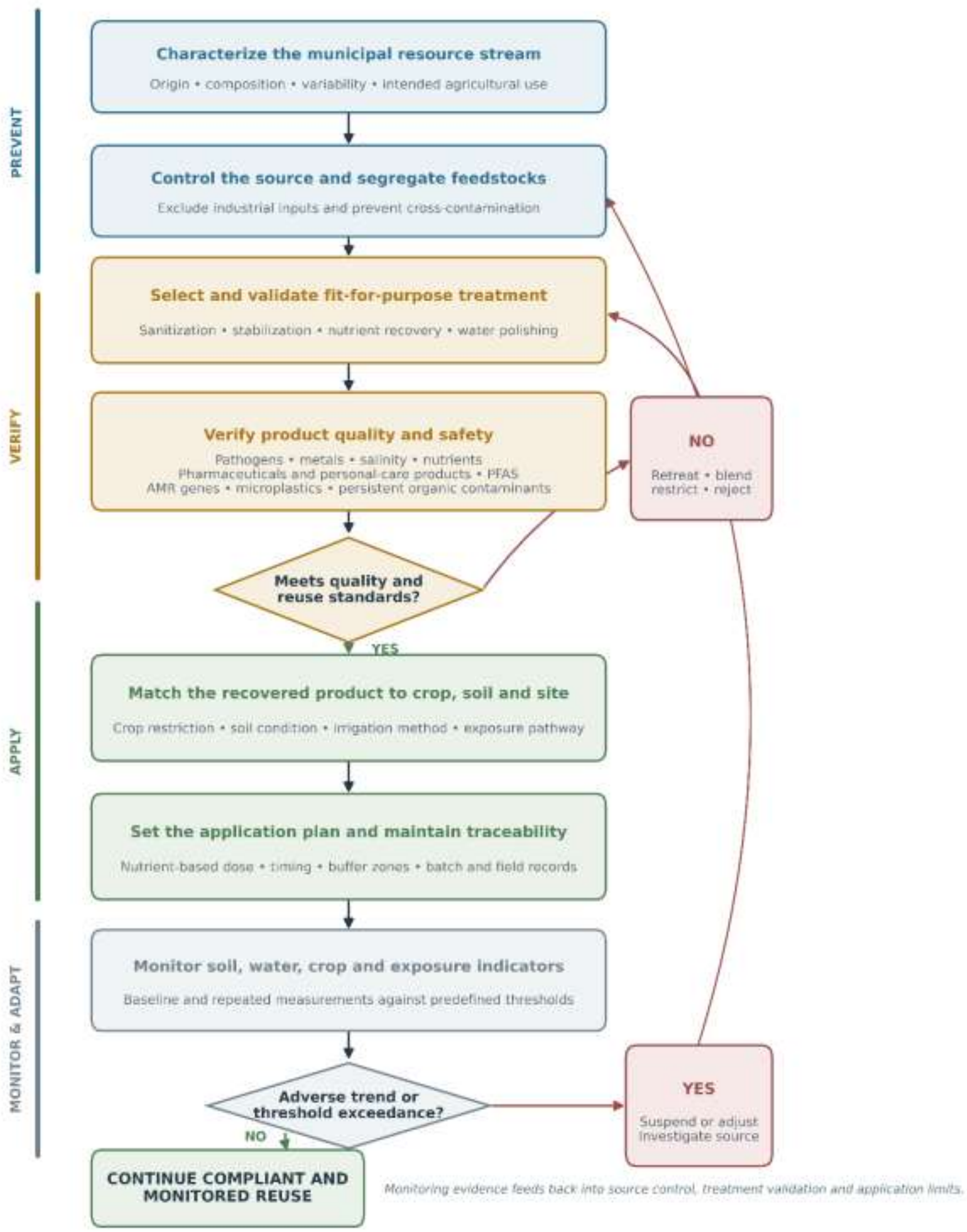

Figure 2. Risk-Based Decision Pathway for the Safe Agricultural Reuse of Recovered Municipal Resources

Application rates should be determined by soil tests, cropping needs, salinity and accumulated contaminant load. Some restrictions might be required for crops consumed raw, sensitive soils, or sites with vulnerable groundwater. Limiting exposure to edible plant parts through drip irrigation or subsurface irrigation, or reducing ammonia loss through injection or rapid incorporation of digestate, can help lessen ammonia emissions. Traceability systems must include information on the source of feedstock, feedstock treatment, product content, use location, and cumulative application history. To ensure the productivity and trust of agriculture, it is important to carry out quality certification, periodic soil and crop testing, and monitoring of new pollutants. Monitoring frameworks need to change as analytical data becomes available that highlights new pollutants and exposure routes that are not currently monitored.
Table 3 summarizes major reuse risks and their mitigation measures.

Table 3. Risks, exposure pathways, and management requirements for agricultural reuse

Risk	Main source	Agricultural or health concern	Mitigation and monitoring	References
Pathogens	Untreated wastewater and inadequately stabilized organic products	Worker exposure, crop contamination, and infection	Sanitization, disinfection, microbial testing, protective equipment, and crop restrictions	(Adegoke et al., 2018)
Salinity and sodicity	Reclaimed water and liquid digestate	Crop stress, reduced infiltration, and soil-structure deterioration	Monitor electrical conductivity and sodium; use blending, drainage, and controlled leaching	(Hashem & Qi, 2021; Rahman et al., 2022)
Nutrient overload	Compost, digestate, biosolids, reclaimed water	Nitrate leaching, phosphorus runoff, eutrophication, and imbalance	Soil testing, nutrient budgets, crop-based rates, and cumulative-load records	(Shrestha et al., 2020)
Heavy metals and trace elements	Sludge, biosolids, contaminated biowaste, reclaimed water	Soil accumulation, phytotoxicity, and food-chain transfer	Source control, product testing, loading limits, and soil–crop monitoring	(Börjesson & Kätterer, 2018; Gu et al., 2019)
Pharmaceuticals and metabolites	Wastewater, sludge, biosolids, reclaimed water	Persistence, crop uptake, and human exposure	Advanced treatment and monitoring of priority compounds in water, soil, and crops	(Martín et al., 2021; Paltiel et al., 2016)
Microplastics	Contaminated compost, digestate, biosolids, wastewater	Persistent soil accumulation and effects on soil organisms and structure	Source segregation, plastic removal, product screening, and field monitoring	(Corradini et al., 2019; Weithmann et al., 2018)
PFAS	Sewage sludge and biosolids	Persistent contamination and potential food-chain transfer	Feedstock control, compound-specific testing, and restrictions on contaminated products	(Saliu & Sauvé, 2024)
Antimicrobial resistance	Wastewater, sludge, biosolids, digestate	Dissemination of resistant microorganisms and resistance genes	Effective treatment, microbial surveillance, and exposure control	(Zhao et al., 2024)
Greenhouse gases and ammonia	Digestate storage and organic-amendment application	Nitrogen loss, air pollution, odour, and climate impacts	Covered storage, injection, rapid incorporation, appropriate timing, and emission monitoring	(Pastorelli et al., 2024; Phung et al., 2020)

8. Sustainability, Governance, and Future Research

8.1 Environmental and Economic Sustainability

Treatment and reuse must result in reduced overall impacts when compared to traditional waste disposal, withdrawal of fresh water, and the manufacture of synthetic fertilizers for agricultural resource recovery to be sustainable. Life-cycle assessment can consider energy use, greenhouse-gas emissions, nutrient loss, infrastructure, transportation, and avoidance of conventional product disposal at a landfill. Assumptions around leakage of methane, substitution of fertilizers, carbon storage, and boundaries of the systems continue to affect the comparisons between composting and anaerobic digestion (Vieira & Matheus, 2019). The environmental impact of municipal biowaste-treatment choices may also appear differently depending on uncertainty in emission factors, which also needs clear assumptions and sensitivity analysis (Lewerenz et al., 2023).

Multiple products are recovered from a single stream to enhance energy and resource efficiency. For example, biogas can be produced in advance of nutrients and organic matter being recovered from digestate in the anaerobic digestion process. Wastewater facilities can also incorporate water reclamation, nutrient removal, energy recovery and biosolids conversion. But more processing may involve chemicals, electric power, equipment and expertise to operate. Life-cycle and techno-economic assessments suggest that the emerging biosolids-recovery technologies offer beneficial fuels, fertilizers, and carbon products; however, the environmental and commercial results differ based on the technology maturity and market conditions (Clack et al., 2024). This balance is present in electrochemical struvite recovery as the production of fertilizer comes with a cost of capital, electricity, chemical inputs, and the need to not discharge any phosphorus (Morrissey et al., 2022).

8.2 Governance and Adoption

Standards for governance should include feedstock quality, treatment performance, pathogen reduction, nutrient composition, salinity, heavy metals, emerging contaminants and permitted agricultural uses. Compost, digestate, biosolids, and reclaimed water should be governed through coherent but product-specific standards that protect human and environmental health while enabling responsible agricultural use. Traceability and product labelling can be enhanced through certification.

Factors affecting adoption are price, reliability, perceived safety, crop-market requirements, and access to technical guidance. Non-users might have negative perceptions about reclaimed water, as it may be more expensive than other water sources and may not be suitable for certain crops or soil conditions. On the other hand, farmers with experience using reclaimed water may be more inclined to use it than those who do not, as they may have developed a positive attitude towards the practice (López-Serrano et al., 2022). Public communication should explain treatment processes, monitoring results, and residual risks transparently while addressing legitimate concerns with evidence. Urban–rural partnerships can connect treatment facilities with nearby farms, provided that transportation, storage, liability, seasonal demand, and quality assurance are addressed. Subsidies, public procurement, and demonstration projects may further support market development.

8.3 Research Gaps and Future Priorities

Long-term field experiments are needed to assess long-term impacts on soil carbon, soil nutrient balance, soil salinity, soil microbial communities, crop safety, and contaminant movement. Common metrics would allow for more meaningful comparisons between feedstocks, technologies, soils, crops and climatic regions. Monitoring should extend beyond heavy metals to include pharmaceuticals, PFAS, microplastics, and antimicrobial-resistance genes. Digital sensors, remote monitoring, decision-support systems, and precision application should be used to match recovered water and nutrients with crop and soil requirements. Because infrastructure, climate, regulations, farmer capacity, and markets vary among regions, context-specific risk–benefit assessments remain necessary. Policy analysis should also look at the effect that economic incentives and fertilizer standards have on the legitimacy and uptake of recycled nutrient products (Cordeiro & Sindhøj, 2024). The next generation of decision-making structures must include feedstock quality, technological performance, agronomic value, environmental risk, cost, regulation and stakeholder acceptance to determine recovery pathways specific to certain agricultural contexts.

9. CONCLUSION

Agricultural resource recovery from municipal biowaste and wastewater provides a viable approach to bridging the gap between waste management and soil management, water stewardship, and food production. Recovered nutrients, reclaimed water, compost, digestate, biosolids and biochar can return organic matter and nutrients to agricultural soils, and lower landfill use, freshwater withdrawals, and synthetic fertilizer use. They can help to enhance soil fertility, aggregation, microbial activity, nutrient cycling and water-holding capacity, especially in resource-poor or degraded production areas. Reclaimed wastewater can stabilize irrigation during drought and seasonal shortages, while waste-derived fertilizers diversify nutrient supplies. Together, these resources strengthen urban, peri-urban, and rural food production by retaining water, carbon, and nutrients in productive use. However, sustainability does not automatically follow resource recovery. Environmental benefits are realised if the composition of the product, treatment performance, soil properties, crop demands, and transport and application rates are appropriate. Careful management is needed to minimize the risk of pathogen, salt, heavy metal, pharmaceutical, microplastic, PFAS, and antimicrobial-resistance determinant contamination. To achieve safe agricultural reuse, it is important to implement source segregation, effective treatment, characterization of the product, specific application for each crop, traceability and long-term monitoring of soils, water, and harvested products. Regulations need to cover both known and new hazards and set out clear quality standards that will give farmers confidence and help the development of markets. The next steps need to be taken through coordination among municipalities, treatment facilities, regulators, researchers, farmers, and food-system actors. Life-cycle assessment, economic evaluation, digital monitoring and long-term field evidence can help to reconcile resource efficiency with public and environmental protection in locally adapted recovery pathways. If these conditions are met, municipal biowaste and wastewater can be reliable agricultural resources that can be used to improve soils, maintain water security and build more circular and resilient food production systems.

REFERENCES

1. Abbey, Lord, Yurgel, S. N., Asunni, O. A., Ofoe, R., Ampofo, J., Gunupuru, L. R., & Ajeethan, N. (2022). Changes in Soil Characteristics, Microbial Metabolic Pathways, TCA Cycle Metabolites and Crop Productivity following Frequent Application of Municipal Solid Waste Compost. Plants, 11(22), 3153. https://doi.org/10.3390/plants11223153

2. Abou Jaoude, L., Kamaleddine, F., Bou Said, R., Mohtar, R. H., Dbaibo, R., & Yanni, S. F. (2025). Treated wastewater reuse and its impact on soil properties and potato and corn growth. Science of The Total Environment, 958, 178130. https://doi.org/10.1016/j.scitotenv.2024.178130
3. Adegoke, A. A., Amoah, I. D., Stenström, T. A., Verbyla, M. E., & Mihelcic, J. R. (2018). Epidemiological Evidence and Health Risks Associated With Agricultural Reuse of Partially Treated and Untreated Wastewater: A Review. Frontiers in Public Health, 6. https://doi.org/10.3389/fpubh.2018.00337
4. Alghashm, S., Qian, S., Hua, Y., Wu, J., Zhang, H., Chen, W., & Shen, G. (2018). Properties of Biochar from Anaerobically Digested Food Waste and Its Potential Use in Phosphorus Recovery and Soil Amendment. Sustainability, 10(12), 4692. https://doi.org/10.3390/su10124692
5. Alnaimy, M. A., Shahin, S. A., Vranayova, Z., Zelenakova, M., & Abdel-Hamed, E. M. W. (2021). Long-Term Impact of Wastewater Irrigation on Soil Pollution and Degradation: A Case Study from Egypt. Water, 13(16), 2245. https://doi.org/10.3390/w13162245
6. Arcas-Pilz, V., Rufí-Salís, M., Parada, F., Petit-Boix, A., Gabarrell, X., & Villalba, G. (2021). Recovered phosphorus for a more resilient urban agriculture: Assessment of the fertilizer potential of struvite in hydroponics. Science of The Total Environment, 799, 149424. https://doi.org/10.1016/j.scitotenv.2021.149424
7. Arosemena Polo, J. D., Toboso-Chavero, S., Adhikari, B., & Villalba, G. (2024). Closing the nutrient cycle in urban areas: The use of municipal solid waste in peri-urban and urban agriculture. Waste Management, 183, 220–231. https://doi.org/10.1016/j.wasman.2024.05.009
8. Börjesson, G., & Kätterer, T. (2018). Soil fertility effects of repeated application of sewage sludge in two 30-year-old field experiments. Nutrient Cycling in Agroecosystems, 112(3), 369–385. https://doi.org/10.1007/s10705-018-9952-4
9. Buchanan, C. M., & Ippolito, J. A. (2021). Long-Term Biosolids Applications to Overgrazed Rangelands Improve Soil Health. Agronomy, 11(7), 1339. https://doi.org/10.3390/agronomy11071339
10. Clack, K., Rajagopal, D., & Hoek, E. M. V. (2024). Life cycle and techno-economic assessment of bioresource production from wastewater. Npj Clean Water, 7(1), 22. https://doi.org/10.1038/s41545-024-00314-9
11. Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E., & Geissen, V. (2019). Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. Science of The Total Environment, 671, 411–420. https://doi.org/10.1016/j.scitotenv.2019.03.368
12. Dereszewska, A., & Cytawa, S. (2023). Circular Economy in Wastewater Treatment Plants—Potential Opportunities for Biogenic Elements Recovery. Water, 15(21), 3857. https://doi.org/10.3390/w15213857
13. Fang, C., Zhang, T., Jiang, R., & Ohtake, H. (2016). Phosphate enhance recovery from wastewater by mechanism analysis and optimization of struvite settleability in fluidized bed reactor. Scientific Reports, 6(1), 32215. https://doi.org/10.1038/srep32215
14. Fragalà, F., Puglisi, I., Padoan, E., Montoneri, E., Stevanato, P., Gomez, J. M., Herrero, N., La Bella, E., Salvagno, E., & Baglieri, A. (2023). Effect of municipal biowaste derived biostimulant on nitrogen fate in the plant-soil system during lettuce cultivation. Scientific Reports, 13(1), 7944. https://doi.org/10.1038/s41598-023-35090-y
15. Ghanbari, M., Naeimi, A., & Bijani, M. (2024). Sustainable management of wastewater use in agriculture: A systematic analysis. Frontiers in Sustainable Food Systems, 8. https://doi.org/10.3389/fsufs.2024.1409293
16. Giacomello, G., Leonardi, N., Assandri, D., & Pampuro, N. (2025). Agricultural and Municipal Biowaste Within the Circular Economy Framework: A Bibliometric Analysis. Agriculture, 15(5), 546. https://doi.org/10.3390/agriculture15050546
17. Gu, X., Xiao, Y., Yin, S., Liu, H., Men, B., Hao, Z., Qian, P., Yan, H., Hao, Q., Niu, Y., Huang, H., & Pei, Q. (2019). Impact of Long-Term Reclaimed Water Irrigation on the Distribution of Potentially Toxic Elements in Soil: An In-Situ Experiment Study in the North China Plain. International Journal of Environmental Research and Public Health, 16(4), 649. https://doi.org/10.3390/ijerph16040649
18. Guerra-Rodríguez, S., Oulego, P., Rodríguez, E., Singh, D. N., & Rodríguez-Chueca, J. (2020). Towards the Implementation of Circular Economy in the Wastewater Sector: Challenges and Opportunities. Water, 12(5), 1431. https://doi.org/10.3390/w12051431
19. Habimana, E., & Sauvé, S. (2025). A review of properties, occurrence, fate, and transportation mechanisms of contaminants of emerging concern in sewage sludge, biosolids, and soils: Recent advances and future trends. Frontiers in Environmental Chemistry, 6. https://doi.org/10.3389/fenvc.2025.1547596
20. Hallas, J. F., Mackowiak, C. L., Wilkie, A. C., & Harris, W. G. (2019). Struvite Phosphorus Recovery from Aerobically Digested Municipal Wastewater. Sustainability, 11(2), 376. https://doi.org/10.3390/su11020376
21. Hashem, M. S., & Qi, X. (2021). Treated Wastewater Irrigation—A Review. Water, 13(11), 1527. https://doi.org/10.3390/w13111527
22. Holatko, J., Brtnicky, M., Mustafa, A., Kintl, A., Skarpa, P., Ryant, P., Baltazar, T., Malicek, O., Latal, O., & Hammerschmiedt, T. (2023). Effect of Digestate Modified with Amendments on Soil Health and Plant Biomass under Varying Experimental Durations. Materials, 16(3), 1027. https://doi.org/10.3390/ma16031027
23. Javier Mateo-Sagasta (IWMI), S. M. Z. (FAO) and H. T. (international consultant) with contributions from J. B. (formerly W. B. (2017). Water pollution from agriculture: A global review - Executive summary (1st ed.). FAO. https://openknowledge.fao.org/handle/20.500.14283/i7754en
24. Kaza, S., Lisa, C., Bhada-Tata, P., Van Woerden, F., & Levine, D. (2018). What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050 [Text/HTML]. World Bank. https://doi.org/https://doi.org/10.1596/978-1-4648-1329-0

25. Kehrein, P., van Loosdrecht, M., Osseweijer, P., Garfí, M., Dewulf, J., & Posada, J. (2020). A critical review of resource recovery from municipal wastewater treatment plants – market supply potentials, technologies and bottlenecks. Environmental Science: Water Research & Technology, 6(4), 877–910. https://doi.org/10.1039/c9ew00905a
26. Kovačić, Đ., Lončarić, Z., Jović, J., Samac, D., Popović, B., & Tišma, M. (2022). Digestate Management and Processing Practices: A Review. Applied Sciences, 12(18), 9216. https://doi.org/10.3390/app12189216
27. Lewerenz, S., Sailer, G., Pelz, S., & Lambrecht, H. (2023). Life cycle assessment of biowaste treatment – Considering uncertainties in emission factors. Cleaner Engineering and Technology, 15, 100651. https://doi.org/10.1016/j.clet.2023.100651
28. López-Serrano, M. J., Velasco-Muñoz, J. F., Aznar-Sánchez, J. A., & Román-Sánchez, I. M. (2022). Farmers' Attitudes towards Irrigating Crops with Reclaimed Water in the Framework of a Circular Economy. Agronomy, 12(2), 435. https://doi.org/10.3390/agronomy12020435
29. Mancho, C., Diez-Pascual, S., Alonso, J., Gil-Díaz, M., & Lobo, M. C. (2023). Assessment of Recovered Struvite as a Safe and Sustainable Phosphorous Fertilizer. Environments, 10(2), 22. https://doi.org/10.3390/environments10020022
30. Martín, J., Mejías, C., Santos, J. L., Aparicio, I., & Alonso, E. (2021). Pharmaceuticals and Their Main Metabolites in Treated Sewage Sludge and Sludge-Amended Soil: Availability and Sorption Behaviour. Molecules, 26(19), 5910. https://doi.org/10.3390/molecules26195910
31. Mora-Salguero, D., Montenach, D., Gilles, M., Jean-Baptiste, V., & Sadet-Bourgeteau, S. (2025). Long-term effects of combining anaerobic digestate with other organic waste products on soil microbial communities. Frontiers in Microbiology, 15. https://doi.org/10.3389/fmicb.2024.1490034
32. Morrissey, K. G., English, L., Thoma, G., & Popp, J. (2022). Prospective Life Cycle Assessment and Cost Analysis of Novel Electrochemical Struvite Recovery in a U.S. Wastewater Treatment Plant. Sustainability, 14(20), 13657. https://doi.org/10.3390/su142013657
33. Nisticò, R., Guerretta, F., Benzi, P., Magnacca, G., Mainero, D., & Montoneri, E. (2019). Thermal Conversion of Municipal Biowaste Anaerobic Digestate to Valuable Char. Resources, 8(1), 24. https://doi.org/10.3390/resources8010024
34. Ofori, S., Abebrese, D. K., Růžičková, I., & Wanner, J. (2024). Reuse of Treated Wastewater for Crop Irrigation: Water Suitability, Fertilization Potential, and Impact on Selected Soil Physicochemical Properties. Water, 16(3), 484. https://doi.org/10.3390/w16030484
35. Ortiz-Liébana, N., Crespo-Barreiro, A., Mazuecos-Aguilera, I., & González-Andrés, F. (2023). Improved Organic Fertilisers Made from Combinations of Compost, Biochar, and Anaerobic Digestate: Evaluation of Maize Growth and Soil Metrics. Agriculture, 13(8), 1557. https://doi.org/10.3390/agriculture13081557
36. Paltiel, O., Fedorova, G., Tadmor, G., Kleinstern, G., Maor, Y., & Chefetz, B. (2016). Human Exposure to Wastewater-Derived Pharmaceuticals in Fresh Produce: A Randomized Controlled Trial Focusing on Carbamazepine. Environmental Science & Technology, 50(8), 4476–4482. https://doi.org/10.1021/acs.est.5b06256
37. Pastorelli, R., Casagli, A., Rocchi, F., Tampio, E., Laaksonen, I., Becagli, C., & Lagomarsino, A. (2024). Effects of Anaerobic Digestates and Biochar Amendments on Soil Health, Greenhouse Gas Emissions, and Microbial Communities: A Mesocosm Study. Applied Sciences, 14(5), 1917. https://doi.org/10.3390/app14051917
38. Pecorini, I., Peruzzi, E., Albini, E., Doni, S., Macci, C., Masciandaro, G., & Iannelli, R. (2020). Evaluation of MSW Compost and Digestate Mixtures for a Circular Economy Application. Sustainability, 12(7), 3042. https://doi.org/10.3390/su12073042
39. Peng, W., & Pivato, A. (2019). Sustainable Management of Digestate from the Organic Fraction of Municipal Solid Waste and Food Waste Under the Concepts of Back to Earth Alternatives and Circular Economy. Waste and Biomass Valorization, 10(2), 465–481. https://doi.org/10.1007/s12649-017-0071-2
40. Phung, L. D., Pham, D. V., Sasaki, Y., Masuda, S., Takakai, F., Kaku, N., & Watanabe, T. (2020). Continuous Sub-Irrigation with Treated Municipal Wastewater for Protein-Rich Rice Production with Reduced Emissions of CH4 and N2O. Scientific Reports, 10(1), 5485. https://doi.org/10.1038/s41598-020-62247-w
41. Puyol, D., Batstone, D. J., Hülsen, T., Astals, S., Peces, M., & Krömer, J. O. (2017). Resource Recovery from Wastewater by Biological Technologies: Opportunities, Challenges, and Prospects. Frontiers in Microbiology, 7. https://doi.org/10.3389/fmicb.2016.02106
42. Rahman, M. M., Shahrivar, A. A., Hagare, D., & Maheshwari, B. (2022). Impact of Recycled Water Irrigation on Soil Salinity and Its Remediation. Soil Systems, 6(1), 13. https://doi.org/10.3390/soilsystems6010013
43. Saliu, T. D., & Sauvé, S. (2024). A review of per- and polyfluoroalkyl substances in biosolids: Geographical distribution and regulations. Frontiers in Environmental Chemistry, 5. https://doi.org/10.3389/fenvc.2024.1383185
44. Sdiri, W., AlSalem, H. S., Al-Goul, S. T., Binkadem, M. S., & Ben Mansour, H. (2023). Assessing the Effects of Treated Wastewater Irrigation on Soil Physico-Chemical Properties. Sustainability, 15(7), 5793. https://doi.org/10.3390/su15075793
45. Shrestha, P., Small, G. E., & Kay, A. (2020). Quantifying nutrient recovery efficiency and loss from compost-based urban agriculture. PLOS ONE, 15(4), e0230996. https://doi.org/10.1371/journal.pone.0230996
46. Smol, M., Adam, C., & Preisner, M. (2020). Circular economy model framework in the European water and wastewater sector. Journal of Material Cycles and Waste Management, 22(3), 682–697. https://doi.org/10.1007/s10163-019-00960-z

47. Sreelakshmi, C., Kiruthika, S., & Jeyalakshmi, R. (2022). A review of chemical and bioelectrochemical process of N, P nutrient recovery as struvite (MgNH4PO4·6H2O). Desalination and Water Treatment, 276, 282–300. https://doi.org/10.5004/dwt.2022.28967
48. Sun, L., Wei, B., Wu, D., Sun, K., Jiao, J., & Zhang, W. (2024). The Effects of Struvite on Biomass and Soil Phosphorus Availability and Uptake in Chinese Cabbage, Cowpea, and Maize. Agronomy, 14(8), 1852. https://doi.org/10.3390/agronomy14081852
49. Toop, T. A., Ward, S., Oldfield, T., Hull, M., Kirby, M. E., & Theodorou, M. K. (2017). AgroCycle – developing a circular economy in agriculture. Energy Procedia, Proceedings of 1st International Conference onSustainable Energy and Resource Use in Food ChainsincludingSymposium on Heat Recovery and Efficient Conversion and Utilisation of Waste HeatICSEF 2017, 19-20 April 2017, Windsor UK, 123, 76–80. https://doi.org/10.1016/j.egypro.2017.07.269
50. UNESCO World Water Assessment Programme. (2017). UN World Water Development Report, Wastewater: The Untapped Resource. UNESCO. UNESCO. https://www.unep.org/resources/publication/2017-un-world-water-development-report-wastewater-untapped-resource
51. Vieira, V. H. A. de M., & Matheus, D. R. (2019). Environmental assessments of biological treatments of biowaste in life cycle perspective: A critical review. Waste Management & Research, 37(12), 1183–1198. https://doi.org/10.1177/0734242X19879222
52. Weimers, K., Bergstrand, K.-J., Hultberg, M., & Asp, H. (2022). Liquid Anaerobic Digestate as Sole Nutrient Source in Soilless Horticulture—Or Spiked With Mineral Nutrients for Improved Plant Growth. Frontiers in Plant Science, 13. https://doi.org/10.3389/fpls.2022.770179
53. Weithmann, N., Möller, J. N., Löder, M. G. J., Piehl, S., Laforsch, C., & Freitag, R. (2018). Organic fertilizer as a vehicle for the entry of microplastic into the environment. Science Advances, 4(4), eaap8060. https://doi.org/10.1126/sciadv.aap8060
54. Zhao, K., Li, C., & Li, F. (2024). Research progress on the origin, fate, impacts and harm of microplastics and antibiotic resistance genes in wastewater treatment plants. Scientific Reports, 14(1), 9719. https://doi.org/10.1038/s41598-024-60458-z
55. Zielińska, M., & Bułkowska, K. (2024). Sustainable Management and Advanced Nutrient Recovery from Biogas Energy Sector Effluents. Energies, 17(15), 3705. https://doi.org/10.3390/en17153705