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SPECIAL FEATURE: REVIEW

Recent Advances in Sludge Management

From sewage sludge to agriculture: governmental initiatives, technologies, and sustainable practices in Japan

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Abstract

Sewage sludge (SS), an underutilized but valuable resource for agriculture, contains essential nutrients, such as phosphorus. In Japan, where dependence on imported fertilizers is high and global price fluctuations persist, using SS as fertilizer presents a sustainable alternative aligned with circular economy goals. This review analyzes Japan's current efforts to repurpose SS, focusing on technological developments and key policy initiatives that promote safe and effective application. Selective phosphorus recovery technologies mitigate resource depletion, while holistic approaches, such as composting and carbonization, maximize sludge utilization for agricultural applications. Government-led initiatives, including public awareness campaigns, quality assurance standards and research support, have facilitated the adoption of sludge-based fertilizers. To contextualize Japan's position, international trends, particularly in the EU, are also examined. These comparisons reveal both common strategies and areas for policy and technological advancement, especially regarding regulation of emerging contaminants. By integrating national case studies with global perspectives, the study offers insights into the economic, environmental, and social benefits of SS reuse, contributing to Japan's goals of resource self-sufficiency and carbon neutrality, while also informing broader sustainable agriculture transitions worldwide.

Keywords Japan · Sewage sludge · Agriculture · Sludge fertilizers · Governmental initiatives

Introduction

Sewage sludge (SS), a byproduct of wastewater treatment, is rich in nutrients and holds great potential for sustainable agriculture. In Japan, 2.35 million tons of SS were generated in fiscal year 2022, of which 50% was used as construction materials after incineration, 26% remained unused, and only about 14%, or 320,000 tons, were used as fertilizer [1]. Leveraging this resource could support Japan's shift toward sustainable agriculture.

Japan's heavy reliance on imported chemical fertilizers (nearly 100% of raw materials, such as ammonium phosphate and urea [2]) poses a significant vulnerability. Since 2022, global geopolitical conflicts and rising energy costs have driven fertilizer prices to unprecedented levels [3]. As of October 2024, 69% of Japan's urea came from Malaysia and 99% of its ammonium phosphate from China [3]. This dependency heightens supply chain risks, underscoring the need for sustainable sludge utilization to bolster agricultural resilience.

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Nutrient recovery, especially phosphorus (P), is central to sludge utilization [4], and has been widely recognized in international frameworks as a key pathway for circular nutrient management [5]. As a non-renewable yet essential nutrient for crop productivity [6, 7], P is rapidly depleting [8]. The overuse of synthetic fertilizers leads to environmental losses, causing eutrophication, GHG emissions, and soil degradation [8, 9]. Innovative recovery technologies, such as struvite crystallization [10, 11], offer promising solutions for capturing phosphorus from SS.

Japan is among the leaders in developing and adopting technologies to transform SS into a valuable agricultural resource [12]. Over the past decades, the country has undertaken extensive efforts to advance both technological solutions and policy reforms that support sludge utilization. However, information on Japan's progress in this area remains limited, as much of the relevant literature is available only in Japanese. This lack of accessibility has hindered the global dissemination of knowledge regarding Japan's innovations and practices in this field.

For the first time, this review brings together the combined expertise of researchers with extensive experience in Japan's sludge management efforts to provide a comprehensive overview of the country's achievements. The review evaluates the current state of SS utilization in Japan, focusing on both technological advancements and policy frameworks that enable its transformation into agricultural fertilizers. To broaden the discussion, Japan's experience is compared with international efforts, especially in the EU, revealing both strengths and gaps in regulating emerging contaminants. The findings offer practical insights to guide future strategies for sustainable sludge reuse in Japan and beyond.

Transforming perceptions of sewage sludge: historical milestones and future directions in Japan

Japan is one of the leading nations in the development and implementation of SS treatment technologies for mitigating environmental pollution and recovering valuable resources. These initiatives have been ongoing for decades, driven by policy shifts, technological advancements, and increasing awareness of resource crises. Such efforts, summarized in Fig. 1, reflect Japan's long-term vision of achieving a circular economy, carbon neutrality, and food security.

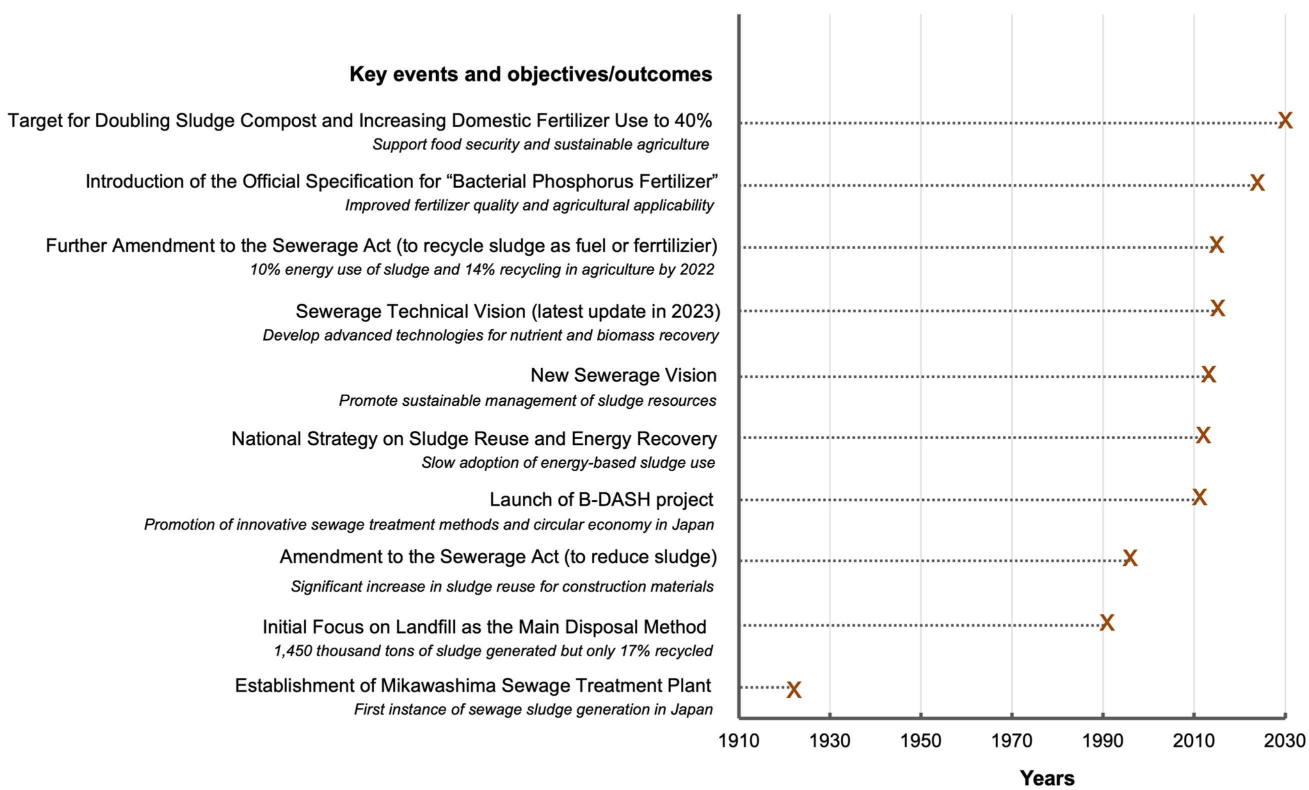

Fig. 1 Historical and strategic milestones in sewage sludge treatment and reuse in Japan

Early stages and transition in sewage sludge treatment

Before the development of sewerage systems, Japan employed a bucket-based collection system for human urine and feces, which was then returned to agricultural land as a natural fertilizer. The 1922 opening of the Mikawashima Wastewater Treatment Plant in Tokyo, which used the trickling filter process, marked the start of SS generation. Over the next 70 years, landfilling was the dominant disposal method [13, 14].

By 1991, SS production reached 1.45 million tons (dry solid), but only 17% was recycled–12% for fertilizer and 5% for non-cement construction materials. At the time, treatment efforts focused on reducing landfill volume, mainly through incineration and reuse of incineration ash, rather than resource recovery [14].

Policies and social trends: advancing circular economy and carbon neutrality

A significant policy shift occurred in 1996 when the Sewerage Act was amended, mandating sewerage system managers to make efforts to reduce sludge volume. Consequently, the proportion of sludge reused as construction materials increased substantially, reaching 50% by 2022 [1].

In 2015, further amendments to the Sewerage Law introduced obligations to make efforts to recycle sludge as fuel or fertilizer, thereby promoting decarbonization efforts. The utilization rate of sludge for energy rose from less than 2% in 2012 to 10% in 2022 [1]. In agriculture, the recycling rate of sludge as fertilizer remained stable from 12% in 1991 to 14% in 2022. Recently, growing concerns over food security have accelerated efforts to expand sludge recycling into fertilizers.

Strategic vision: the new sewerage vision and technological development

In 2014, Japan introduced the "New Sewerage Vision: Continuity and Evolution of the Circular Path", formulated by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) in collaboration with the Japan Sewage Works Association (JSWA) [15]. This vision presents policies for managing and utilizing SS-derived resources, such as water, organic matter, phosphorus, and renewable energy, which remain underutilized. To address long-term challenges, the vision proposes establishing resource collection hubs and integrating water and biomass projects to improve regional management efficiency. In the medium term, the "New Sewerage Vision" sets out specific goals, including the centralization of resource collection and supply, the development of efficient sludge utilization plans in coordination with biomass projects, and the expansion of initiatives on a regional scale. It also emphasizes collaboration with the agricultural sector to recover nutrients like phosphorus and promote local food production and consumption [15].

To implement the "New Sewerage Vision" and tackle sludge management challenges, MLIT's Sewerage and Wastewater Management Department and the National Institute for Land and Infrastructure Management developed the "Sewerage Technical Vision" in December 2015, with the latest update issued in March 2023 [16]. This vision provides a roadmap for advancing 11 technical fields in the sewerage sector, with objectives segmented into three phases: short-term (2025), medium-term (2030), and long-term (2050). The "Regional Biomass" domain focuses on recovering and reusing resources from SS, including phosphorus and other minerals. The medium-term goals include developing technologies for phosphorus recovery from methanogenic fermentation filtrate and producing high-value products from incinerated sludge ash via drying, incineration, thermal melting, and fermentation, while ensuring product safety and reliability [16].

The implementation of these objectives has been strongly driven by practical projects, and the B-DASH (Breakthrough by Dynamic Approach in Sewage High Technology) project, launched in 2011, has played a key role in advancing sludge management technologies [17]. By fiscal year 2024, 23 out of 61 full-scale demonstration projects (approximately 38%) implemented under the B-DASH initiative were related to sludge treatment and utilization technologies, with 10 projects (around 16%) targeting phosphorus recovery and agricultural reuse. Concurrently, selective phosphorus recovery technologies, such as magnesium ammonium phosphate (MAP) crystallization and composting techniques, are being actively developed and implemented [18] to improve resource recovery, reduce pollution, and support a circular economy.

Ensuring food security and the future of nutrient recovery

Amid rising geopolitical tensions, energy instability, and fertilizer costs, Japan has taken targeted measures to enhance food security by repurposing SS as fertilizer. Under the "Policy Framework for Strengthening Food Security" [19], Ministry of Agriculture, Forestry and Fisheries (MAFF) and the MLIT are jointly advancing SS utilization to address shortages, aiming to double SS and compost use by 2030 and raise domestic phosphorus-based fertilizer usage to 40%.

To support these objectives, MLIT issued a 2023 directive encouraging wastewater facilities to prioritize SS use in fertilizer production [20]. In that same year, a major milestone in Japan's fertilizer control system was the introduction of the "Microbe phosphate fertilizer" category [21], officially recognizing SS as a viable fertilizer material. This new specification requires quality management plans to ensure consistent nutrient content, particularly phosphorus, thereby enhancing safety and reliability. Compared to traditional sludge fertilizers, this classification significantly broadens the scope of SS applications, including its use as a raw material for fertilizer production. Supported by recent policy reforms, Japan is now actively implementing targeted technical development and demonstration projects. These efforts not only address fertilizer shortages but also advance a circular economy and strengthen long-term food security.

Technologies for bringing sewage sludge to agriculture

This section explores the technological advancements that enable the application of SS in agriculture in Japan, categorized into three main groups, as shown in Fig. 2: technologies for selective phosphorus recovery, technologies for direct utilization of sludge as phosphorus-containing materials, and technologies for composting. The phosphorus recovery technologies extract phosphorus for reuse, while direct utilization methods retain its fertilizer-level content for agricultural application. Composting, meanwhile, stabilizes organic matter and enhances soil health by converting sludge into nutrient-rich compost.

To support the implementation of these technologies, organizations, including the MLIT [22–24], the JSWA [25], Japan Institute of Wastewater Engineering and Technology [26, 27], and Japan Sewage Works Agency (JS) [28] have developed and published comprehensive guidelines, manuals, and case studies. These documents provide technical insights into resource recovery, including selective phosphorus recovery and broader strategies for the effective utilization of sludge-derived resources.

Technologies for selective phosphorus recovery

Phosphorus recovery technologies, which extract phosphorus in the form of inorganic compounds, were originally developed to solve issues, such as pipe clogging, and stabilize effluent quality in wastewater treatment [29, 30]. Beyond technical objectives, these technologies have since evolved into essential tools to counter global phosphate depletion.

In Japan, awareness of phosphate-related environmental issues began in the 1970s [31], with the first scientific reports on phosphorus recovery technologies emerging in the mid-1980s. Notably, Ando (1983) emphasized both resource risks and the potential for recovery from wastewater [32]. Earlier developments in the 1970s focused on phosphorus removal to reduce water pollution [33–35], including the mitigation of eutrophication in enclosed water bodies such as lakes and inner bays [36–39]. Continuous innovation since then reflects Japan's long-standing commitment to phosphorus recycling, reinforcing its shift toward a circular economy and reduced dependence on imports.

Phosphorus recovery in the sewage treatment process

In sewage treatment processes, phosphorus exists in various forms and can be recovered through multiple approaches, depending on the treatment stage and target medium. Figure 3 shows the main phosphorus recovery pathways from sewage treatment processes in Japan, highlighting key technologies applied at different treatment stages.

Magnesium ammonium phosphate method The magnesium ammonium phosphate (MAP) method is one of the earliest and most widely implemented technologies for phosphorus recovery. By adding magnesium, phosphorus and nitrogen are crystallized into struvite ($MgNH_4PO_4.6H_2O$) and subsequently recovered. In Fukuoka city, efforts to prevent eutrophication in Hakata

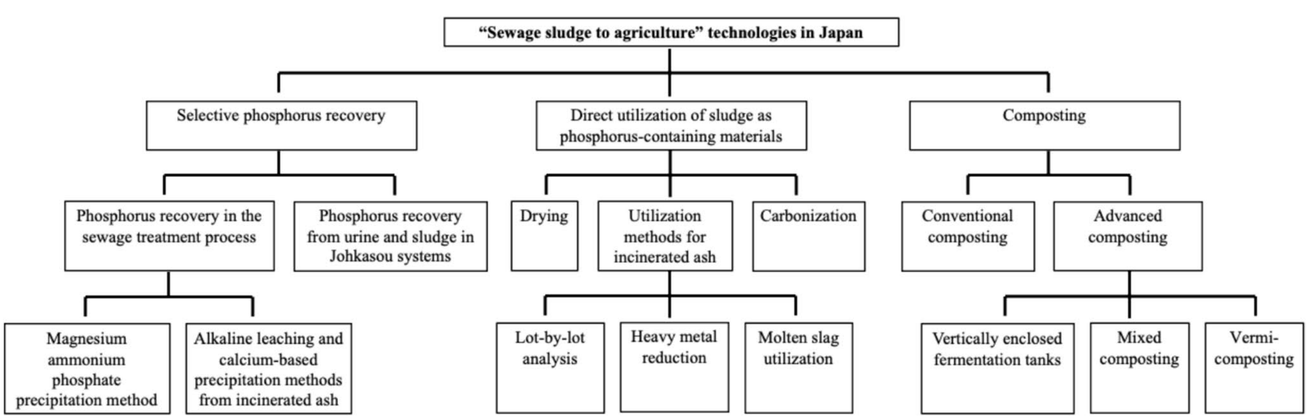

Fig. 2 Overview of sewage sludge-to-agriculture technologies in Japan

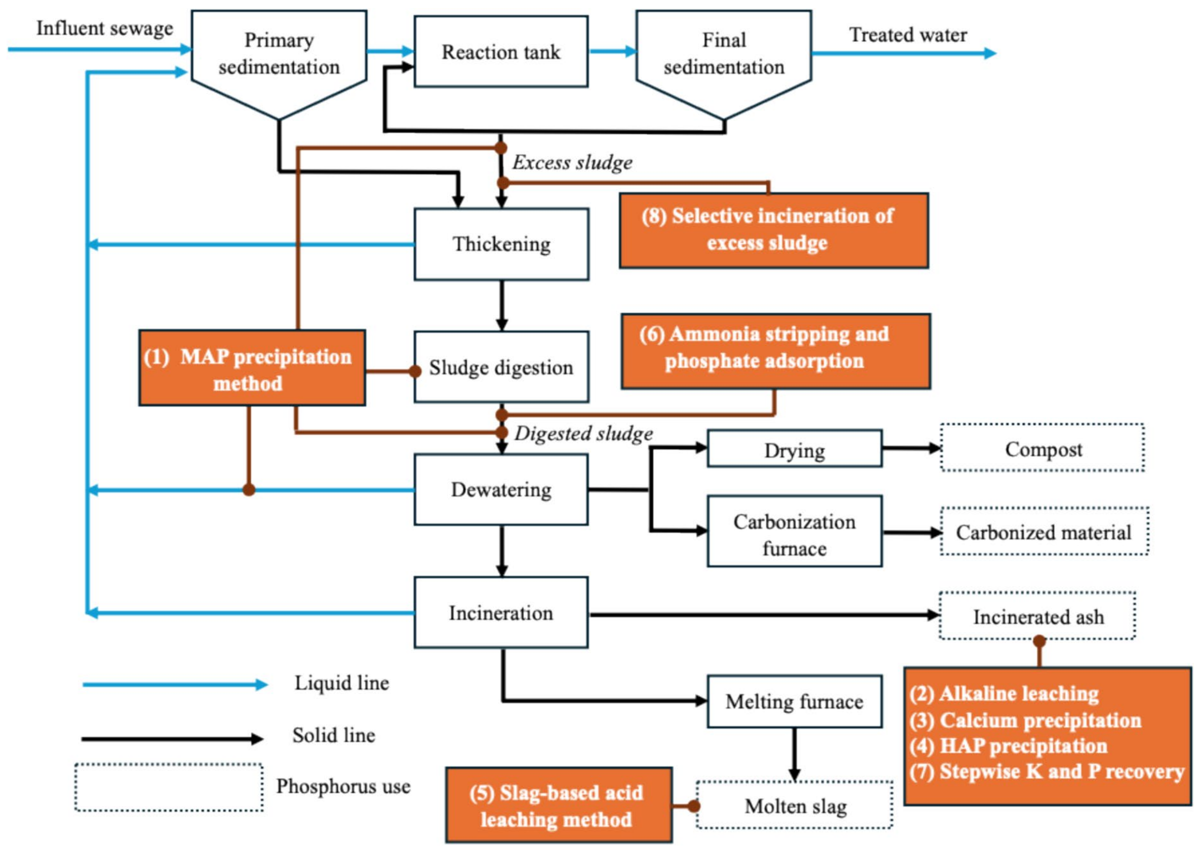

Fig. 3 Roadmap of phosphorus recovery techniques from the sewage treatment process in Japan

bay were initiated in 1993 using the anaerobic-oxic process for phosphorus removal. When phosphorus was released in anaerobic digestion tanks, it combined with magnesium and ammonia to form MAP crystals that accumulated in water pipelines, causing blockages. Consequently, MAP recovery technology was first implemented on a full scale in 1996 at Wajiro Sewage Treatment Center in Fukuoka city and later in Shimane prefecture [37–39].

At its early stage, the MAP method was particularly applied to recover phosphorus from two key sources in sludge digestion processes: digestate dewatering filtrate and digestate. In Japan, where organic matter accounts for approximately 80% of SS [40], anaerobic digestion (AD) is considered one of the most cost-effective sludge treatment methods [41], and plays a critical role as an intermediate technology for resource recovery. During AD, proteins in excess sludge (comprising 50–60% of total organic matter) are hydrolyzed into amino acids and further converted into ammonium nitrogen [42, 43], which accumulates in the liquid phase instead of being oxidized. Meanwhile, phosphorus and metal salts are released and remain in the liquid phase. This concentration of phosphorus and nitrogen in digestate dewatering filtrate and digestate creates ideal conditions for the efficient implementation of the MAP precipitation method.

The MAP recovery technology targeting the liquid extracted during the dewatering of anaerobically digested sludge has been developed and implemented at a sewage treatment plant in Shimane prefecture. This plant discharged treated water into a lake, where eutrophication has become a critical issue, necessitating the removal of nutrient during the treatment process. Initially, nutrient removal was achieved through advanced treatment methods; however, the return flow from sludge treatment, containing high phosphorus concentrations, disrupted the stability of phosphorus removal efficiency. To address this challenge, a MAP recovery system was introduced in 1998 [39]. The system achieved a treatment capacity of 500 m^3/day and produced high-quality MAP free from heavy metals, which has been applied as fertilizer [44, 45].

During AD, phosphorus concentration increases, leading to pipeline blockages at the outlet of digestion tanks. Phosphorus recovery conducted after sludge dewatering cannot resolve these blockages or recover MAP formed inside the digestion tank. To address this, a technology for direct MAP recovery from digestion tanks was developed and implemented [36, 46–49]. Magnesium is added to digested sludge to generate MAP and the crystals are collected by liquid cyclone together with MAP naturally generated in digestion tank. Pilot-scale experiments with a processing capacity of 50 m^3/day achieved recovery rates of 33% TP and 93% PO_4-P, ensuring stable phosphorus recovery. In 2012, a full-scale facility was launched at a sewage treatment plant in Kobe city, achieving phosphorus recovery rates of 40% TP and 90% PO_4-P with a treatment capacity of 239 m^3/day. The implementation of this technology not only stabilized phosphorus recovery but also reduced dewatered sludge volume by 3.3% and successfully prevented pipeline blockages [50]. The long-term experiment spanning three years and eight months also confirmed that the MAP method suppresses large-scale phosphorus crystallization and ensures stable phosphorus recovery. Furthermore, the recovered phosphorus was used to develop local fertilizers for horticulture and rice cultivation, promoting regional phosphorus recycling. The results of this demonstration research have been formalized as guidelines [51] and introduced as full-scale projects at the Wajiro Sewage Treatment Center in Fukuoka city in 2022 [37, 38].

In recent years, demonstration studies in the B-DASH Project have broadened the application of the MAP precipitation method to excess sludge (through AD) [52] and anaerobic digested sludge [53], while improving recovery methods from anaerobic digested sludge dewatering filtrate [54]. For technologies targeting excess sludge, focusing on the fact that most of the phosphorus in the sewage is concentrated by activated sludge and transferred to excess sludge, resulting in a much higher phosphorus concentration than raw sludge, excess sludge and raw sludge are anaerobically digested separately, and phosphorus recovery is performed by applying MAP precipitation technology only to the excess sludge. This initiative began in 2024 at the Seibu Sewage Treatment Plant in Fukuoka city [52]. For technologies targeting anaerobic digested sludge, demonstration research at the Tamatsu Sewage Treatment Plant in Kobe city commenced in 2022, has focused on enhancing reaction efficiency by modifying completely mixed reactors, increasing phosphorus recovery rates, maintaining high seed crystal concentrations, and standardizing particle size [53]. For technologies targeting anaerobic digested sludge dewatering filtrate, demonstration research was initiated in 2022 at the Hokubu Sludge Treatment Plant in Yokohama city. This study focuses on automated magnesium injection, low-temperature melting with digester gas waste heat, and replacing liquid cyclones with passive flow methods to efficiently recover phosphorus and enhance MAP's applicability as fertilizer and raw material [54].

In summary, through the implementation of the MAP precipitation method, significant benefits have been realized, including reduced return water load in anaerobic digestion, stabilized phosphorus removal efficiency, and effective resource recovery. Since its implementation in 1996 in Fukuoka city, the MAP method has proven practical, producing recovered MAP with a guaranteed phosphorus pentoxide content of 23%, officially registered as fertilizer, and achieving sales of 37.5 tons in fiscal year 2022 in Shimane prefecture [55].

Phosphorus recovery from incinerated ash via alkaline leaching and calcium-based precipitation In Japan, the shortage of waste disposal sites has led to the widespread incineration of SS, resulting in SS ash (SSA), which is rich in phosphorus. However, SSA also contains heavy metals (e.g., Cu, Zn, Ni, Cd, Hg, As) that pose safety risks. Although not legally restricted, the direct use of SSA in phosphate fertilizer is typically limited to around 2.5% to meet standards for nutrient content and heavy metal concentrations [56]. To enhance phosphorus recycling while ensuring safety, methods to separate phosphorus from heavy metals are required.

The alkaline leaching method addresses this issue by selectively extracting phosphorus through pH adjustment, rendering heavy metals insoluble [57–59]. Initially developed in 1994 to utilize SSA for brick manufacturing, this application declined by 2008 due to reduced demand and aging facilities. The focus then shifted to phosphorus recovery and the reuse of residual ash in construction, marking a significant advancement in resource recovery.

To further improve phosphorus recovery efficiency, a combination of alkaline leaching and calcium-based precipitation was introduced. In this process, calcium hydroxide ($Ca(OH)_2$) is added to the extracted solution, precipitating phosphorus as calcium phosphate. An example is the 2010 application at a sewage treatment plant in Gifu prefecture [58–60]. Sodium hydroxide extracted phosphorus ions under 50–70 °C, followed by calcium hydroxide to precipitate calcium phosphate at 20–50 °C over 9 h. The recovered phosphorus was processed into secondary phosphate fertilizer, while the remaining ash was reused in construction. This method demonstrated a phosphorus recovery rate of 30–40% [58, 59]. This technology was developed under a national SS resource recovery technology development project [60] and subsequently introduced in Tottori city in 2013 [61]. In addition, the hydroxyapatite (HAP) precipitation (or crystallization) method offers an alternative approach for phosphorus recovery. This method induces crystallization of hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$), producing a more stable and structurally defined product, with broader industrial and agricultural applications. Successful applications of the HAP precipitation method have been reported in Gero city and Kita-Shiobara village [22], demonstrating its efficiency and scalability in phosphorus recovery.

Fundamental research While many phosphorus recovery technologies have progressed to demonstration or full-scale implementation, fundamental research plays a pivotal role in addressing existing challenges and exploring innovative approaches to optimize phosphorus recovery. These studies focus on enhancing recovery efficiency, mitigating contaminants (e.g., heavy metals), and identifying methods for simultaneous recovery of multiple nutrients, such as phosphorus, ammonia, and potassium.

Fundamental research focuses on extracting phosphorus from molten SS slag and enhancing the phosphorus content in sludge incineration ash as an initial step toward phosphorus recovery. For example, Nakao et al. [62] developed a process to recover phosphorus from sewage molten slag. By immersing slag in sulfuric acid and applying ultrasonic vibrations, they successfully extracted nearly 100% of the phosphorus into the leaching solution. The study further explored methods to recover phosphorus as a solid material while removing mixed metals, ensuring a cleaner end product. To address the issue of heavy metals in incinerated ash, Sone et al. [63] proposed separating primary sludge and excess sludge before incineration. Their findings demonstrated that incinerating excess sludge separately produces ash with higher phosphorus content and lower heavy metal concentrations, making it a promising alternative to phosphate rock. The research also focused on improving incineration processes to increase phosphorus recovery and prevent operational issues, such as clogging.

In addition to phosphorus, fundamental research explores the simultaneous recovery of multiple nutrients, which is essential for sustainable resource utilization. Takashima et al. [64] investigated nutrient recovery systems targeting ammonia and phosphorus from high-concentration, high-temperature anaerobically digested sludge. Ammonia stripping was performed on withdrawn digested sludge, with partial return to the digester, while phosphorus was selectively recovered using adsorption–desorption processes. This demonstrates the potential for integrated recovery systems to maximize nutrient recycling. Moreover, Yoshida et al. [65] examined methods to recover potassium and phosphorus from incinerated SS solid fuel ash. Using a stepwise extraction process, potassium was first recovered without losing phosphorus, followed by phosphorus extraction. Repeating the two extraction processes has improved recovery rates and enabled the production of solid materials suitable as raw inputs for by-product fertilizers.

Phosphorus recovery from urine and sludge in Johkasou systems

According to the survey results on the actual conditions of municipal waste and wastewater treatment in fiscal year 2022 by the Ministry of the Environment, in Japan, 17% of the population relies on Johkasou systems (household wastewater treatment facilities), while 4% utilize night soil treatment systems [66]. Most of the sludge from Johkasou systems is treated at human waste management facilities together with urine and feces. In Japan, there are approximately 870 such facilities [67], of which only around ten implement phosphorus recovery technologies [68]. The technologies employed at these facilities are comparable to those used in conventional sewage treatment plants, where phosphorus is recovered as either MAP or calcium phosphate. For instance, in Akita prefecture, a treatment facility with a processing capacity of 65 m^3/day recovers phosphorus as calcium phosphate after the removal of organic matter and nitrogen, achieving a recovery rate of 24% [69].

Technology for utilizing sludge as a phosphorus-containing material

Building upon the advancements in selective phosphorus recovery technologies discussed earlier, alternative approaches focus on harnessing the phosphorus content in sludge more holistically. These methods emphasize utilizing SS directly as a resource for fertilizers or fuels, bypassing the need for selective phosphorus recovery processes. Technologies for drying and carbonizing sludge, for instance, aim to convert sludge into phosphorus-enriched materials suitable for agricultural or energy applications. Unlike selective recovery processes that isolate phosphorus compounds, these technologies integrate sludge treatment into broader resource utilization frameworks, with several approaches already reaching demonstration and practical application stages.

Drying technology

Drying technologies for SS aim to reduce disposal costs especially at small- and medium-scale treatment plants while facilitating its efficient use as fertilizer or fuel. One of these technologies integrates sludge dehydration and drying systems, combining a mechanical two-phase centrifugal dehydrator with a circular-flow dryer utilizing thermal air circulation. A notable feature of this system is the use of high molecular and inorganic coagulants in the centrifugal dehydrator, which produces sludge with low moisture, lightweight properties, and small particle size. The circular-flow dryer enhances the process by recirculating hot air within its chamber, effectively drying the sludge and reducing its bulk density through a circular exhaust system, simplifying operations, and saving space and labor [70]. A demonstration study of this system conducted in 2016–2017 at a sludge treatment scale of 270 kg-wet/hour (equivalent to 1.8–3.2 tons/day of dried sludge) [71]. It achieved a 51% reduction in total costs-encompassing construction, maintenance, and sludge disposal-and a 63% reduction in energy consumption at a processing capacity of 20,000 m^3/day, meeting JIS Z7312 BSF-15 standards for fertilizer regulations [70, 71]. Following these results, implementation proceeded at six facilities, including Matsugashima Treatment Plant in Ichihara city [72, 73].

Beyond its application in energy recovery, the utilization of dried SS as fertilizer has also gained attraction. Takao et al. [74] reported the effectiveness of utilizing dried SS as fertilizer on golf courses, observing good turf growth comparable to existing fertilizers. They also reported that the introduction of the dewatering and drying system has enabled the annual sale of 70 tons of dry solid as fertilizer, contributing to the reduction of maintenance costs.

Following this trend, dried SS, previously used solely as solid fuel, has increasingly been repurposed for fertilizer applications. For example, Nagoya city has utilized dried sludge as solid fuel and plans to produce "Microbe phosphate fertilizer" in 2024, containing 4.0% nitrogen and 3.0% phosphorus pentoxide [75]. Similarly, Kitakyushu city has implemented sludge fuelization, registering its product as "Microbe phosphate fertilizer" with guaranteed components of 4.0% nitrogen and 3.2% phosphorus pentoxide [76].

To achieve effective utilization of SS in wide areas, a steam-based indirect drying system has been developed. This technology adapts to variations in sludge properties, reduces life cycle costs (LCC), and produces stable dried products throughout the year. The products meet fertilizer composition standards and do not inhibit plant growth. This technology was selected as an innovative technology by the JS in 2021 and has been implemented in a full-scale sewage treatment facility [77]. The technology of utilizing an automated regenerative heat pump also achieves high drying efficiency while saving energy and reducing cost and produces dried products for fertilizer and fuel applications [78].

Carbonization technology

Carbonization technologies, while primarily focused on fuel applications, have also been explored for producing fertilizers from carbonized materials. At the Fukuyama city Matsunaga Purification Center, a full-scale demonstration study investigated phosphorus recovery from dewatering filtrate using biochar, primarily derived from carbonized sewage sludge [79]. In 2023, the Kesennuma City Final Treatment Plant initiated demonstration studies utilizing ultra-high-temperature, energy-efficient carbonization systems to produce activated carbon substitutes and fertilizers [80].

Furthermore, hydrothermal carbonization technology, aimed at producing both fuel and fertilizer, utilizes dewatered sludge heated in pressurized tanks to enhance dehydration efficiency and solid–liquid separation. By adding carbonization accelerants, it produces carbon-rich slurry, which is then pressed to obtain carbonized material with approximately 30% moisture content. This process minimizes energy consumption by leveraging waste heat from digester gas power generation [81].

Utilization technologies for incinerated ash

As part of a demonstration project for utilizing SS incinerated ash as fertilizer, the Arakawa Water Circulation Center in Saitama prefecture ensures that harmful components remain within standard limits through lot-by-lot analysis. The center is advancing efforts to register the ash as a "Microbe phosphate fertilizer", containing 16% phosphorus pentoxide, by 2024, with plans for its application as a fertilizer material [82]. In Tokyo and Akita prefectures, a feasibility study initiated in 2022 focuses on reducing heavy metal content in incinerated ash using methods such as high-temperature dust collection and water washing, enhancing its suitability as a fertilizer material [83, 84].

Further, basic research explores the fertilizing potential of molten SS slag. According to Terasaki et al. [85] molten slag from SS in Toyama prefecture, traditionally used as a construction material, has demonstrated compliance with official fertilizer specifications, including phosphorus pentoxide content and phytotoxicity test safety requirements. The research confirmed its effectiveness as a fertilizer comparable to commercial products, with no harmful substance concerns.

Microbe phosphate fertilizer

Efforts to utilize SS as a raw material for phosphorus-containing fertilizers have been gaining momentum. The MAFF has actively promoted the use of fertilizers derived from sewage resources. To ensure the quality of these fertilizers, a new official specification for "Microbe phosphate fertilizer" has been established [21]. The "Microbe phosphate fertilizer" is a specific fertilizer category defined under the Japanese Fertilizer Control Act. It is produced using sewage sludge-derived materials, such as activated sludge or its incinerated ash. The product must meet strict standards including a minimum total phosphate (P_2O_5) content of 1% and comply with maximum allowable concentrations for heavy metals (As, Cd, Hg, Ni, Cr, and Pb). These regulations ensure both nutrient value and environmental safety.

With growing demand for fertilizers made from SS, registrations for "Microbe phosphate fertilizer" are increasingly replacing traditional sludge-based fertilizers. As of December 2024, five products have been officially registered: one incinerated ash fertilizer (Saitama Prefecture Arakawa Water Circulation Center [82]), two dried solid fuel products (Nagoya City Sorami Sludge Recycling Center [75]; Kitakyushu City Hiagari Purification Center [76]), and one compost product (Kagoshima City SS Composting Facility) [86].

Technology for composting

In addition to the phosphorus-related technology, composting is one of the main methods for using SS in agriculture. It transforms the organic fraction of sludge into nutrient-rich fertilizer, effectively inactivates pathogens, stabilizes the final product, and enhances soil fertility. This process also enables the co-treatment of other organic wastes, broadening its applicability in agricultural settings.

Conventional composting technology and its practices

The use of SS as fertilizer is a long-established practice in Japan, with around 1000 treatment plants currently adopting composting methods [87]. This approach is also anticipated to contribute to decarbonization through the reduction of chemical fertilizer usage [88]. In Akita prefecture, a private company has produced ~600 tons of SS-based compost annually since 2002 using a simple fermentation process [89]. Additionally, new composting facilities are being introduced using the design, build, and operate (DBO) method to enhance sludge treatment capacity [90]. In Saga city, composting facilities were established in 2009 at the Saga Sewage Purification Center, producing approximately 1600 tons of compost annually by incorporating fermented byproducts, waste soil, chaff, and bamboo chips into dewatered SS [91]. In Shiga prefecture, a composting facility was built at the Takashima Purification Center using the DBO method, with operations scheduled to commence in 2024. Similar to Saga city, this facility utilizes ultra-high-temperature aerobic fermentation technology and is projected to produce approximately 500 tons of compost annually [92].

Advanced composting technologies

To enhance sludge treatment and maximize the value of organic matter, various advanced composting methods have been developed. These innovations improve product quality, reduce operational costs, and increase sustainability while meeting environmental standards.

One such innovation is the vertically enclosed fermentation tanks, introduced in 2023 at the Shinjiko Seibu Wastewater Treatment Plant in Shimane prefecture. This method replaces traditional composting techniques with enclosed fermentation tanks, providing significant space savings, odor containment, and improved labor efficiency through a fermentation process control system [93, 94].

Mixed composting is another advancement, combining SS with organic materials, such as cattle manure [95, 96], roadside tree pruning [97], and food waste [98]. Localized applications include blending with shochu dregs, bamboo sawdust, or rice bran to produce compost tailored for specific crops, such as low-potassium compost for tea cultivation [99, 100].

Vermicomposting technology, which utilizes earthworms to facilitate aerobic decomposition, offers an energy-saving, low-emission solution that reduces heavy metals (Cu, Zn, Cd) while enhancing compost quality [101, 102].

Application of sewage sludge fertilizers in agriculture and its challenges

The limited adoption of SS fertilizer is largely attributed to farmers' and the public's concerns regarding the nutrient efficacy and heavy metal content of the sludge. Addressing the challenges of sludge-derived "Microbe phosphate fertilizers" requires considering nutrient efficacy, heavy metal safety, and stable distribution and pricing from farmers' perspectives. Unlike chemical fertilizers, nitrogen and phosphorus in SS release nutrients slowly due to gradual mineralization, while recovered phosphorus in forms of MAP and HAP is comparable to the effectiveness of chemical fertilizers. This section summarizes the types and characteristics of SS fertilizers, explores challenges in agricultural application, and highlights national research projects currently underway.

Types, efficacy, and applications of sewage sludge-based fertilizers

Types of sewage sludge fertilizers

Various types of fertilizers derived from SS have been developed, including dried sludge, fermented compost, and compounds (e.g., MAP and HAP), which are recovered through the treatment of wastewater, sludge, or incinerated sludge ash. Although MAP and HAP are widely used, some alternative recovery methods can yield other forms of phosphorus, such as iron-bound phosphorus [103]. For example, a method involving the melting of ash with magnesium and calcium oxides to create fertilizer has been developed [104, 105]. Calcium silicate-based adsorbents, after recovering phosphorus from wastewater, have also been shown to be effective for cultivation, such as growing komatsuna (*Brassica rapa var. perviridis*) [106].

Factors affecting the efficacy of these fertilizers

There are four key factors influencing the efficacy of SS-based fertilizers: the solubility of phosphorus fertilizers, the mineralization process of organic phosphorus, the impact of flocculants, and the reaction of inorganic phosphorus with soil components. First, the solubility of phosphorus fertilizers depends not only on the compound form but also on factors, such as the degree of crystal development and particle size in solid fertilizers [107]. According to Goto et al. [108], recovered MAP with a larger particle size demonstrated slightly lower fertilization efficacy when applied to komatsuna. Besides, phosphorus in incinerated sludge ash is often challenging for crops to absorb [109, 110], but research indicates that controlling production conditions, such as calcium addition, can enhance phosphorus solubility [111]. Flocculants, commonly used in wastewater treatment to neutralize the negative charge of particles and facilitate sedimentation, can react with inorganic phosphoric acid in water, potentially reducing phosphorus availability to plants. Commonly used flocculants include lime, iron, aluminum, and polymers. Lastly, inorganic phosphorus can react with soil components, further decreasing its availability to crops. This issue is particularly relevant in Japan, where nearly half of upland soils are volcanic ash soils with high active aluminum content, which strongly adsorbs inorganic phosphorus and affects fertilizer performance in field applications.

Trials in the field and the pots to examine the efficacy of these fertilizers

The earliest recorded trials of SS application in Japan date back to around 1970 [112, 113]. By the 1980s, studies began investigating the average phosphorus content of SS and its effects on the chemical and physical properties of agricultural soils [114]. More recently, fertilizers derived from recovered HAP [115] and compost [116] have shown comparable or slightly lower yields than chemical fertilizers.

Hattori et al. [117] quantified the forms of phosphorus in two soil types after incorporating six air-dried sludge materials, classifying them into calcium-bound, iron-bound, and aluminum-bound forms. After a four-week incubation at 28 °C, calcium-bound phosphorus predominantly increased in sandy soils, while iron-bound phosphorus (and aluminum-bound phosphorus in some cases) increased in volcanic ash soils. Hayakawa [118] reported that SS treated with lime and iron flocculants, as well as their incinerated ashes, led to increased iron- or aluminum-bound phosphorus in soil. Similarly, in a field study using pulp mill effluent sludge treated with aluminum sulfate and polymers, the phosphate absorption coefficient (PAC)—indicating the soil's phosphorus adsorption potential—increased [119]. However, Inoue et al. [120] and Sugito et al. [121] found no significant change in PAC when using lime- and ferric chloride-treated sludge compost, though an increase in plant-available soil phosphorus was observed. These findings indicate that phosphorus availability is affected by flocculant type and dosage, as well as soil characteristics. Maeda et al. [122] further investigated organic nitrogen fractions in sludge-based fertilizers by separating and quantifying different nitrogen forms. Vegetable crops were cultivated using materials containing various nitrogen fractions, including non-protein nitrogen and soluble proteins (considered fast- to slow-releasing), as well as membrane-bound proteins and cell wall constituents (classified as slow- to persistent-releasing). The relationship between crop yield and the fractionated nitrogen components was systematically analyzed.

Assessment and optimization for practical applications

Efforts are continuously being made to expand the application of compost and evaluate its lifecycle costs compared to conventional waste treatment methods. Research also addresses safety concerns and quality improvement. For instance, Maeda et al. [123] evaluated tomatoes, eggplants, and strawberries cultivated with SS-based versus chemical fertilizers. While yields were comparable, tomatoes and strawberries showed improved flavor, suggesting enhanced soil fertility and organic retention. Similarly, Akao et al. [124] conducted an economic evaluation in Iwamizawa City, revealing that SS reuse as fertilizer offered greater added value than disposal as industrial waste. However, drying costs remain a major challenge, as they account for the bulk of fertilizer production expenses. The authors emphasized the value of their evaluation framework in demonstrating the local and economic significance of SS fertilizer.

Building upon these efforts in compost application and lifecycle cost reduction, technological advancements have also been introduced to improve the production process and quality of SS-based fertilizers. In Fukuoka city, earlier MAP facilities produced 20–140 tons/year of granular fertilizer (2–3 mm). In 2022, new equipment using magnesium chloride and sodium hydroxide was introduced, allowing recovery from anaerobically digested sludge and yielding finer granules (0.2–0.3 mm). This upgrade has improved phosphorus utilization efficiency and fertilizer quality [37].

Measures to promote the spread of sewage sludge fertilizers to farmers

The effectiveness of sludge fertilizers has been confirmed; however, their adoption by farmers remains uncertain due to existing concerns. This section examines the challenges in encouraging farmers to use sludge fertilizers and highlights efforts to address these issues.

Designing sewage sludge fertilizers for practical use

Farmers typically source fertilizers, whether chemical or organic, from agricultural cooperatives, which also provide guidance on proper usage. However, sludge-derived fertilizers remain unfamiliar to most farmers, as they are not commonly distributed through agricultural cooperatives that typically supply and advise on fertilizer use. This limited awareness presents a barrier to adoption. To address this, various initiatives have been introduced to improve accessibility and understanding. These include conducting cultivation tests in collaboration with agricultural cooperatives, high school, and universities [125–128], seminars on sludge fertilizer use [129], and the dissemination of cultivation calendars that incorporate sludge fertilizer applications [130]. Such efforts have helped farmers integrate sludge fertilizers into routine practice. Additionally, the ADSON method [131], originally developed to estimate nitrogen availability in livestock manure, has been adapted for sludge compost and dried sludge to facilitate fertilizer planning [132]. Further, sludge-based fertilizer systems are being incorporated into farm management software to support practical implementation [133].

Field application of sewage sludge fertilizers

Application challenges of sludge fertilizers are closely tied to their form and compatibility with farmers' equipment. Conventional chemical fertilizers are easily applied using commonly available equipment, such as broadcasters, which most farmers own. Similarly, MAP and HAP sludge fertilizers are processed into granular forms or mixed with chemical fertilizers, making them straightforward to use without additional adaptation challenges. However, compost, dried, and dewatered sludge often require specialized equipment for spreading, which most farmers do not possess. Even with interest in using compost, this technical barrier hinders its widespread adoption on farmland [134].

To overcome this issue, some communities have established sludge fertilizer user associations, which collectively own spreading machinery and take responsibility for application services [135, 136]. In other cases, compost is pelletized to allow spreading using existing farmer-owned equipment, simplifying its application and increasing its accessibility [137, 138].

Raising awareness and disseminating information

The limited public awareness of sludge fertilizers and safety concerns from farmers, due to their origin in sewage treatment, present significant barriers to widespread adoption. Sludge fertilizers are a valuable domestic resource, but misconceptions and hesitations must be addressed to ensure their utilization.

At the national level, the MLIT and MAFF organizations have undertaken initiatives to promote sludge fertilizer use. These include disseminating advanced examples of successful applications and developing manuals to facilitate their adoption in agricultural practices [139–142]. Locally, efforts are focused on increasing public awareness through school classes, guided tours of fertilizer production facilities, and free distribution or sale of sludge fertilizers during public events [135, 143, 144].

To further alleviate concerns, regular measurements of heavy metal content and fertilizer components are conducted, with results being transparently disclosed to both farmers and residents. These efforts aim to ensure confidence in the safety and quality of sludge fertilizers while encouraging broader acceptance [144].

National initiatives and research projects for sewage sludge utilization in agriculture

To facilitate the widespread adoption of compost and other fertilizers derived from SS, a national research project [145] spearheaded by the National Agricultural and Food Research Organization (NARO) has been underway since 2023. The project focuses on developing low-cost fertilizer production methods and validating their agronomic effectiveness through field trials. It is being implemented across major Japanese cities with regionally tailored approaches.

In Iwamizawa city, Hokkaido, researchers are developing high-quality compost by blending sewage sludge with local byproducts such as rice husks. In Takashima city, Shiga prefecture, SS produced within the region is subjected to ultra-high-temperature aerobic fermentation, after which it is processed into powder or pellets to improve usability as compost. Similarly, in Kagoshima and Kirishima cities, a novel SS-based fertilizer is being developed with a tailored composition to meet the specific needs of local crops, such as tea, sweet potato, and horticultural produce. This fertilizer is manufactured by integrating SS with sweet potato shochu dregs, a regional byproduct that is otherwise underutilized, into granulated form to ensure ease of handling.

In Kobe city, researchers are developing optimal storage and inspection protocols, including testing frequency and parameters for heavy metals, to ensure the quality of recycled phosphorus fertilizers. Meanwhile, in Hita city, Oita prefecture, efforts are focused on the development of technology to utilize fine crystals of recycled phosphorus derived from sewage in liquid form. These are blended with concentrated bio-liquid fertilizer (Bio-CLF) derived from anaerobic digestion, enabling phosphorus recovery without granulation and reducing both capital and operational costs.

Ongoing field trials and crop cultivation tests are evaluating the agronomic performance of these fertilizers produced through various advanced technologies. Comprehensive reports detailing the outcomes of these initiatives are expected to be released in the near future.

Positioning Japan's technologies in a global context and toward sustainability

Global perspectives on the agricultural use of sewage sludge

In many countries, SS is recognized as a renewable source of organic matter, nitrogen, and phosphorus for agricultural soils [146]. In the United States, approximately 48% of SS is used for agriculture, compared to 18.6% in China [147]. In the European Union (EU), the figure is around 34% [148], though it varies significantly among Member States. For instance, in several EU15 countries, such as the Walloon Region of Belgium, Denmark, France, Ireland, Spain, and the UK, more than half of the SS is reused in agriculture. In contrast, Romania, the Brussels Region, and the Flemish Region of Belgium report no agricultural reuse, while in Finland and Netherlands, less than 5% is applied to land [149]. These variations reflect broader differences in environmental policies, food safety priorities, and technological capabilities across regions.

In EU, common treatment routes for agricultural reuse of SS include composting [150], direct land application after biological or chemical stabilization [151], ash-based phosphorus recovery through thermochemical processes (incineration, pyrolysis, and gasification) followed by alkaline leaching, precipitation, or HAP crystallization [152, 153], struvite precipitation from filtrate [154], and carbonization to produce phosphorus-rich biochar [155]. Composting and ash-based phosphorus recovery are currently the most widely adopted strategies [156], while phosphorus recovery from thermal treatments (pyrolysis and incineration) is increasingly prioritized over direct land application and composting. This shift is driven by concerns about heavy metals, organic pollutants (e.g., drug residues, hormones, pesticides, persistent organic pollutants), microplastics, and pathogens [157, 158]. It has led to Regulation (EU) 2019/1009, which bans the sale of fertilizing products containing composts or digestates made from SS under the CE marking, Europe's conformity label for health, safety, and environmental standards, effective from July 2022 [146].

Currently, the use of SS in agriculture in EU is governed by Directive 86/278/EEC, adopted in 1986 [159]. However, this directive is now considered outdated, as it fails to address emerging contaminants (e.g., per- and polyfluoroalkyl substances (PFAS), microplastics, pharmaceuticals, and endocrine-disrupting compounds)[160] . In response, the EU has released the evaluation of the directive in SWD-2023-final (159), including effectiveness, efficiency, coherence and relevance. These results and lessons learned in the evaluation support broader initiatives like the EU Green Deal, the Zero Pollution Action Plan, and the Circular Economy Strategy [160]. Moreover, although phosphorus has been officially recognized as a critical raw material, there is no EU-wide legal requirement for phosphorus recovery from sludge, except in a few countries like Germany [161], where phosphorus recovery from incinerated ash is mandatory. Nevertheless, these ongoing regulatory efforts reflect a broader transition in the EU towards a more unified, comprehensive, and environmentally sound framework for sewage sludge management.

Japan's unique position and future development directions

Japan offers a diverse and adaptable portfolio for sewage sludge (SS) treatment and agricultural reuse, including MAP and HAP crystallization, drying, carbonization, composting, and direct fertilizer application. Unlike Switzerland or Austria, where land application of SS is banned or the Czech Republic, where phosphorus recovery is not actively promoted due to a lack of clear policy incentives, resulting in most incinerated ash being used in construction or landfilling, and thereby leading to potential phosphorus losses [162]. Japan permits its use under strict standards outlined in the Fertilizer Control Act. A notable example is the legal classification of "Microbe phosphate fertilizer," which requires defined nutrient content and batch-based quality testing.

Japan's well-developed wastewater infrastructure and high population density further support the implementation of resource recovery technologies, with strong involvement from central agencies such as the MLIT, MAFF, and local governments. However, unlike Germany, where phosphorus recovery from sewage sludge has been legally mandated [163], Japan does not yet have a national regulation requiring phosphorus recovery. Deployment remains localized and driven by municipal discretion. Moreover, while the EU and Germany are tightening regulations on emerging pollutants, Japan's current regulatory framework remains focused primarily on heavy metals. Although efforts have begun to monitor PFAS in sludge through the development of analytical methods and preliminary risk assessments, no legally binding thresholds have been established so far (MAFF 2024) [164]. A recent domestic study by Matsunaga et al. (2024) analyzed dewatered sludge from 34 wastewater treatment plants across Japan and reported total PFAS concentrations ranging from 4.6 to 370 ng/g-dry, with PFOS being the most prevalent compound [165]. PFOS levels were notably higher in anaerobically digested sludge, and slight increases in PFOA, PFNA, and PFUnDA were observed when inorganic dewatering agents were used. In addition, a preliminary risk assessment by MAFF (2024) modeled a worst-case scenario where leafy vegetables were cultivated using sludge-based fertilizer with the highest detected PFOA level (250 μg/kg) [166]. Assuming no leaching and uptaking into crops to the same concentration as soil, the estimated intake remained below the tolerable daily intake (TDI) of 20 ng/kg body weight/day set by Japan's Food Safety Commission [166]. While these findings suggest a relatively low current health risk, further scientific knowledge, including on PFOS concentration trends [165] and on PFAS transfer from agricultural soil to crops [166] is expected.

Moving forward, Japan may benefit from updating its recovery and use framework toward a more harmonized and forward-looking approach across municipalities. Scaling up proven technologies and aligning with the latest global evolvements will help Japan maintain its leadership in sludge-to-agriculture innovation while ensuring long-term environmental safety and sustainability.

Conclusions and future perspectives

This review summarizes the governmental policy framework and technological progress regarding the agricultural use of SS in Japan, highlighting the challenges and efforts aimed at expanding its adoption among farmers. It is expected to provide a comprehensive perspective on Japan's efforts toward sustainable agriculture using SS through the lenses of circular economy, decarbonization, and sustainable nitrogen and phosphorus management. A notable characteristic of this paper is its emphasis on technological advances that have been successfully put into practical use in Japan, offering insights that are directly applicable to real-world practices. In order to expand the agricultural use of SS in the future, future efforts should focus on technological improvements, such as enhancing fertilizer quality and ease of handling, while also verifying agronomic effectiveness and ensuring safety to increase acceptance among farmers and consumers. As discussed in Sect. "National initiatives and research projects for sewage sludge utilization in agriculture", a national project led by NARO aims to promote the agricultural use of SS as part of a sustainable food system in Japan. Addressing emerging contaminants is essential for safe reuse. Continued research and technological innovation will be key to advancing secure and sustainable SS utilization in agriculture.

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