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Sewage Sludge: A Review of Business Models for Resource Recovery and Reuse

Avinandan Taron, Shirish Singh, Pay Drechsel, Chaya Ravishankar and Andreas Ulrich

Resource Recovery & Reuse Series

The Resource Recovery and Reuse (RRR) Series originated in 2014 under the CGIAR Research Program on Water, Land and Ecosystems (WLE), and continues since 2021 under the CGIAR Initiatives on Resilient Cities and Nature-Positive Solutions. The aim of the RRR series is to present applied research on the safe recovery of water, nutrients and energy from domestic and agro-industrial waste streams. IWMI's research on RRR aims to create impact through different lines of action research, including (i) developing and testing scalable RRR business models, (ii) assessing and mitigating risks from RRR for public health and the environment, (iii) supporting public and private entities with innovative approaches for the safe reuse of wastewater and organic waste, and (iv) improving rural-urban linkages and resource allocations while minimizing the negative urban footprint on the peri-urban environment. IWMI works closely with the World Health Organization (WHO), Food and Agriculture Organization of the United Nations (FAO), United Nations Environment Programme (UNEP), United Nations University (UNU), and many national and international partners across the globe. The RRR series of documents present summaries and reviews of the research and resulting application guidelines, targeting development experts and others in the research for development continuum.

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Sewage Sludge: A Review of Business Models for Resource Recovery and Reuse

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Front cover photograph: Treated wastewater in clarifier before its final discharge into the Litani River, Ablah, Syria (credit: Jano Hatem).

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ACRONYMS AND ABBREVIATIONS

AbfKlärV	Klärschlammverordnung (German Sewage Sludge Ordinance)
CAGR	Compound annual growth rate
CFR	Code for Federal Regulations
CNG	Compressed natural gas
DBO	Design, build, operate
DBOO	Design, build, own, operate
EEA	European Environment Agency
GGE	Gasoline gallon equivalent
GmbH	Company with limited liability (German abbreviation)
GWI	Global Water Intelligence
GWRC	Global Water Research Coalition
ISO	International Organization for Standardization
MGD	Million gallons per day
MLD	Million liters per day
MPN	Most probable number
MSW	Municipal Solid Waste
NET	Negative emission technology
NuReSys	Nutrients Recovery Systems
PE	Population equivalent
PPP	Public-private Partnership
RRR	Resource Recovery and Reuse
SPV	Special Project Vehicle
Srl	Società a Responsabilità Limitata (limited liability company)
SSD	Sewage Sludge Directive
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TS	Total solids (dry matter)
UBA	Umweltbundesamt (German Environment Agency)
ULB	Urban local body
USEPA	United States Environmental Protection Agency
UWWTD	Urban Wastewater Treatment Directive
WWTP	Wastewater Treatment Plant

SUMMARY

Sewage sludge generated from wastewater treatment systems carries a stigma as an environmental hazard, especially where it is inefficiently and unsustainably managed as in many low- and middle- income countries. Alternative options are needed given the increasing concerns and policies restricting sewage sludge dumping in landfills and elsewhere, and a growing awareness about the resource value of sludge within a circular economy.

Modern resource recovery technologies allow for the capture of biosolids, nutrients or energy from sewage sludge and the reduction of the amount to be disposed of. Water utilities, municipalities and private entities are increasingly engaging in these opportunities.[1]

This study reviews existing approaches and business models for resource recovery and moves the discussion beyond technical feasibility. Case studies were analyzed in support of four main sets of business models depending on the targeted resource: (i) organic fertilizers, (ii) crop nutrients, (iii) energy, and (iv) organic fertilizers and nutrients along with energy.

The extraction of organic fertilizers through dewatering, thickening, stabilization or long-term storage drives the first set of models followed by technological advances in phosphorus recovery. The business models on energy similarly start from conventional energy recovery processes (anaerobic digestion) and move toward incineration. The discussion covers recent advances in gasification and pyrolysis. Transforming sewage sludge into biochar, for example, can support soil fertility and carbon sequestration. The final set covers integrative approaches supporting soil fertility and energy needs.

While technologies and business models generally have a favorable policy environment, the regulatory framework may restrict the use of recovered (waste-derived) resources for certain applications, for example, in agriculture. Emerging economies, such as China and India, with high population growth and sludge generation are under pressure to formulate progressive regulations and policies for safe resource recovery while investing heavily in wastewater treatment. A similar push is needed to increase industry acceptance of recovered products like phosphorus to penetrate agricultural markets despite the currently still cheaper phosphate rock, which is a finite resource.

[1] Biosolids are the organic materials resulting from the treatment of domestic sewage in a wastewater treatment facility (i.e., treated sewage sludge). Biosolids can be a beneficial source of essential plant nutrients and organic matter for crop production or landscaping depending on the presence of contaminants.

1. INTRODUCTION

This study reviews existing sewage sludge reuse efforts with a focus on related business models. The review extracts and describes models based on a comparative analysis of similar cases for a particular resource recovery option based on an understanding of the drivers, relevance, concepts, value chain and products, risks and benefits, and financial parameters. Thus, instead of building theoretical business models, each model is based on existing cases. As these models depend on technical options and the regulatory environment, this report will provide insights to guide the selection of business models.

Sewage sludge is a by-product of wastewater treatment plants connected to a sewer system.[2] Where sewage sludge management is unsustainable, it can result in a potential threat to human and environmental health because of a wide variety of domestic and industrial contaminants entering the system (Spinosa 2011). With population growth, progressive expansion of wastewater networks and industrial development, the quantity of sewage sludge generated in municipal wastewater treatment plants (WWTPs) is increasing. Sludge produced by WWTPs amounts to a small percentage by volume of processed wastewater, but its handling can account for 40–60% of total operating costs, which calls for volume and cost-reducing strategies, ideally combined with cost recovery (Foladori et al. 2010; Spinosa 2011). The situation is alarming in large and densely populated cities with limited land for treatment and regulatory pressure to end sludge disposal on over-full landfills. Fortunately, sewage sludge is increasingly recognized as a resource for energy recovery and soil amelioration (ADB 2012; GWI 2023a). Figure 1 shows the variety of resource recovery options, from those still under development to mainstreamed technologies.

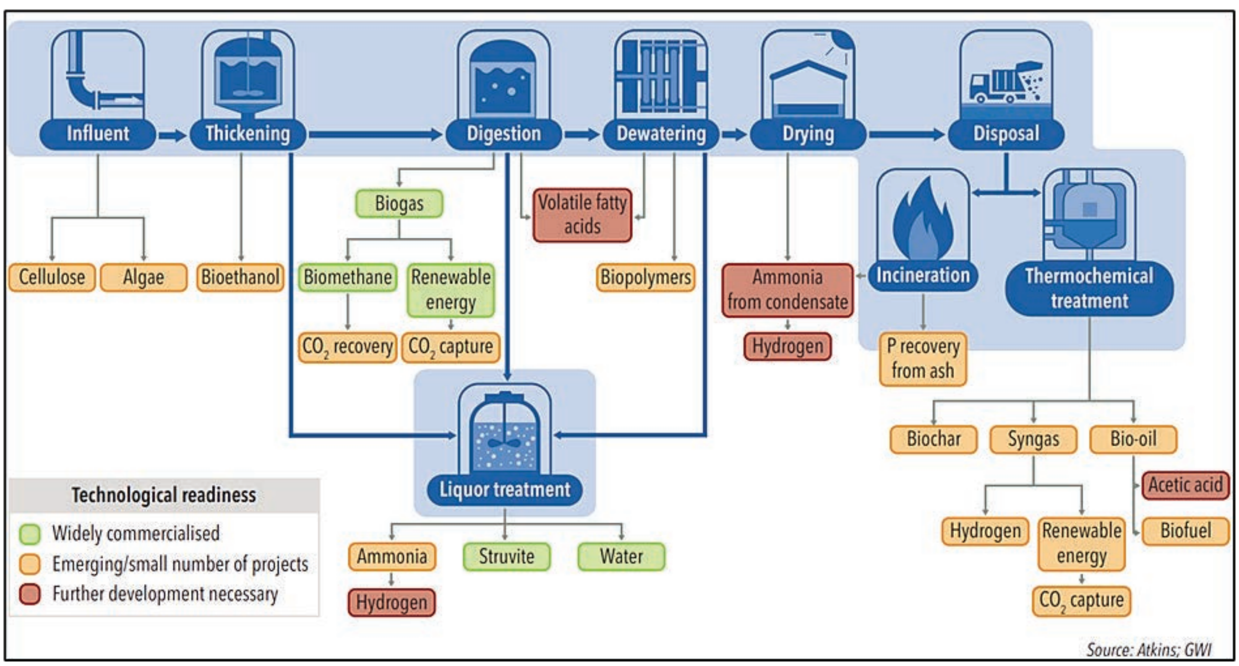


FIGURE 1. RESOURCE RECOVERY OPTIONS FOR SEWAGE SLUDGE (SOURCE: GWI 2023a).

[2] **Sewage sludge** generated in wastewater treatment plants should be differentiated from **fecal sludge** accumulating in on-site sanitation systems like septic tanks (**septage**) or pit latrines. Business models and technological options for fecal sludge are presented in Issues 2, 3, 6 and 18 of the Resource Recovery and Reuse report series.

To incentivize resource recovery and reuse (RRR) a regulatory framework is needed with clear sets of end-of-waste criteria and related standards which define when waste resources become a legal secondary raw material and can be traded and used.

In contrast to fecal sludge captured in household septic tanks not connected to a public sewage system, the chemical contamination of sewage sludge can be much higher as it may be derived from residential and industrial suburbs and street runoff. Hence, quality control and regular chemical analysis for heavy metals and organic chemicals are important for sewage sludge recycling. This applies, in particular, to using sludge on land to improve soil fertility where depending on the soil type, it can reduce or even offset the use of chemical fertilizers. Where the application of sludge on land is not possible or risky in view of contaminants, its transformation into the relatively safer biochar or use as energy after anaerobic digestion could be options. Co-incineration of sewage sludge as a renewable fuel source can be applied in the power and cement industries, especially for contaminated sewage sludge, whereas mono-incineration enables the recovery of phosphorus from ash. This is increasingly done in high-income countries. Carbon footprint analysis is widely applied in developing sludge management strategies and selecting technical pathways for sludge treatment and disposal.

1.1 Sewage sludge related regulations, treatment, and disposal options

Business models related to waste management and resource recovery, and in particular those related to a potential hazard like sewage sludge, depend on what local, national or regional regulatory frameworks allow and the available technical options. Although many countries do not have explicit regulations on sewage sludge, they may refer to existing guidelines as a reference for developing them. This section briefly describes some often-referenced sewage sludge regulations and treatment and disposal options and their costs.

1.1.1. Regulatory Frameworks

Common disposal and reuse regulations for sewage sludge cover agricultural and non-agricultural land application use, incineration, landfilling, energy recovery (heat and electricity), use in construction, and open environment disposal. From a regulatory perspective, the main challenge is land application as this can imply direct contact with farm workers and indirectly with consumers through groundwater or the food chain. This implies a need for stricter health and environmental standards for reuse than for landfilling or incineration. Typically, regulations for the reuse of sludge for agricultural or non-agricultural purposes include thresholds for a range of contaminants and management requirements for the reduction of these hazards in the form of heavy metals, pathogens, organic compounds and disease vectors.

Global guidance is available from the International Organization for Standardization (ISO) which has two standards on sludge recovery, recycling, treatment, and disposal: ISO 19698:2020 on the beneficial use of biosolids-land applications, and ISO/TR 20736:2021 as guidance on the thermal treatment of sludge. ISO is developing more standards such as ISO/NP TR 22707 as guidance on the processes and technologies for inorganics and nutrient recovery.[3]

The European Union Regulatory Environment

Operators of WWTPs within the European Union (EU) need to comply with set directives. While earlier regulations related to waste materials such as sewage sludge had, as their main objective, the prevention of risks to the environment and human health, more recent revisions support waste reuse and resource recovery as targeted in the European Union's Circular Economy Action Plan (2020).

Urban Waste Water Treatment Directive 91/271/EEC, Amended 98/15/EC (UWWTD) sets regulatory practices for the collection, treatment and discharge of urban and industrial wastewater. Adopted in 1991, the UWWTD contains limited provisions on wastewater and sludge reuse and recovery of valuable components. On July 13, 2018, the European Commission published the Consultation on the Evaluation of the Urban Wastewater Treatment Directive ahead of a potential revision. Since its adoption, new technical advances in treatment techniques for waste and emerging pollutants have been developed to foster energy efficiency and recovery.

Waste Framework Directive 2008/98/EC. This directive is the main driving force behind current waste management practices. It sets out several principles and methods that member states must implement. The most important principles affecting sludge management practices are:

- Application of a waste management hierarchy: This hierarchy gives priority to waste prevention and encourages reuse and recovery techniques. The final disposal of waste is only a last resort after all other options have been considered.
- Introduction of 'the end-of-waste criteria' concept: This Directive explains when waste can be recategorized as secondary raw material.

Sewage Sludge Directive 86/278/EEC (SSD). This directive was adopted to encourage the correct use of sewage sludge in agriculture and regulate its use to prevent harmful effects on soil, vegetation, animals and humans.

[3] Standards by ISO/TC 275. https://www.iso.org/committee/4493530/x/catalogue/p/1/u/1/w/0/d/0

The principal benefit of the SSD is its role in the protection of human health and the environment against the harmful effects of contaminated sludge in agriculture. It prohibits the use of untreated sludge on agricultural land unless it is injected or incorporated into the soil. The directive does not prescribe specific treatment technologies, which gives countries some flexibility in what they choose to adopt. The directive requires a regular examination of sludge quality and soils at an interval of at least 12 months to check for environmental hazards. The SSD also requires that sludge be used in a way that accounts for the nutrient requirements of plants and that the quality of the soil and surface and groundwater is not impaired. The SSD emphasizes safeguarding the environment and human health more than reuse opportunities.

The SSD does not address contaminants of emerging concern (e.g., organic chemicals such as pharmaceuticals, micro-plastics or cosmetics containing polycyclic aromatic hydrocarbons or per- and polyfluoroalkyl substances), and thus has recently been under review for revision. Over the years, several European Union Member States have either set stricter requirements than those imposed by the directive or have simply banned sludge use in agriculture on public health grounds.

Fertilizer Regulation (EC) No. 2003/2003. The conditions for making fertilizers available within internal markets have been partially harmonized through Regulation (EC) No. 2003/2003 of the European Parliament and the Council, which almost exclusively covers fertilizers from mined or chemically produced, inorganic materials. However, nearly half the fertilizers on the EU market with organic components are not covered by No. 2003/2003. A new EU Circular Economy Fertilizing Products Regulation (EU) 2019/1009 was consequently approved by the European Parliament and the Council of the European Union in 2019, repealing No. 2003/2003.

The new version widens the scope of the regulation to include inorganic, organo-mineral and organic fertilizers, organic soil improvers, liming products, growing media, plant bio-stimulants and agronomic fertilizer additives, including secondary raw materials such as those recovered and bio-based fertilizing products. This will considerably facilitate market availability of both organic products containing recycled nutrients (e.g., processed biosolids, digestates, composts, biochars) and inorganic recovered phosphate products (e.g., struvite, phosphates recovered from sewage sludge, incineration ash). Fertilizing materials certified to comply with the new essential requirements outlined in the EU Fertilizer Regulation (minimum nutrient content, quality and safety criteria) will be authorized for the EU internal market, whereas products registered as fertilizers in one Member State cannot be exported or will require a new registration dossier for sale in another Member State except where they have been mutually recognized by the authorities of the importing Member State.[4]

Landfill Directive 1999/31/EC. This directive provides measures, procedures and guidance to prevent or reduce negative impacts on the environment, particularly the pollution of surface water, groundwater, soil and air and the global environment, including greenhouse gas effects, as well as any other risk to human health that might result from landfilling with sewage waste. However, the directive also supports resource recovery and reuse. According to the Directive, the amount of biodegradable municipal waste had to be reduced to 50% in 2009 and 35% in 2016 compared to a 1995 baseline. By 2035, the amount of all municipal waste in landfills should be reduced to 10% or less of the total amount of municipal waste generated (by weight).

This directive has led countries to seek alternative methods such as land application of sludge, incineration and biogas production. Many EU countries have prohibited the disposal of sludge in landfills. These countries include Austria, Belgium, Denmark, Finland, Luxembourg, the Netherlands, Germany, Sweden and Estonia. The remaining EU countries are decreasing the amount of sludge sent to landfills to meet the new directive targets. Although the directive mentions pre-treatment and quality monitoring, it does not set limits on the amount of waste to be disposed of. These are usually set by national and regional regulations or individual landfill site operators.

Directive 2000/76/EC on the incineration of waste. This directive provides air pollution limits for sulfur and nitrogen oxides, hydrochloride, particulates and heavy metals and dioxins. The level of sludge pre-treatment required is not defined in the regulation for either mono-incineration or co-incineration (coal-fired thermal plants or cement industries).

Directive (EU) 2018/2001 on the promotion of energy from renewable sources. This directive mainly sets a target for renewable energy, biogas and syngas obtained from wind, solar or organic waste, including sludge generated through sewage treatment.

Circular Economy Action Plan (2020). Under section 3.7 on Food, Water and Nutrients, the action plan says, "The Commission will develop an Integrated Nutrient Management Plan to ensure more sustainable application of nutrients and stimulate the markets for recovered nutrients." The Commission will also consider reviewing directives on wastewater treatment and sewage sludge and will assess natural means of nutrient removal such as algae.

[4] Nutriman Newsletter. The new fertilizer regulation – consequences for farmers. https://nutriman.net/news/new-fertiliser-regulation-consequences-farmers

Presently, the sewage sludge produced in the European Union has four main destinations: agriculture (49.2%), incineration (24.9%), cultivation and land reclamation (12.4%), landfill (8.7%) and other destinations for the remaining amount (4.9%) see Campo et al. (2021). The dominant sewage sludge disposal methods by EU country are listed in Table 1.

TABLE 1. SEWAGE SLUDGE DISPOSAL PATHWAYS IN EUROPE.

Disposal method	Countries
Agriculture	Bulgaria, Croatia, Czechia, Denmark, Ireland, Lithuania, Spain and Sweden, Italy[a]
Compost and other applications	Cyprus, Estonia, France, Hungary, Luxembourg, Slovakia,
Landfills	Malta, Romania
Incineration	Austria, Belgium, Germany, Greece, Netherlands, Switzerland, Turkey
Other[b]	Latvia, Poland, Portugal, Slovenia

Source: EEA (2021).
[a] Both compost and agricultural use. The data about waste management for 2019 reveals that in Italy, 56% of sewage sludge was disposed of (of which 13.2% was in landfills and 7.7% by incineration and 57% was biologically treated for agricultural use) and 41% was recovered, of which 67.9% was by activities of recovery/reuse of organic substances (ISPRA 2021).
[b] Includes temporary storage at wastewater treatment plants and landfills, reuse at plant sites and in forestry and reclamation of land including agricultural land (Poland and Romania), export to other countries (e.g., in Slovenia, sludge is exported to Hungary), landscaping and landfill coverage (e.g., Sweden).

The United States (US) Regulatory Environment

The U.S. has strict regulations for sludge disposal. The Federal Municipal Sludge Regulations 40 Code for Federal Regulations (CFR) Part 503 are more detailed than those in the EU Sewage Sludge Disposal regulation. Pollutant limits and management practices for all three types of sludge disposal (land application, incineration, and landfill disposal) are covered in one document. The regulation was issued in 1993 and is part of the Clean Water Act.

Land application of municipal sludge – Part 503, subparts B and D. Subpart B specifies the pollutant limits for a range of heavy metals under ceiling concentrations, cumulative pollutant loading rates, monthly average concentrations and annual pollutant loading rates. Subpart D places restrictions on the pathogens and vector attraction reduction in sludge by prescribing treatment steps to be performed. The subpart distinguishes Class A and Class B sludge based on the number of pathogen indicators present in the sludge after treatment. Class A biosolids contain minimal fecal coliforms (< 1,000 MPN/g total solids dry weight) or *Salmonella* (< 3 MPN/4 g of total solids dry weight) and can be freely purchased in shops and applied virtually without regulation to agricultural lands.[5]

Class B biosolids have a higher level of pathogens (monthly geometric mean of fecal coliforms < 2,000,000 MPN) or colony-forming units per gram of dry weight and can be used for land reclamation and farming with certain restrictions. These concern the minimum duration between the application of biosolids and harvesting of certain crops, animal grazing or public exposure and access. These minimum durations significantly reduce health hazards to levels equivalent to those achievable with the unregulated application of Class A biosolids (Table 2).

For agricultural use, 40 CFR Part 503.14 requires that biosolids must be applied to land at the appropriate agronomic rate, which is the sludge application rate designed to provide the nitrogen needed by a crop or vegetation grown on the land. The agronomic rate depends on crop type, geographic location and soil characteristics.

[5] The 'most probable number' (MPN) is a statistical method used to estimate the viable number of bacteria in a sample.

TABLE 2. MINIMUM DURATION BETWEEN APPLICATION OF CLASS B BIOSOLIDS AND HARVEST, GRAZING AND ACCESS.

Class B biosolids	**Period between land application and harvest, animal grazing and public access**		
Criteria	**Surface application**	**Incorporation**	**Injection**
Food crops in which the harvested parts may touch the soil or biosolid mixture (beans, melons, squash, etc.)	14 months	14 months	14 months
Food crops in which the harvested parts grow in the soil (potatoes, carrots, etc.)	20–38 months[a]	20–38 months	20–38 months
Food, feed and fiber crops (field maize, hay, sweet corn, etc.)	30 days	30 days	30 days
Grazing animals	30 days	30 days	30 days
Public access restrictions			
High potential for public exposure[b]	1 year	1 year	1 year
Low potential for public exposure	30 days	30 days	30 days

Source: USEPA (1993a, 1993b, 1995); Jayathilake et al. 2019.
[a] The 20-month duration between application and harvesting applies when surface applied biosolids stay on the surface for four months or longer before incorporation into the soil. The 38-month duration is in effect when the biosolids remain on the surface for less than four months before incorporation.
[b] This includes application to turf forms, which place turf on land with a high potential for public exposure. Stockpiling Class B biosolids on an open field should be avoided and, if practiced, runoff to surface water or any adjacent land where community members may be exposed must be avoided.

According to Subpart D, one of the following recommended methods should be used to treat sewage sludge before agricultural land application (also see USEPA 1993a, 1993b, 1995).[6]

- Aerobic digestion for 40 days at 20° C or 60 days at 15° C.
- Anaerobic digestion for 15 days at 35 to 55° C or 60 days at 20° C.
- Air drying for at least three months. Two of the months must have average daily temperatures above freezing.
- Composting or co-composting at temperatures greater than 40° C for five days. The temperature of all the material being composted must be greater than 55–65° C for at least four hours during the five days.
- Lime stabilization to bring the pH higher than 12 for 30 minutes or bring the pH higher than 9 for more than six months if the temperature is above 35° C or moisture is below 25%.

Land filling of municipal sludge Part 503, Subpart C. The US regulations are less restrictive than in the EU, where reduction targets are set for sludge going to landfills. There are currently no federal targets or national incentives in place to reduce the amount of biodegradable waste going to landfills.

The lack of such directives in the US is reflected in the landfill statistics. In 2021, about 43% of the sewage sludge produced in the US was dumped in landfills (Figure 2), a share that was only 22% in 2019. Land applications in 2021 absorbed 42%; 10% less than in 2019. The incinerated share remained similar (14–16%). In the European Union, agriculture and land reclamation absorbs about 61%, incineration 25%, and landfills receive only 9% (Campo et al. 2021).

Landfill disposal methods are primarily regulated through Landfilling Regulation 1993 US Code Chapter 40 Part 258 and the supporting legislation on Toxicity Characteristic Leaching Procedure defined in 40 CFR 261.24. These legislations establish minimum criteria for all municipal solid waste landfills that are used to dispose of sewage sludge to ensure the protection of human health and the environment. They also define when a solid waste exhibits toxicity. A common disposal method is spreading sludge on the surface of a land area at regular intervals where it is left to dry. The sludge is then plowed into the ground. Sludge

[6] Part 503 considers domestic septage as sewage sludge.

disposed of in this way must meet the defined thresholds (e.g., for heavy metal concentrations).

Incineration of sludge. The two main pieces of legislation that regulate the operation of incinerators are 40 CFR Part 503 Subpart E of the Clean Water Act and 40 CFR Part 129 of the Clean Air Act. These regulations set standards for air pollutants from the combustion process and restrictions on site-specific concentrations for arsenic, cadmium, chromium, lead and nickel in sewage sludge being fed to an incinerator. The exact values are based on site-specific variables such as incinerator type, dispersion factor, control efficiency, feed rate, and stack height.

Regulations in Other Countries: A Brief Description

Alternatives to landfilling are considered in some countries for their benefits, while in other countries public health and environmental concerns make land application an exception (Table 3). In Brazil, for example, where land application for agriculture is allowed, it is difficult to comply with guidelines that define about 60 chemical and microbiological indicators which are in part more stringent than elsewhere and do not consider local and regional specifics and capacities, making it unfeasible to adopt a circular alternative to landfilling. The limitations are different in Oman, where the national legislation supports composting and reuse of sludge in agriculture but still lacks legislation for other options such as converting it to a fuel or using it for manufacturing bricks (Jaffar et al. 2017).

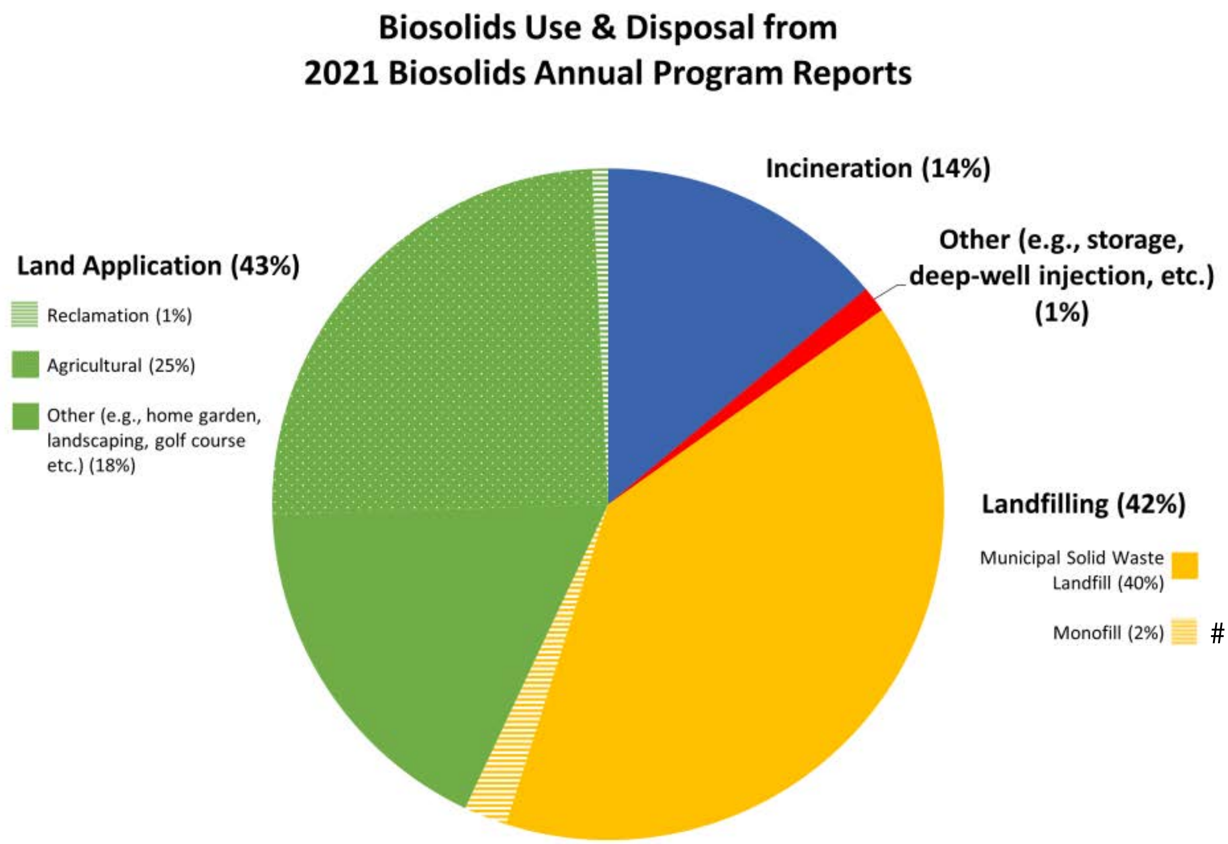


FIGURE 2. DISTRIBUTION OF BIOSOLID USE AND DISPOSAL IN THE USA 2021.

A monofill is a landfill that has been designed to handle only one material.

Source: United States Environmental Protection Agency. https://www.epa.gov/biosolids/basic-information-about-biosolids.

TABLE 3. SEWAGE SLUDGE RELATED REGULATIONS IN SELECTED COUNTRIES (STATUS 2021).

	Japan	Australia	New Zealand	China	UAE	Oman	Brazil
Legislation guiding sewage sludge management	• New Sewage Law (1970s) • Fertilizer Law (1950) • Waste Management and Public Cleaning Law (1970) • Soil Contamination Countermeasures Law (2001)	• Federal Clean Water Act (1970s) • State Fertilizers Act and Waste Act • National Water quality management strategy • Guidelines for Sewerage Systems Biosolid Management (2004) • State-specific guidelines	• New Zealand Guidelines for Biosolids application on land (2003)	• Pollution and control of treatment and disposal of municipal sludge (2009) • Land improvement (GB/T 24600–2009) • Gardening (GB/T 23486–2009) • Agriculture (CJ/T30-009) • Forest application (CJ/T 362- 2011) • Landfilling regulation (GB/T23485-2009) • Incineration regulation GB/T24602-2009; and more	Laws are different for different Emirates, e.g. • Abu Dhabi Recycled Water and Biosolids Regulation RWB) 2010; • Dubai Water Environment Regulations (EN 5.0)	• MD 145/93 dated June 13, 1993, Regulations for Wastewater Reuse and Discharge by the Ministry of Regional Municipalities, Environment and Water Resources	• Agricultural application of sludge Resolution CONAMA No. 375/2006 • Landfilling Law No. 12.305/2010 National Policy on Solid Waste
Landfilling	Allowed only for incinerating ash (being discouraged)	Abandoned in most states except Virginia	Major disposal method	Allowed for municipal and industrial sludge and as a cover for landfills	Allowed	Was a major disposal method but most WWTPs now follow USEPA regulations for producing sludge for composting and land applications	Major disposal method; historical records of discarding sludge into open environments
Agricultural use (basic inspected parameters)	Not widely used (carbonized, dried and composted sewage sludge or sewage sludge ashes used)	Major use (heavy metals, organic compounds, pathogens, disease vector reduction)	Promoted but still scarce use (heavy metals, organic compounds, pathogens, disease vector reduction)	Major use (heavy metals, Organic Compounds, pathogens, disease vector reduction)	Promoted with restrictions only on heavy metals and organic compounds	Promoted with restrictions only on heavy metals	Promoted but rarely used (different pathogenic indicators (coliforms, Salmonella, helminths, viruses), different nutrients, 11 heavy metals and 34 organic substances)

(Continued)

TABLE 3. SEWAGE SLUDGE RELATED REGULATIONS IN SELECTED COUNTRIES (STATUS 2021). (CONTINUED)

	Japan	Australia	New Zealand	China	UAE	Oman	Brazil
Other application uses	None	Forestry, land reclamation, mine sites	Forestry, land reclamation, mine sites, landfills, agriculture	Forestry, land reclamation, mine of e.g. mine sites, and building materials production	Land reclamation	Land reclamation	None
Thermal treatment	Major use (highly promoted (>70%)	Not preferred, limited application	Not applied	Incineration, thermal hydrolysis and anaerobic digestion common	Not applied	Not applied	Not applied
Phosphorus recovery from sewage sludge	Highly promoted, commercial applications	Viewed as a need	Not yet	Viewed as a need	Not yet	Not yet	Not yet

Source: Adapted from Christodoulou and Stamatelatou (2016) for Japan Australia and New Zealand; GWI (2012) and Wei et al. (2020) for China, UAE, Oman and Brazil.

1.1.2. The legislation, technology and disposal costs nexus

The operational costs of sludge treatment and disposal are, in general, a function of the technology used, the reuse target (energy, compost, etc.) and transport distance (Foladori et al. 2010). However, local, national, or regional regulations can use fees to steer or restrict certain disposal options and pathways and demand sludge quality standards. This will determine the technological preference, disposal and reuse options and treatment costs. The Chinese government, for example, introduced regulations that prevent landfills from accepting sludge with a solid content below 40%. As government policies alter, disposal costs are also likely to change (GWI 2012).

Common sludge management systems include sludge screening, thickening, dewatering, and drying for further processing or disposal. At each step in the process, WWTP managers can select from several technical options. The solution selected for each treatment step must balance efficiency, performance and reliability alongside cost, capacities required for operation and other technical considerations aside from the disposal or resource recovery target. Table 4 shows the cost range of different strategies for management of sewage sludge in Europe.

TABLE 4. DISPOSAL AND REUSE COSTS IN EUROPE.

Methods of sludge use	Minimum (USD /ton)	Maximum (USD /ton)
Land application	28	235
Landfilling	140	285
Composting	168	347
Thermal drying	90	235
Incineration	90	490

Source: Capodaglio and Olsson (2020)

Specific costs of sewage sludge disposal in Germany and Italy are shown in Table 5.

TABLE 5. SEWAGE SLUDGE DISPOSAL COSTS IN GERMANY AND ITALY.

Country	Reuse and disposal	Cost of sewage sludge management range (EUR/ton of dry residue)	Remarks
Germany[a]	Agricultural sludge application	160 – 320	Pre-treatment: Costs for drying sewage sludge are between EUR 20–25/ton of dry solids. Cost variations reflect different amounts and transport costs.
	Co-incineration	280 – 400	
	Mono-incineration	280 – 480	
Italy[b]	Agriculture	129	In Italy, the management of sludge (loading, transport, analysis and recovery or disposal), was estimated at 15–40% of the costs of a WWTP[c]
	Incineration (cement factories)	120 (115)	
	Landfill	212	

Source: Author's creation.

[a] Roskosch and Heidecke 2018; [b]Domini et al. 2022; [c]ATIA ISWA Italia 2019.

In the US, where cost data are reasonably well documented, disposal costs vary greatly between states. The distances involved in hauling can be long and greater than the cost of land application. In New York, for example, costs are relatively high (> USD 330/ton of dry solids) because material is sometimes trucked to distant states. On the other hand, cities, such as Phoenix, Arizona, which have naturally hot dry air to facilitate drying, and an abundance of nearby land for application, have much lower land application costs (< 165 USD/ton of dry solids) (GWI 2012). An example of a simple cost comparison is shown in Table 6. A direct comparison of disposal costs across states or countries suffers from regional variations in tipping fees, variations in fuel costs and hauling distances and state and local taxes.

TABLE 6. COMPARATIVE COST (USD) OF SEWAGE SLUDGE DISPOSAL OPTIONS (PER WET TON).

Management	New Hampshire	Pennsylvania	CSWD (Vermont)[a]
Landfill	USD 75	USD 75	USD 94
Land application	USD 40	USD 62	USD 130 (class A) USD 100 (class B) USD 90 (Grasslands)
Incineration	USD 71	USD 71	No data

[a] Chittenden Solid Waste District, Vermont.
Source: Kelly and Twohig 2018.

The cost of various management options relative to each other can be more consistent. It appears from the example in Table 6 that land application can provide a cost advantage over landfilling and incineration, similar to the data in Table 4. The New Hampshire and Pennsylvania studies show there is a distinct economy of scale with an increasing cost advantage over other disposal options with an increasing volume of biosolids being managed. In Vermont, this cost differential is not expected to be as great as in other jurisdictions, primarily due to the costs added for monitoring that are not required in most other jurisdictions. These requirements, though not unique to Vermont, include more frequent analyses of biosolids, groundwater, soil, and plant tissue testing, a ban on field storage of biosolids (meaning that a storage facility at a WWTP is necessary) and requirements to incorporate biosolids into the soil following application. An additional cost in Vermont comes from the imposition of the Franchise Tax on Waste Facilities. While landfilling and incineration are subject to tax, composting and land application are not (Kelly and Twohig 2018).

In general, it is difficult to compare costs between alternative options, predominantly regarding what expenditures should be included in the calculation of a total cost. A comparison of the relative costs of switching from one management strategy to another can be similarly confounded. This is largely due to cost differentials derived from upfront processing charges related to preparing sludge for disposal (electricity, auxiliary heating, dewatering, chemical addition, monitoring, product quality assurance, transportation, etc.) rather than from tipping fees charged by end-management facilities (Kelly and Twohig 2018). An attempt at comparison specific to the Chittenden County case in Vermont is shown in Table 7.

1.2 Market potential for management and reuse of municipal sewage sludge

The global biosolids market is estimated to be around USD 1.7 billion in 2023, and is anticipated to grow at compound annual growth rate (CAGR) of 4.5-4.7% up to 2.6-2.7 billion at the end of 2033 (Fact.MR 2022; GWI 2023a). Figure 3 shows the breakdown for biosolids applications in agriculture, non-agriculture and for energy recovery and the market shares by main regions. Other regions to observe are Latin America and South Asia and Oceania, and with the relatively smallest expected volume of 0.1 billion the Middle East and Africa.

Bloomberg (2021) summarized the key findings from the Fact.MR survey as follows:

- The leading biosolids markets will remain North America, Europe, and China.
- With around 60% market share, the agricultural segment will continue to dominate the biosolids market through 2031.
- Based on product type, class A and class A (Exceptional Quality[7]) types are projected to account for over half of overall biosolids sales during the forecast period.

[7] Class A (Exceptional Quality) sewage sludge meets the most stringent pollutant, pathogen, and vector attraction reduction requirements under US EPA's regulations. https://www.epa.gov/sites/default/files/2020-11/documents/land-application-classa-memo-2020.pdf

TABLE 7. SLUDGE MANAGEMENT OPTIONS, BENEFITS, AND COSTS IN VERMONT.

Management Option	Benefit	Cost per wet ton
Liquid sludge → dewatering → landfill	• none	USD 91–95
Liquid sludge → dewatering → Casella Grasslands facility	• land applied as EQ	USD84–89
Liquid sludge → dewatering → thermal drying	• land applied as EQ	USD 200–285
Liquid sludge → dewatering → thermal drying → gasification	• produces methane usable as fuel	USD 300–350
Liquid sludge → dewatering → composting	• land applied as EQ	USD 110–175
Liquid sludge → dewatering → alkaline stabilization	• land applied as EQ	USD 100
Liquid sludge → mesophilic anaerobic digestion → dewatering	• land applied as Class B • produces methane usable as fuel	USD 130–150
Liquid sludge → thermophilic anaerobic digestion → dewatering	• land applied as EQ • produces methane usable as fuel	USD 140–160
Liquid sludge → mesophilic anaerobic digestion → thermophilic anaerobic digestion → dewatering	• land applied as EQ • produces methane usable as fuel	USD 110–130

Note: EQ: Exceptional Quality biosolids subjected to an advanced pathogen reduction treatment process
Source: Kelly and Twohig 2018

Key drivers, according to Bloomberg's summary are:

- Increasing adoption of biosolids as an affordable alternative to chemical fertilizers within the agriculture sector will boost the market.
- Implementation of stringent norms and regulations on the use of chemical fertilizers is positively impacting the biosolids market.
- Rise in the number of wastewater treatment plants along with favorable governmental support will accelerate the biosolids demand during the forecast period.
- Expanding scope of biosolids in non-agricultural and heat generation applications is projected to create lucrative opportunities for the market players.

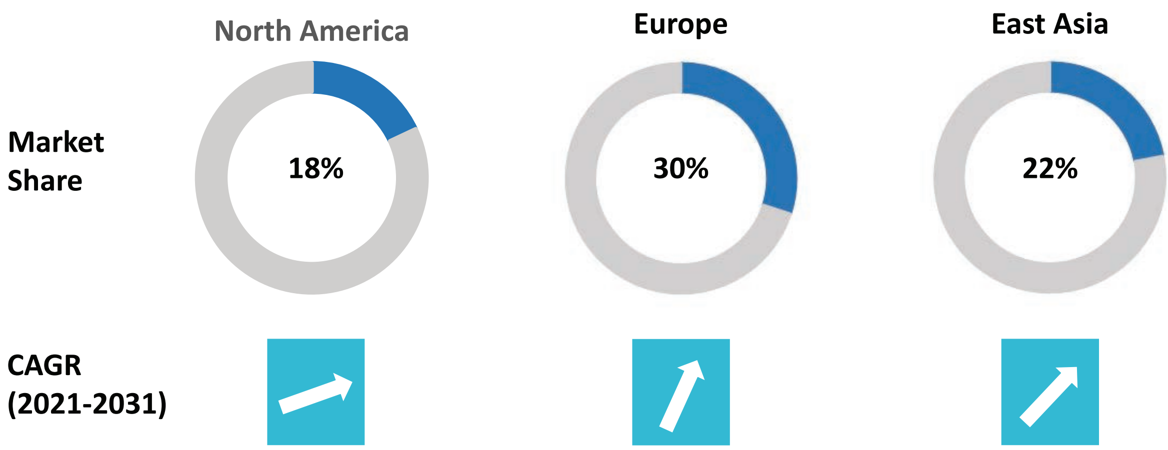
Key restraints are:

- High cost associated with sludge treatment plants is likely to limit the market growth in some regions.
- Availability of conflicting information regarding biosolids on the public domain is expected to create negative impact on the market demand.

The situation in European countries mirrors this summary but also shows likely changes. The main destinations of sewage sludge in Europe are so far agriculture (49%), incineration and energy production (25%), cultivation and land reclamation (12%), landfill dumping (9%), and other destinations (5%) (Campo et al. 2021). However, countries like Germany, the Netherlands, and Switzerland are shifting from using sewage sludge for agriculture towards incineration (EEA, 2021). Table 8 provides a description of disposal mechanisms in selected countries.

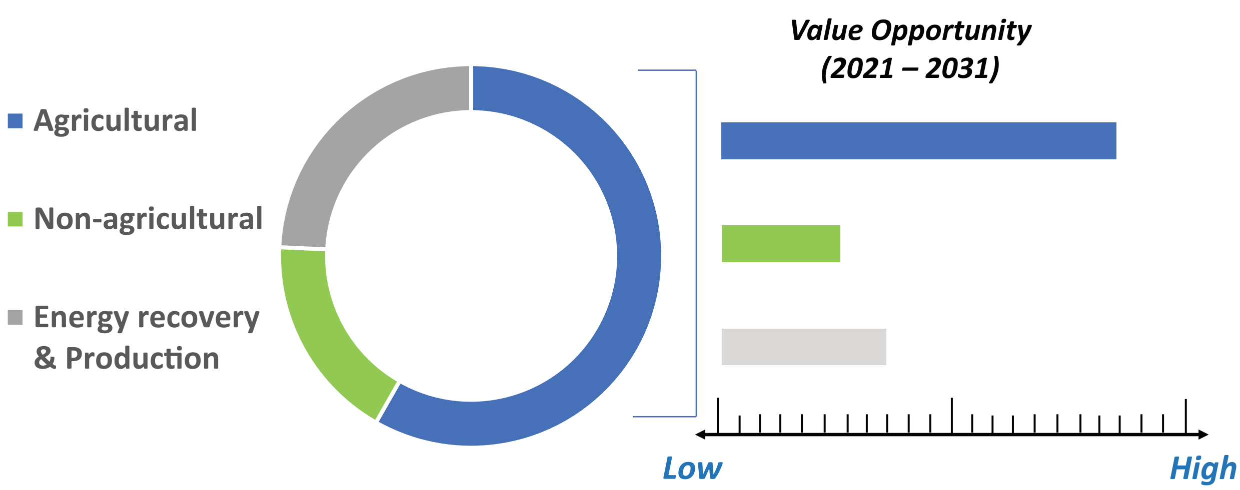
In Asia, there is huge potential for resource recovery in India and China. India is planning to expand its existing capacity for sewage treatment. Over 1,700 million liters per day (MLD) treatment capacity is in the planning or construction stage.[8] It has been estimated that the sector has the potential to generate 15.3 × 10^5 and 8.6 × 10^5 MWh of energy annually from incineration and anaerobic digestion, respectively (Singh et al. 2020). In China, 5,476 municipal WWTPs were operating, leading to an annual sludge productivity of 39 million tons (8% water content). Overall, 29% of the sludge in China was disposed of via land applications, followed by incineration (27%) and sanitary landfills (20%) (Wei et al. 2020). Further regulations like direct reuse of treated water to substitute groundwater and restrict wastewater discharge from industries is increasing importance on wastewater treatment and resulting sludge disposal or reuse (GWI 2023b). Further regulations like direct reuse of treated water to substitute groundwater and restrict wastewater discharge from industries is increasing importance on wastewater treatment and resulting sludge disposal or reuse (GWI 2023b).

[8] https://cpcb.nic.in/status-of-stps/ (accessed on November 5, 2022)



Note:
Pie chart indicates market share by region.
Arrow indicates the relative growth of the market in the region.

Source: https://www.whatech.com/og/markets-research/materials-chemicals/732574-biosolids-market-value-expected-to-reach-us-2-4-billion-by-2031 (accessed on May 5, 2023)



Source: https://www.factmr.com/report/biosolids-market (accessed on October 31, 2022)

FIGURE 3. REGIONAL ANALYSIS OF SEWAGE SLUDGE MARKETS AND VALUE SHARE OF REUSE OPTIONS.

TABLE 8. SEWAGE SLUDGE DISPOSAL PATHWAYS IN EUROPEAN COUNTRIES.

Country	Disposal of sewage sludge
Italy	Organic matter recovered and reused following a biological treatment has grown at an average rate of 8% per year between 2009 and 2018, with the total volume increasing from 4.4 to 7.8 million tons. The total production is about 395,000 tons dry solids/year[a]. Mininni et al. (2019) describe the use of sewage sludge as follows: • 9.9% is used in agriculture without further treatment • 26.4% and 5.6% is used in compost and soil conditioner production respectively • 5.9% is sent to incineration or co-incineration plants • 35% is sent to external sludge centers for further treatment (manly chemical and physical processes) before recovery/disposal • 17.2% is sent to landfills
France	Over 1 million tons of dry solids are produced from wastewater treatment plants.[b] Pradel (2019) describes the use of sewage sludge as follows: • 4% of the sludge produced is used for land applications (agriculture and urban landscaping) • 31% composting, • 22% incineration • 3% landfill • 1% in cement plants
UK	The financial value to UK agriculture of nutrients in biosolids is around USD 73 million per annum constituting mainly phosphate and nitrogen as well as sulfur, potash and magnesium. A strong demand from farmers (worth USD 400 per hectare) in nutrients drives the market: • Around 87% of all biosolids are applied to agricultural lands • 4% incinerated • 3% goes to industrial use (cement plants) • 6% for land reclamation or restoration
Germany	Roskosch and Heidecke (2018) indicate the following uses of sewage sludge: • Disposal via thermal treatment (70%) om coal-fired plants, cement works and co-incineration with municipal waste, maintaining a limit that sewage sludge should not exceed 20% • Sludge applications in agricultural (20%) • Landscaping (10%) Landfilling of sewage sludge is no longer permitted in Germany since 2005. Application of sewage sludge in organic farming, forests, gardens, grasslands, arable land and fruit and vegetable cultivation is also prohibited in Germany.
Netherlands	About 1.5 million tons of dewatered sewage sludge (2% dry matter) is produced per annum and used for:[c] • Mono-incineration (50%) • Drying and co-incineration in bio-energy plant/HVC, and in and cement plants) (25%) • Composting (biological drying) and co-incineration in power plants (19%) • Co-incineration along with municipal solid waste (6%)

Notes;
[a] https://smartwatermagazine.com/blogs/madhuri-patil/biological-wastewater-treatment-market-italy-driven-growth-pulp-paper-industry (accessed on November 5, 2022)
[b] https://www.eureau.org/resources/publications/members-reports/5299-public-water-and-waste-water-services-in-france/file (accessed on November 5, 2022)
[c] https://www.nweurope.eu/media/3386/1_p4y_environ2018_hvc-snb_ruijter.pdf (accessed on November 5, 2022)

The Middle East and North Africa is extending wastewater treatment systems and will need capacity to deal with increased sludge volume. GWI (2012) estimated a CAGR of 8% (2011–2017) with a market size of USD 780 million in 2017. Sewage generation across the region is rising by 25% every year.[9]

For example, Kuwait has six wastewater treatment plants with a combined capacity for treating 12,000 m^3 of municipal wastewater per day. This produces around 250 tons of sludge daily. Similarly, Tunisia has approximately 125 wastewater treatment plants which generate around one million tons of sewage sludge every year. In Jordan, over 105,000 tons of dried sewage sludge are produced in 29 wastewater treatment plants annually, and the volume is expected to increase to 139,000 tons by 2035. Most sludge is stored on-site or transported to unsuitable landfills which negatively affects the quality of the surrounding water sources and causes high greenhouse gas emissions. These practices waste both energy and material resources and lead to high disposal costs.[10]

Most of the sewage in Middle East and North African countries is sent to landfills. Sewage sludge generation is bound to increase at rapid rates due to the increase in the number and size of urban habitats and growing industrialization. Learning from European countries like Germany and Switzerland, sewage disposal for reuse in the cement industry as an alternative fuel might be one way to tackle the growing volume of sewage sludge.

1.3 The business model approach

The term 'business model' in our context follows the definition by Magretta (2002) and Osterwalder and Pigneur (2010):

A business model is defined by who your customers are, which markets you operate in, who your partners are, what costs you have, where your revenues come from, which activities you engage in, and how value is created and delivered to customers, within its enabling environment.

The approach helps to capture from a 'business perspective' what is needed to understand resource recovery and reuse (RRR) solutions for sewage sludge, such as their costs, the potential for revenue generation, required partnerships, and engagement between diverse stakeholders. The term 'business' in this context should not imply 'profit generation' but the conscious creation of value with a market orientation, aiming at maximizing **waste reduction** and **resource and cost recovery**.

Business models for managing sewage sludge and leading to resource recovery and reuse depend on several factors, such as:

- Existing government priorities, regulatory frameworks and financial instruments (taxes, fees).
- Management choices given assets and operations as it influences the characteristics of the generated sludge (e.g., decentralized treatment technology).
- The internal capacity or availability of a partner to support product-specific distribution, sales, and marketing activities of the recovered resource.

All business models are presented in a common template, starting with the Business Model Canvas (Osterwalder and Pigneur 2010) which describes the building blocks of the value proposition (see Annex 1). The business description, including the model relevance and strategies, is followed by the risks and benefits and financial parameters. Five indicators are used to determine each Business Performance Potential: (i) profitability and cost recovery, (ii) social impact, (iii) environmental impact, (iv) scalability and replicability, and (v) innovation. Each criterion was evaluated with a three-level scale, except the environmental criteria. The scoring of parameters and the resulting rank of indicators was based on qualitative and quantitative data (see Otoo and Drechsel 2018, page 27-29, and Annex 2).

The suitability of the business model canvas for businesses in the domain of resource recovery and reuse was verified by Otoo and Drechsel (2018). The strength of the canvas lies in its simplicity and ability to provide a holistic qualitative overview of the essential components of the business model while falling short in providing quantitative data which would depend largely on the scale of a particular case. The canvas is best used for planning activities to map options for developing a business strategy.

The models presented here are based on empirical cases. The presentation of each model is followed by examples of such cases. **The analysis of the business models was constrained by the limited availability of (e.g. financial) data provided by the studied cases.**

[9] https://www.ecomena.org/sewage-cement/ (accessed on November 5, 2022)
[10] https://www.giz.de/en/worldwide/102143.html (accessed on November 5, 2022)

1.3.1. Navigating this Report

The present report analyses business models derived from existing cases in several countries. The models are categorized into those which are:

(i) recovering biosolids (for soil amelioration)
(ii) recovering specific nutrients (phosphorus; carbon/biochar)
(iii) recovering energy (biogas, electricity)
(iv) recovering carbon, nutrients, and energy

Figure 4 provides an overview of these options based on the to be recovered resource and technology used. The fourth (vertical) resource recovery and reuse pathway in the figure for recovering nutrients and energy is called a hybrid business model which uses a combination of technologies. The strengths, weaknesses, opportunities, and threats (SWOT) are compared for each model in the text.

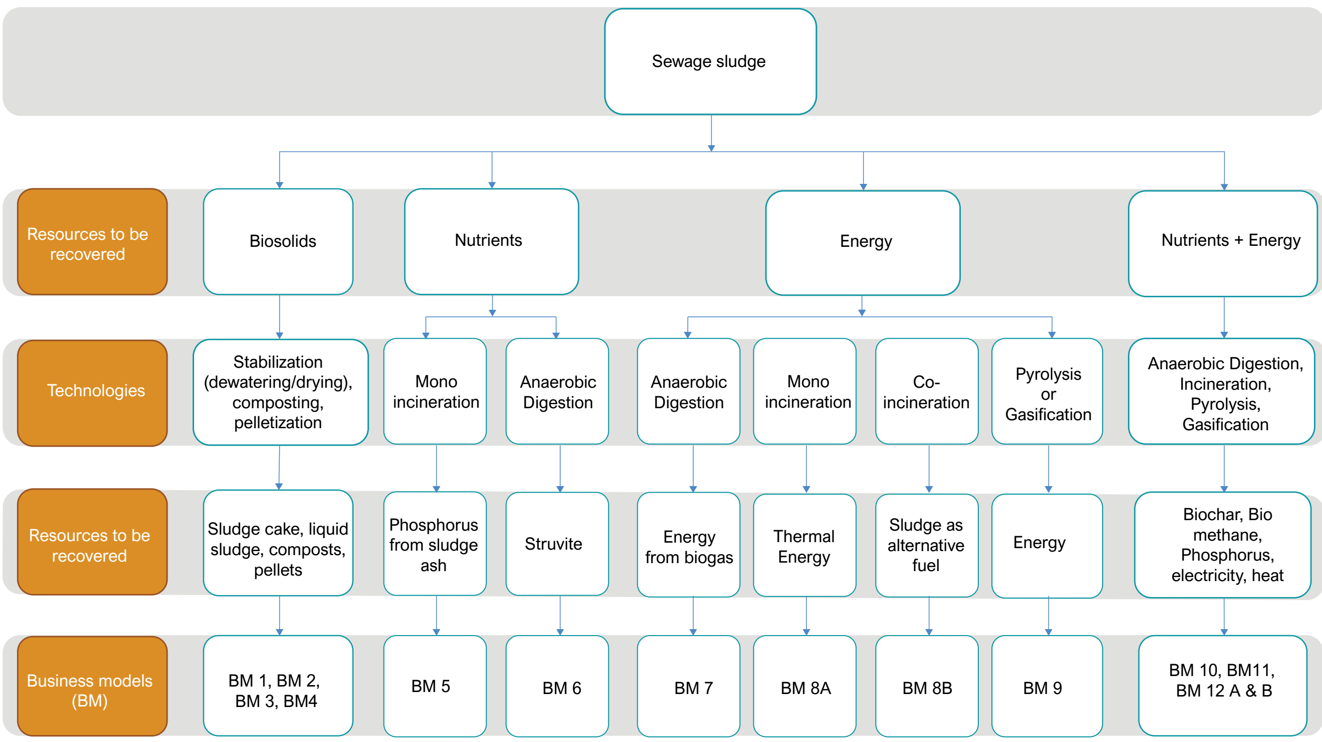


FIGURE 4. PATHWAYS FOR NUTRIENT AND ENERGY RECOVERY FROM SEWAGE SLUDGE.

Source: Author's creation.

2. RECOVERING BIOSOLIDS

Introduction

The application of well-treated municipal sewage sludge as biosolids in agriculture and landscaping is one option for safe sludge disposal as it provides an opportunity to support the circular economy across the sanitation and agricultural sectors while saving money on more expensive disposal costs or fees. It allows to (i) recycle essential nutrients (N, P, secondary nutrients, and micro-nutrients), and (ii) improve soil physical, chemical, and biological properties due to the high organic matter (i.e., biosolids) content of the sludge. The support of the circular economy is especially important in view of the non-renewable plant nutrient phosphorus (Cordell and White 2011).

The commercial value of generated biosolids can be increased depending on market demand by subjecting them to processes that enhance their safety, storability, and ease of application (e.g., through composting and pelletizing) or boost their fertilizer value (e.g., through blending with other nutrient sources). Using sludge as an organic fertilizer could reduce dependence on conventional fertilizers, but as the nutrient levels are much lower in organic than chemical fertilizers, biosolids help mostly to ameliorate soils low in organic matter, than to replenish nutrient-poor soils like an industrial fertilizer could do.

Sludge use, in particular in agriculture, needs to follow strict safety standards because of chemical pollutants and pathogens, which many treatment systems cannot eliminate to a risk-free level. Its use should therefore be based on (post) treatment processes and best practices as defined in regional, national, or local guidelines.[11]

The most important consideration is that the biosolids should be pathogen free and maintain the standards regarding chemical contaminants such as heavy metals and pharmaceutical residues (Box 1). Although land application is a convenient disposal pathway for sludge, several countries have tried to restrict the use of sewage sludge for and beyond agriculture. For example, many European countries have set even more stringent limits for heavy metals, synthetic organic compounds, and microbial contamination than the European Sewage Sludge Directive (SSD) 86/278/CEE.[12] In Germany, the use of sewage sludge in organic farming, forests, gardens, grasslands, arable land, and fruit and vegetable cultivation has been prohibited under Sewage Sludge Ordinance (1992, amended 2017). Similarly, Italy set its limit values at the lower end of the ranges specified in the SSD for sewage sludge applied to soil.[13] China's Ministry of Agriculture banned the use of sludge for farmland applications. Land-use options for sewage sludge is limited to soil enhancement for degraded soils, abandoned mining sites, forests and urban greening (Dong et al. 2018).

However, the enforcement of these regulations varies between countries, which can push more responsibility on product safety to the WWTP operator as the second model presented here will show.

This section will introduce four business models which we observed.

1. A service provider formally contracted by wastewater treatment plants (WWTPs) to collect and (further) treat the sludge for land application within a well-respected regulatory framework
2. Farmers, farmer associations or an informal service provider relieving WWTPs of their (at least partially treated) sludge within a suboptimal institutional and regulatory environment.
3. A service provider collecting organic waste from different sources including WWTPs to produce a quality co-compost for land application.
4. A service provider collecting settled sludge from the WWTP to produce pellets from it which can be mixed with other soil ameliorants or fertilizer for land application.

BOX 1. PRECAUTIONS WITH LAND APPLICATION AND MANDATORY REGULATORY COMPLIANCE.

For any type of land application, the users are responsible for providing the following information to regulatory bodies:

(i) Classification of the sludge and origin
(ii) Chemical analysis of the sludge
(iii) Information about sludge storage
(iv) GPS information or cadastral information for fields where the sludge will be used
(v) Soil composition
(vi) Crops and plants to be treated if the sewage analysis and classification is found suitable for cultivation
(vii) Proposed amount of application and frequency
(viii) Details of the agreement between the farmer and sludge provider and the date of application

Additional risk management measures should be taken to prevent the transmission of pollutants or pathogens through:

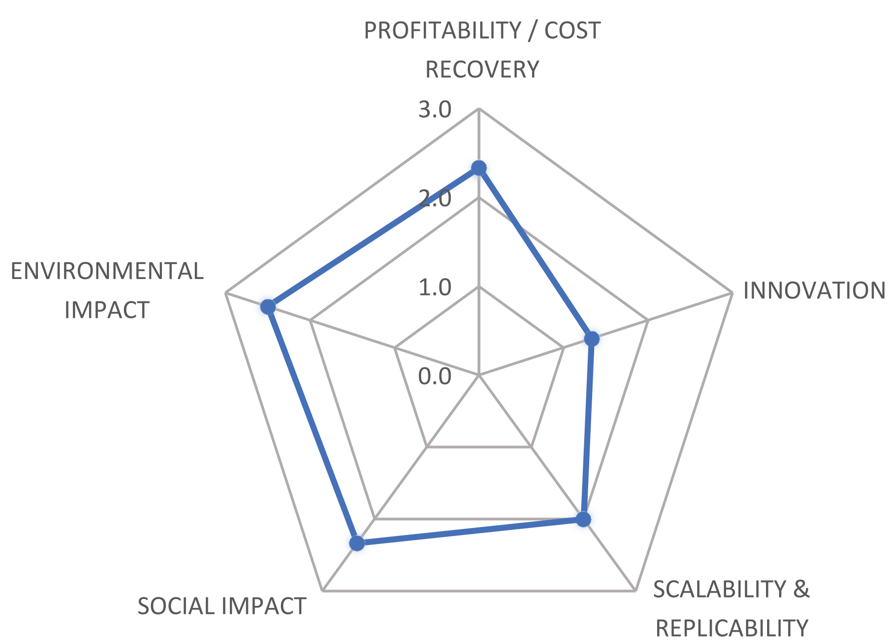
- Prohibiting applications in environmentally sensitive areas
- Prohibiting applications on steep slopes and areas where the water table is close to the soil surface
- Limiting contact between biosolids and vectors such as mosquitos, flies and rodents
- Requiring buffer distances around residential areas, wells, streams, rivers and sinkholes
- Restricting crop harvesting and grazing for specified time intervals after biosolid application
- Mandatory training of individuals responsible for land application programs

Source: United States Environmental Protection Agency Part 503.3. Standards for the Use or Disposal of Sewage Sludge (1993) (modified).

[11] See rgulations mentioned in the previous section.
[12] Like Denmark, Estonia, France, Germany, Czech Republic, Sweden, Poland, Belgium, and The Netherlands while countries like Italy, Ireland, and Portugal have set their regulatory limits as per the lower limits of the SSD. https://www.slideshare.net/dakar2/sewage-sludge-management-legislation-in-italy-121782867?from_action=save (accessed on January 5, 2023)
[13] In Italy, National Decree 75/2010 governs the use of fertilizers which are produced from sewage sludge and manure and are used in agriculture. The limits are set under National Decree 99/1992 as revised by Decree 130/2018. The regulation bans the application of sludge on flooded soils, land intended for pasture or animal feed five weeks before harvest, land intended for horticulture and fruit growing, or when cropping is in progress.

BUSINESS MODEL 1: FORMAL SLUDGE COLLECTION AND TREATMENT FOR USE

Brief	**Businesses collecting and treating biosolids for land application** (see Business model 2 for similar services by the informal sector)
Location	Peri-urban and rural areas
Waste input type/stream	Stabilized sewage sludge
Value offer	Biosolid collection, drying and/or stabilization and sanitization of biosolids, application on farms. Documentation of the process and report to regulators.
Environmental risk mitigation	Land application of biosolids should be undertaken with the utmost precautions following all regulatory compliances for pathogens and chemical pollutants, in particular if agricultural land is targeted for food production. Regulators need to be highly vigilant about the process of biosolid application.
Organization type and profit objective	Private entities operating with a profit motivation.
Major stakeholders	Municipalities and WWTP operators, private entity processing the biosolid and applying in farms, farmers and regulators.



Business performance of recovering stabilized sludge.

- The business model scores high on profitability and cost recovery, and social and environmental impacts. For farms, addition of soil enrichers (phosphorus, carbon and nitrogen) reduces the costs for chemical fertilizers.
- This is an effective disposal mechanism with relatively low environmental and social impact, compared to disposal in landfills or incinerators. However, the most important requirement for the businesses is to monitor the quality of biosolids and the condition of the soil before application.
- The land application should be restricted for specific crops or as specified under regulations.
- The business is subject to any changes or additional restrictions by the regulatory framework on biosolid characteristics during the contract period.

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Simple and low-cost resource recovery technique based on simple sludge treatment and management. • Adapted to extensive farming operations with maize and cereal cropping patterns as well as fodder or forests.	**Weaknesses** • Dependent on rigid quality management of sewage sludge and acceptance of treated sludge by contracted farms.
External origin	**Opportunities** • Adaptation of technology to low- and mid-income countries for low-risk sludge from non-industrial sources and with suitable agricultural, landscaping or forestry soil and land conditions.	**Threats** • Changing regulatory frameworks that minimize use of sewage sludge on land. • Persistent reluctance of consumers to buy food produced with sludge-based fertilizers.

Business Model Description

A business model involves the engagement of an entity bridging the gap between municipalities and farmers through the collection and application of stabilized municipal sludge (biosolids) e.g., to farmlands. These businesses are mostly privately owned and can take several forms:

- operate solely in the collection and transportation, treatment/storage, and land application of the biosolids, and
- part of a larger operation that includes other services along with biosolids management; like construction, operation and maintenance of wastewater treatment plants.

The business process is driven by the payment of disposal fees by treatment plant operators to external sewage sludge management (SSM) service providers eligible for collection, treatment and disposal of sewage sludge according to quality standards set out in environmental laws and regulatory frameworks. Typically, private service providers are contracted long term by WWTPs operators or operating agencies of WWTPs which lack space for sludge storage, disposal or use. Disposal fees for sludge are paid per cubic meter by the contracting WWTPs.

The SSM business transports stabilized sludge to its facilities where it is stored, homogenized in tanks and treated e.g., with quicklime (Calcium oxide) to achieve an exothermic reaction to inactivate pathogens. Others rely on sludge drying, e.g. via heat treatment. Stabilized sludge is then transported by truck, for example, to contracted farmers where sludge is applied by specially designed vehicles during field preparation and early growth stages of fodder crops and maize. To prevent leaching or runoff, the practice is limited to appropriate soils and topographies. Quality control of sludge products is provided by both the treatment plant and the SSM service provider. Field applications are documented according to regulatory requirements by agricultural and environmental departments.

The model is based on the demand from small to medium WWTPs without sludge storage facilities that provide only basic wastewater and sewage sludge treatment in regions where the application of stabilized sludge meets farmers' demands for low-cost organic fertilizer (Canvas 1).

Outsourcing SSM to the private sector is practiced mostly by small WWTPs in agricultural regions. Application of sludge after chemical stabilization and pathogen inactivation falls into the low-cost category of SSM and is typically practiced in non-elevated, scarcely populated agricultural regions in the US wheat belt and the mid-west, where organic fertilizer is in high demand.

Expansion of the SSM business within a region is determined by sludge transport costs and available agricultural land for reuse near storage and treatment facilities. According to business cases from the US, UK and Italy, successful businesses have set up additional storage and treatment facilities in neighboring districts and states. A schematic representation of the technical options (drying, chemical treatment) is provided in Figures 5 and 6.

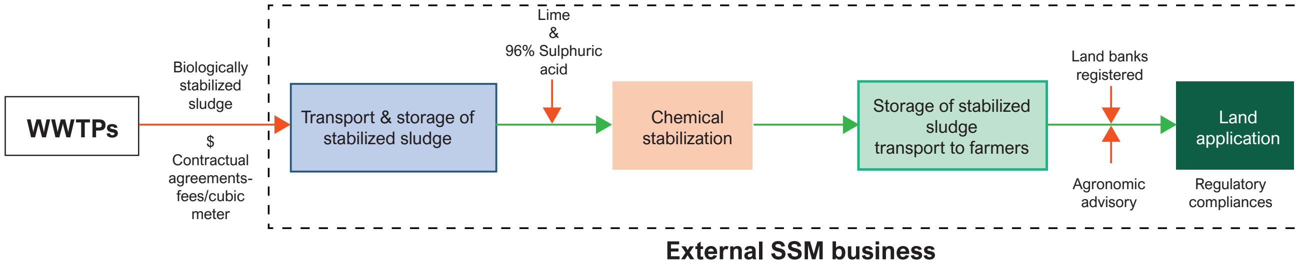


FIGURE 5. BUSINESS MODEL FOR USE OF CHEMICALLY STABILIZED SLUDGE.

Source: Author's creation.

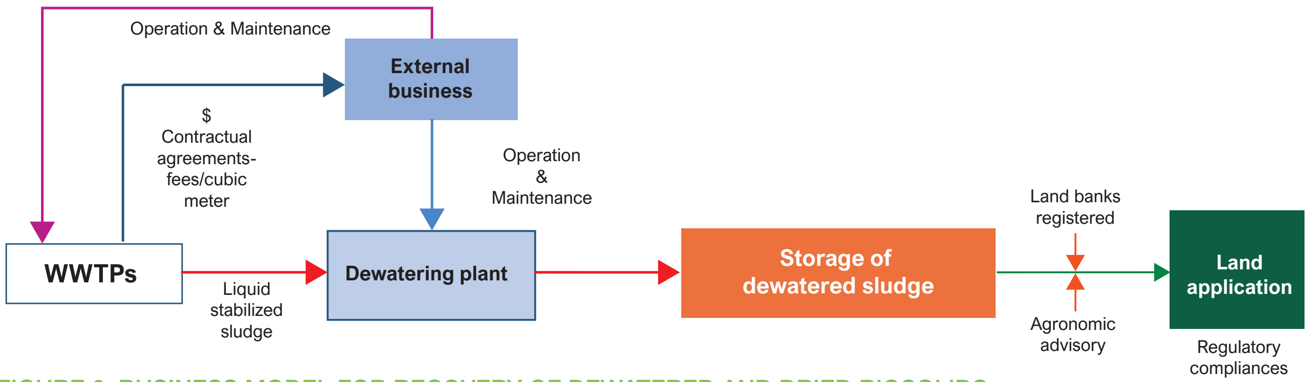


FIGURE 6. BUSINESS MODEL FOR RECOVERY OF DEWATERED AND DRIED BIOSOLIDS.

Source: Author's creation.

Partners

- Regulatory bodies
- Farmers
- Urban local bodies

Activities

- Collection and transport of stabilized sludge
- Storage of sludge and chemical stabilization
- Contracts with sludge users
- Documentation required for regulators

Resources

- Dedicated vehicles for collection and transport of sludge
- Available land and contracts with farmers
- Long-term contracts with WWTPs or local authorities and farms

Value propositions

- Collection, transportation, and treatment of sludge
- Nutrient recovery
- Process documentation which includes sludge analysis, soil testing and determining the application rate for different crops
- Safe and productive disposal of sewage sludge

Customer relationships

- Direct with dedicated vehicles for collection of stabilized sludge
- Land application of biosolids

Channels

- Long-term contractual agreements with customers and direct engagement with them

Customer segments

- Wastewater treatment plant operators and urban local bodies
- Farmers

Cost structure

- Infrastructure for storage of processed liquid sludge
- Salary and wages
- Operation and maintenance of vehicles
- Fuel costs and utility charges

Revenue streams

- Main revenue from recycling and disposal fees obtained from WWTP/municipality operators

Environmental and social costs

- Occupational health risks might arise due to handling of waste

Environmental and social benefits

- Safe application of sludge i.e. recovering the nutrients and reducing pollution
- Job creation
- Minimizes capital investments and operational costs for sludge disposal

CANVAS 1: FORMAL COLLECTION AND USE OF BIOSOLIDS

Case Studies

Alan SRL, Italy

Alan SRL has two plants in northern Italy (Sommo and Bascapè)[14] which receive biological sludge from urban WWTPs and industries. The sludge is treated with lime followed by sulfuric acid to stabilize it and obtain biomass that meets regulatory requirements (Table 9). This treatment process allows for the recovery of organic substances and nutrients, supporting a circular economy. These end products are transported to farms affiliated with the business. Application of the end product (organic fertilizer) is done with tractors and manure spreaders according to regulatory restrictions.

Centro di Ricerche Ecologiche (CRE), Italy

Centro di Ricerche Ecologiche (Center for Ecological Research) (CRE) is a UNI EN ISO 9001 and 14001 certified business that produces certified fertilizers through biological treatment and recovered sludge in agriculture.[15] The center has two plants in Maccastorna and Meleti and recovers 250,000 tons of biosolids every year through lime treatment. CRE collaborated with 250 farms where the certified organic sludge is applied. CRE is 75% of Gadfer, which looks after the logistics of the sludge value chain. Through ownership of a wide range of vehicles (tractors and trailers equipped with roll-off bodies, trucks and work vehicles), Gadfer can cover all the requirements in terms of capacity. Having suitable vehicles for access to agricultural fields offers the possibility of carrying out transport related to the agronomic recovery of sludge.

Burch Hydro Inc, USA

Burch Hydro Inc. (presently a subsidiary of Synagro Technologies Inc. from January, 2023) is a biosolids management company based in Ohio providing land application of treated municipal sludge and lime sludge.[16] Among the services offered are transportation of treated sludge and further treatment to stabilize it with lime to meet the US Environmental Protection Agency (EPA) regulation 503 and working with farmers to develop a market for biosolids for land application.[17] The biosolids are transported to the registered farm fields (permitted through EPA). The business is specialized in different types of land application such as (i) surface application of liquid, (ii) sub-surface injection (liquid sludge), (iii) surface application of dewatered material, and (iv) incorporation. It maintains and uses equipment suitable for land application of liquid materials. These units have high-flotation tires to minimize ground compaction during land application. Liquid sludge products are applied with field applicator units designed to prohibit spills and provide even application during surface application. Biosolids in liquid form are injected below the soil surface or incorporated at the time of application. Biosolids, lime sludge and other products managed by Burch Hydro which are in semi-solid form are applied using ‘side-slinger’ type manure spreaders. Biosolids in dry form are also incorporated if required following surface application to prevent issues with runoff and odor.

Merrell Bros. Inc., USA

Merrell Bros. works across several states in the USA with offices in Texas, Indiana, Missouri and Florida.[18] The company manages biosolids for municipalities, industries and agricultural operations. The company is specialized in transporting biosolids (liquid and dewatered) from WWTPs to land application sites complying with all state and federal regulations. They maintain a fleet of vehicles (semi-tankers and trucks) and machines (terragators) capable of handling any amount of sludge for the mechanical application of biosolids.

Cleanaway Waste Management Ltd., Australia

Cleanaway provides waste management solutions and services to several sectors and industries. One service

TABLE 9. DETAILS OF ALAN SRL RECOVERY PLANTS.

Plant	Process description	Volume of sludge handled
Sommo	Phase 1: use of lime to stabilize the sludge Phase 2: pure lime and liquid CO_2 is added to obtain calcium carbonate[a]	48,500 tons annually
Bascapè	Phase 1: use of lime to stabilize the sludge Phase 2: 96% sulfuric acid is added thus activating hydrolysis that generates calcium sulfate[b]	66,000 tons annually

[a] In compliance with the Decreto Legislativo 75/2010 on fertilizers and soil conditioners.
[b] In compliance with the Decreto Legislativo 75/2010 2010 on fertilizers and soil conditioners.
Source: https://alansrl.it/impianti/

[14] https://alansrl.it/impianti/ (accessed on September 10, 2022)
[15] http://www.cresrl.net/ (accessed on September 10, 2022)
[16] http://burchhydro.com/Services/Biosolids-Program-Management (accessed on September 12, 2022)
[17] https://www3.epa.gov/npdes/pubs/owm0031.pdf (accessed on July 13, 2022)
[18] https://merrellbros.com/ (accessed on September 12, 2022)

is land application of treated and stabilized sludge both in liquid and dewatered form across Australia.[19] Liquid biosolids are injected below the surface of the soil using specialized equipment. The liquid sludge is treated, monitored and applied in accordance with Australian regulatory requirements. The company takes care of logistics management of organics transport to the site. Cleanaway carries out market surveys and biosolids research as well as stakeholder engagement and community consultations on the application of biosolids.

Severn Trent Plc. UK

Severn Trent Plc. has been operating in the UK from 1974 with the establishment of Severn Trent Water Authority. The Authority was established through the amalgamation of the Severn River Authority, the Trent River Authority, and the sewage disposal responsibilities of the councils within its area. The business recycles annually about 600,000 tons of biosolids on approximately 30,000 hectares of land. For this, the sludge is dewatered, in part using thermal hydrolysis treatment, while lime additions are only used occasionally. The methane produced is used to power the sites. Severn Trent has a team of farm liaison officer trained in Fertilizer Advisers Certification and Training Scheme. The farm liaison officers complete a mapped field risk assessment, outlining health and safety and environmental hazards. The actual cost savings for farmers compared with buying conventional fertilizers has been estimated as over £200 per hectare on nitrogen, phosphate, potash and sulfur. The public company maintains stock for year-round delivery and have specialized contractors for delivery and spreading of biosolids.[20]

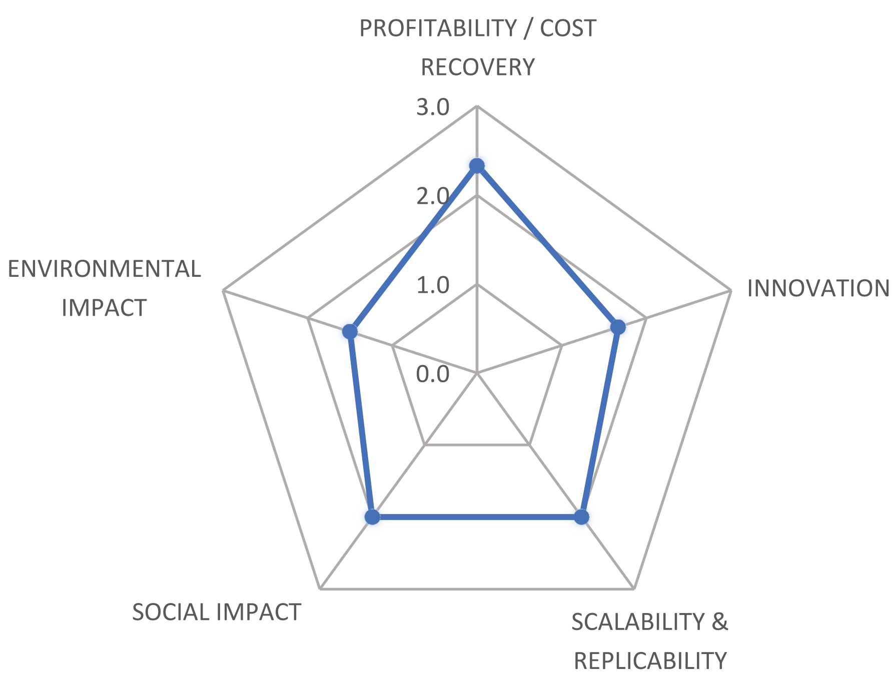
Lystek International Inc, USA

Lystek International offers biosolids processing solutions for municipal wastewater treatment plants and organic waste materials from industrial, commercial and agricultural sectors.[21] The company offers patented design and build services to implement thermal hydrolysis and associated systems. It also produces LysteGro, a pathogen-free, nutrient-rich fertilizer that meets the standards of a USEPA Class A material. LysteGro is also registered with the Canadian Food Inspection Agency. The company can be contracted to provide a comprehensive biosolid management system which includes fertilizer sales and marketing, regulatory engagement, and agronomic planning, and coordination of transportation and field application. The core of the Lystek technology is a process involving a combination of heat, alkali, and high shear mixing to produce a high-solid, pathogen-free and nutrient-rich biofertilizer product. One advantage of the Lystek process is that it produces a safe, stable, low viscosity biofertilizer with a solid concentration in the range of 14–17%. The product can be transported and applied using conventional handling equipment. The company claims its biofertilizer can also be used as raw material for commercial anaerobic digestion plants as it enhances methane production and the subsequent profitability of biogas plants.

[19] https://www.cleanaway.com.au/waste/biosolids-waste-management/ (accessed on September 12, 2022)
[20] https://www.severntrent.com/sustainability-strategy/environment/bioresources/biosolids/ (accessed on April 24, 2023)
[21] https://lystek.com/ (accessed on August 10, 2022)

BUSINESS MODEL 2. INFORMAL SLUDGE COLLECTION AND TREATMENT FOR USE

Brief	**Businesses involved in recovering dewatered/dried biosolids** (similar to Business model 1 but with informal sector partners) *The model is not recommended but reality in many low-income countries. There are options to reduce its environmental risks.*
Location	Peri-urban and rural areas
Waste input type/stream	At least partly stabilized sludge from a treatment plant
Value offer	Sludge (treatment and) use for resource recovery
Environmental risk mitigation	Where (there is a risk that) regulations and land monitoring are absent or not observed, it is imperative for the WWTP operator to accept responsibility and to offer only safely treated sewage sludge that complies with international standards for chemical and microbial contaminants.
Organization type and profit objective	Mostly informal or semi-informal agreements offering the WWTP a solution for its waste and farmers an organic fertilizer
Major stakeholders	Urban local bodies and WWTP operators, private entities, farmers, regulators if available.



Business performance of recovering dewatered and dried biosolids.

- This model is rated high on providing social and environmental benefits as it can effectively close the resource loop, IF safety regulations are followed.
- The model reduces the burden of disposal costs for local bodies and hence lower bills for the authorities and citizens.
- Disposal is only safe if formalized but can create environmental harm if reuse takes place informally without monitoring.
- The model is a profitable proposition for a private entity and where there are informal agreements with farmers it provides a win-win solution with a reduction in transaction costs.
- The model has potential for vertical scaling; however, horizontal scaling might face challenges due to ambiguity of product acceptance in a new market (e.g., among farmers for land application).

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Low capital expenditure and operating expense requirements. • Low technological know-how required, hence semi-skilled workers can be hired. • Adapted to an environment with missing regulations or their enforcements.	**Weaknesses** • The absence of a regulatory framework and weak legal status results in environmental risks and low credit worthiness of a business and minimizes the potential for growth and sustainability.
External origin	**Opportunities** • Low expenditure is needed by utilities and WWTPs to ensure sewage sludge disposal. • Quality control measures (composting, quality analysis) by the WWTP or operator can enhance safety, and increase demand for the product.	**Threats** • Contamination of sewage sludge will lead to a contaminated fertilizer products if no quality control is in place. • New regulatory frameworks and quality standards for biosolid fertilizers may affect the sustainability of the model.

Business Model Description

The model is common in countries where the informal sector is involved in (or even leading) the collection of dewatered and dried biosolids for land applications and regulatory bodies do not have the capacity to implement (monitor) safety standards. The model is from a technical perspective largely similar to the previous one while potentially missing environmental safety compliances once the sludge is leaving the WWTP. In other cases, the end-users are directly served by the WWTP, which is even more risky from an environmental and human health perspective. The model thus puts more responsibility on the WWTP operator to offer a well-treated and stabilized product for collection and reuse. If this is not the case, sludge treatment has to continue off-site the WWTP including on the farm. This is also the case in the situation described by Buijs et al. (2018) e.g., from Ghana and India where septic sludge (septage) is collected from household on-site sanitation systems and deposed off on farms. In these cases, the households pay the operators for collecting the septage and the farmers pay (a token) for the delivery of the liquid fertilizer. Sludge storage between collection and on-farm disposal is seldom, thus the only treatment steps (for pathogens) are the septic tank and (months-long) sun-exposure on farm in the dry season before the sludge is mixed with the soil. If this exposure is sufficiently long before cereals are grown, pathogenic risks can be controlled (Keraita et al. 2014). However, in contrast to septic sludge, sewage sludge has a much higher probability of chemical contaminants, which calls for regulations on disposal frequency and amounts, to avoid heavy metal accumulation in soils. The cases from Tunisia are addressing this challenge pro-actively (see below).

As the WWTPs consider the sludge as a costly waste, it is offered for free to informal handlers, allowing the WWTP to save on alternative disposal costs. The handler is charging farmers for the (ideally composted) sludge as organic fertilizer (Canvas 2). From the handler's (or service provider's) point of view, the growth of the business depends highly on sludge processing costs, sludge transport costs and sludge demand in operational proximity. Demand can be high in areas with plantation crops but depends on farmers acceptance. A schematic representation of the business model for recovering dewatered and dried biosolids through informal entities is provided in Figure 7.

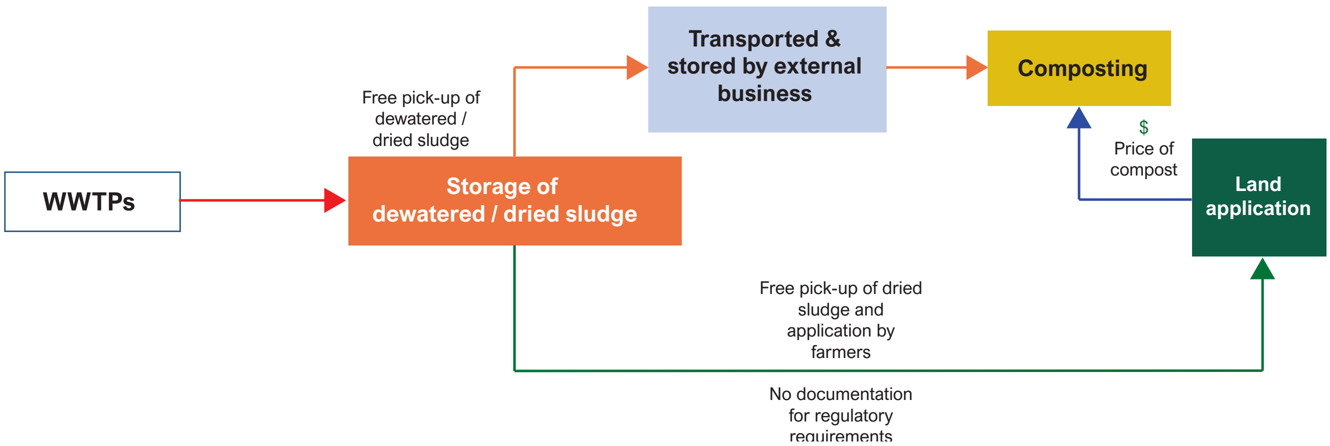


FIGURE 7. INFORMAL BUSINESS MODEL FOR THE RECOVERY OF DEWATERED AND DRIED BIOSOLIDS.

Source: Author's creation.

Case Studies

Partners
- Urban local bodies and /WWTP operators
- Farmers or farmer associations
- Regulatory bodies (if available)

Activities
- Collection and transport of dewatered and dried sludge
- Storage of sludge and (if possible) composting
- Contracting

Resources
- Dedicated vehicles for the collection and transport of sludge
- Land available for further sludge treatment

Propositions
- Collection of dewatered and dried (ideally fully stabilized) sludge for land application.
- Recovery of organic matter and nutrients
- Savings in alternative disposal costs for the WWTP operator

Customer relationships
- Direct relationships between businesses of farmers and WWTP operators
- Direct interactions between the business entity and farmers/ plantations

Channels
- Long-term contractual agreements for sludge procurement
- Direct trading or enrollment of farmers in farmers' associations

Customer segments
- WWTP operator
- Farmers or farmer representatives

Cost structure
- Salary and wages
- Operation and maintenance of vehicles
- Fuel costs and utility charges
- Land rent if leased

Revenue streams
- Sale of dried sludge, compost

Environmental and social costs
- Health risk of laborers' handling the dewatered/dried sludge during transportation or during composting
- Possible environmental risks if sludge treatment was insufficient

Environmental and social benefits
- Safe disposal of sludge if regulations are followed
- Recovery of organics for soils
- Creation of jobs

CANVAS 2: INFORMAL COLLECTION AND USE OF BIOSOLIDS

Colombo, Sri Lanka

The Ratmalana Municipal Sewage Treatment Plant in the south of Colombo has a treatment capacity of 25,500 m^3/day. The Ja-Ela WWTP, north of Colombo, has a treatment capacity of 14,500 m^3/day. It was foreseen that a sanitary landfill would be established to handle sludge from these plants, but this has not been implemented. Based on an informal arrangement, the dewatered sludge from the plants is - for the time being - collected by an organic fertilizer trader who facilitates transport, storage, and drying of the biosolids at its premises in a rural area near Colombo. Compliance with environmental regulations is a potential bottleneck which is compounded by the dependance of the National Water Supply and Drainage Board on this single entity for sludge disposal as there is no alternative.

Hyderabad, India

Hyderabad's sewage treatment plant is on the periphery of Amberpet City and has a treatment capacity of 339,000 m^3/day. The main biological treatment stage of the large WWTP is based on anaerobic upflow and anaerobic sludge blanket technology followed by an aerobic lagoon as a polishing unit. Sludge is anaerobically stabilized within the UASB reactors with a retention time of 33 days before excess sludge is removed and pumped to a belt-filter press for dewatering. That process results in the production of approximately 165 cubic meters of stabilized and dewatered sludge per day. Dewatered sludge is further dried openly in windrows by the WWTP before it is removed (unregulated and for free) by fertilizer producers, horticulturalists, and sugar cane farmers at irregular intervals.

El Kef and Jendouba, Tunisia

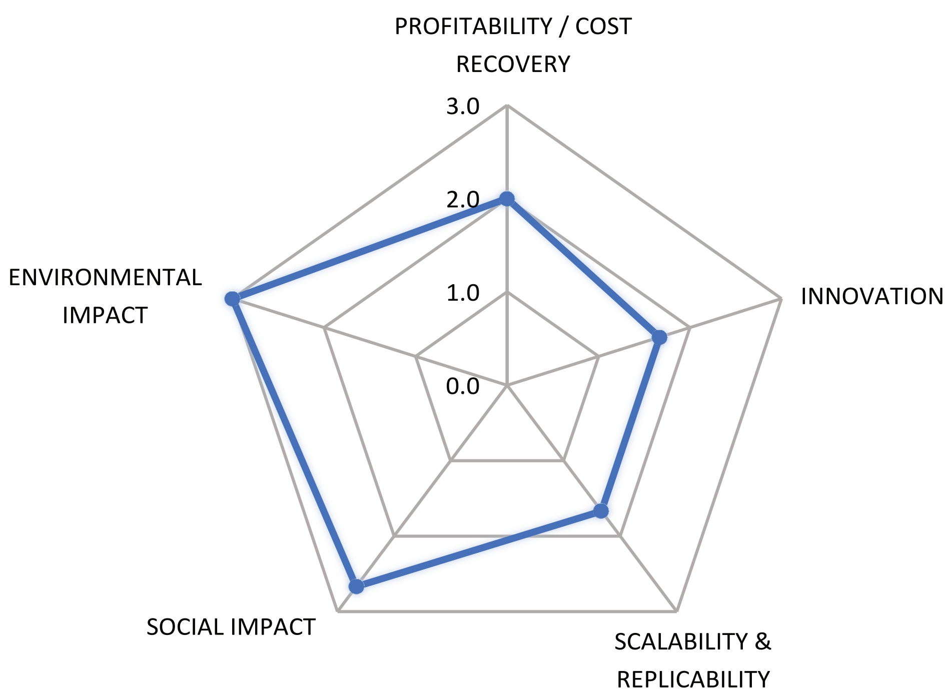
These cases show positive examples where the WWTP is trying to offer well-treated sludge and link with a large number of farms to reduce the risk of contaminant accumulation. Both treatment plants are located in the northern cereal belt of Tunisia. The WWTPs produce about 600 to 1,275 tons of sewage sludge annually. The plants do not operate mechanical driers and rely on 14- 25 drying beds, respectively, for dewatering and drying sludge to a dry matter content of 70% within 60-66 days. Drying beds are manually emptied by plant staff during the summer and the partially dried sludge is further decomposed in uncovered windrows which also serve as areas for sludge storage. In their respective districts, 419 and 876 ha of suitable farmland are available for sludge application, over four times the area officially required to minimize the accumulation of chemical contaminants. Dried sewage sludge is collected informally by farmers or agricultural companies and applied during the first soil preparation on fields designated for cereal crops. Environmental monitoring ends however at the WWTP[22]. The informal business model saves the plant operators between USD 30,000 and 45,000 in operational costs per annum compared to disposal in controlled landfills or co-incineration in cement plants.

Source: All cases through author's field visits, 2015-2020

[22] Status 2015.

BUSINESS MODEL 3: PRODUCING CO-COMPOST

Brief	**Production of co-compost from sewage sludge and other organic waste**
Location	Peri-urban and rural areas
Waste input type/stream	Dewatered sewage sludge, organic domestic waste, green waste (yard trimmings, wood waste, leaves), food waste
Value offer	Dewatered sludge used for co-compost which is otherwise disposed of in landfills, implies savings in disposal costs, resource recovery, and revenue from sales of co-compost.
Environmental risk mitigation	Chemical contaminants in the compost must be monitored.
Organization type and profit objective	Public or private, incl. not-for-profit.
Major stakeholders	Urban local body, public entity (WWTP operator), service provider for solid waste management.



Business performance of producing co-compost.

- The business model scores high on environmental and social impact since it links to and includes also other organic waste streams for volume and risks reduction and can offers many jobs.
- The scalability of the business is a challenge since the availability and integration of waste streams can be constrained and requires appropriate institutional arrangements, especially when incorporating private businesses competing for the same (waste) feedstock.
- Public businesses integrating waste streams for co-compost are mostly run to maximize social impacts rather than earn profits and hence private-public partnership models can be considered for long-term feasibility and scalability.

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Sale of quality controlled organic fertilizer to commercial farms and government institutions for use in agriculture, horticulture, and gardening. • Strong social and environmental benefits.	**Weaknesses** • Profitability depends on availability of poor soils and crops that require heavy doses of quality compost. • Requires a strong network of stakeholders across supply and demand.
External origin	**Opportunities** • Further blending of compost with sawdust etc. could be a substitute for peat where peat use is increasingly restricted. • Transformation into biochar could further reduce the sludge volume but also nutrient value. • Carbon market	**Threats** • Blending treated sludge with other compost feedstock is banned by leading compost business networks such as the European Compost Network. • In many developing countries, there are no specific guidelines for compost quality, which may reduce acceptance among farmers or open informal reuse doors.

Business Model and Description

The business model transforms sludge into a soil ameliorant. The composting helps eliminating pathogens, but not chemical contaminants. The co-composting of sludge and another organic feedstock can improve the composting conditions (carbon-nitrogen ratio) and final co-compost quality. It is a win-win for carbon rich feedstock (like market waste) and nitrogen-rich feedstock (likes sludge). Co-composting is thus often a request to meet particular reuse demands like of horticulture crops and particular soil types. In the case of private composting providers, contractual agreements with treatment plant operators stipulate after-treatment sludge quality and collection fees based on the sludge volume. Service providers need to consider management and disposal of sludge-derived products according to the standards set by the relevant regulatory bodies. Any additional treatment as specified in regulations implies the collection and transport of sludge from treatment plants to facilities where it can be further homogenized, stabilized, dewatered, and stored before being mixed and composted with e.g. organic solid waste from neighboring areas. Various co-composting mixtures can be certified according to national standards and sold for landscaping or forestry, or if of high quality to horticulturalists, farmers, and gardeners in bulk or packets through retailers and wholesalers.

The model is based on demand from landscapers, farmers and commercial gardeners for large quantities of sludge-based co-compost. A continuous income from disposal fees from treatment plants will allow entrepreneurs, such as fertilizer traders and blenders, to make long-term investments in infrastructure, equipment, and land (Canvas 3). A basic requirement for the business is the availability of land for processing and storing large quantities of co-compost without disturbing neighboring residents.

Expansion of a sewage sludge management business within a region is determined by transport costs and available agriculture land for reuse near storage and treatment facilities. According to business cases from the US and Italy, successful businesses have set up additional storage and treatment facilities in neighboring districts and states. A schematic representation of the business model producing co-compost is shown in Figure 8.

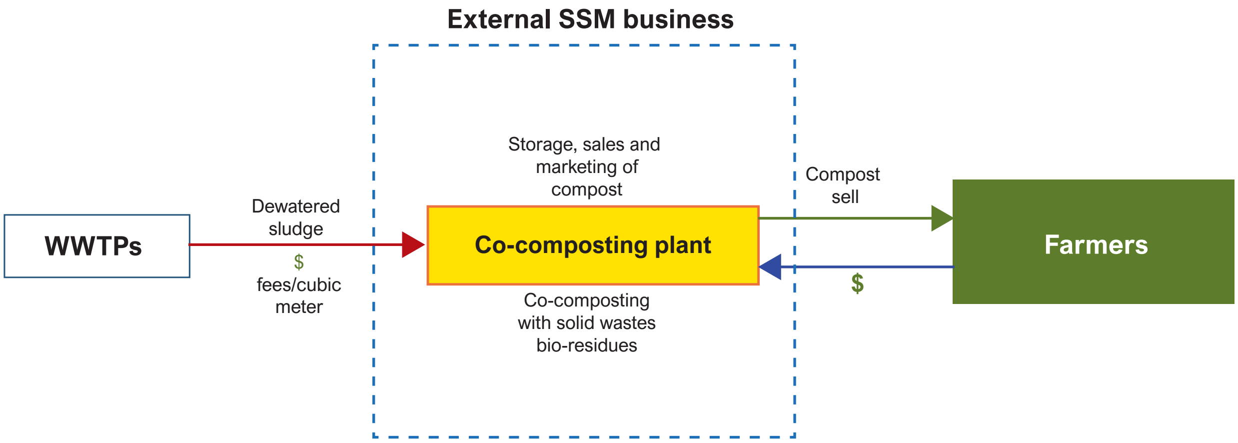


FIGURE 8. BUSINESS MODEL FOR PRODUCTION OF CO-COMPOST.

Source: Author's creation.

Partners

- Urban local bodies, public water utilities and private service providers (where compost production is leased out), public and
- private providers for solid waste management

Activities

- Sludge stabilization
- Collection and transport of sludge for composting
- Transport of green waste for co-composting
- Composting, packaging, marketing and sales of quality compost

Resources

Dedicated vehicles for the collection and transport of dried sludge; land for co-composting

Value propositions

- Savings from a reduction in disposal costs of sewage sludge to landfills
- Production of quality compost (ISO standards)
- Use of other waste streams for resource recovery and reuse
- Recovery of organic material and nutrients for soils and crops, or landscaping

Customer relationships

- Direct relationships between WWTP operators and business entities
- Direct links with farmers for compost and fertilizer sales

Channels

Through bulk and wholesale outlets of either the private service provider or the public water utility

Customer segments

- WWTP operators and urban local bodies
- Farmers

Cost structure

- Capital costs: mechanical equipment, vehicles, land for drying beds and composting
- Salary, wages, interest.
- Operation and maintenance of WWTPs, composting yards
- Fuel costs and utility charges.

Revenue streams

- Revenues generated from disposal fees from WWTPs/municipalities.
- Revenue from sale of compost (organic fertilizers) to farmers.
- Carbon market (maybe in association with other service providers)

Environmental and social costs

- Labor health risks might arise due to the handling of sewage sludge and other waste streams.

Environmental and social benefits

- Safe application of sludge recovering the nutrients and reducing pollution.
- Job creation.
- Land requirement for landfills is reduced in the long term as there is less disposal to landfill sites.

CANVAS 3. CO-COMPOSTING

Case Studies

Azienda Agri Allevi SRL, Italy

Allevi is a traditional agricultural company that began experimenting with the use of non-hazardous waste as soil conditioners and then scaled up for third parties.[23] The company operates mostly in Italy providing solutions to municipalities. It reported a revenue of USD 7 million in 2018 by producing, distributing and applying about 20,000 m^3 of co-composted biosolids annually through contracted farms (about 60 in number over an area of 6,000 hectares). The company collects 200,000 tons of waste annually which comprises: (i) waste from agriculture, aquaculture, silviculture, horticulture, hunting and fishing, food processing and preparation, (ii) wastes from wood processing and production of pulp paper and cardboard, (iii) wastes from processing leather and fur as well as the textile industry, (iv) wastes from organic chemical processes, and (v) sludge produced by wastewater treatment plants. The company adds value by specifying the correct use of sludge, methods of use, and period of application. This is especially important for soils poor in organic matter that have been subjected to mineral fertilizers which have depleted the humus-rich soil horizon. The company produces co-compost using different mixtures of the above listed feedstocks. The sludge is pre-treated with lime followed by sulfuric acid to stabilize it and to recovery both, the organic matter and nutrients contained in the sludge.

Kala, Oman

In 2007, a decision was made to build a modern centralized sludge treatment facility capable of treating the sludge produced by all WWTPs operating in Haya and making a quality product that meets local regulations and US EPA standards for Exceptional Quality by commissioning a compost plant at Al Multaqa in Amerat. In December 2010, Haya Water, a public sector unit in charge of wastewater services in the Governorate of Muscat in the Sultanate of Oman, launched Kala Compost, a product produced at the Kala plant. Kala Compost is produced from the 150 to 250 tons of wet municipal sludge generated each day by treatment plants under the management of Haya Water. Haya Water Utility established the Kala compost plant as part of its efforts to protect the environment and meet the regulatory requirements of restricted landfill disposal at the Al Amerat landfill site. Kala Compost is produced according to the following steps:

- Dewatered sludge from Haya Water's WWTPs is transported by truck to the Kala Composting Plant.
- The dewatered sludge is mixed with a bulking agent (green waste such as yard trimmings, wood waste, horse bedding, leaves, etc.).
- The mixture of dewatered sludge and green waste is composted using an open agitated windrow system.

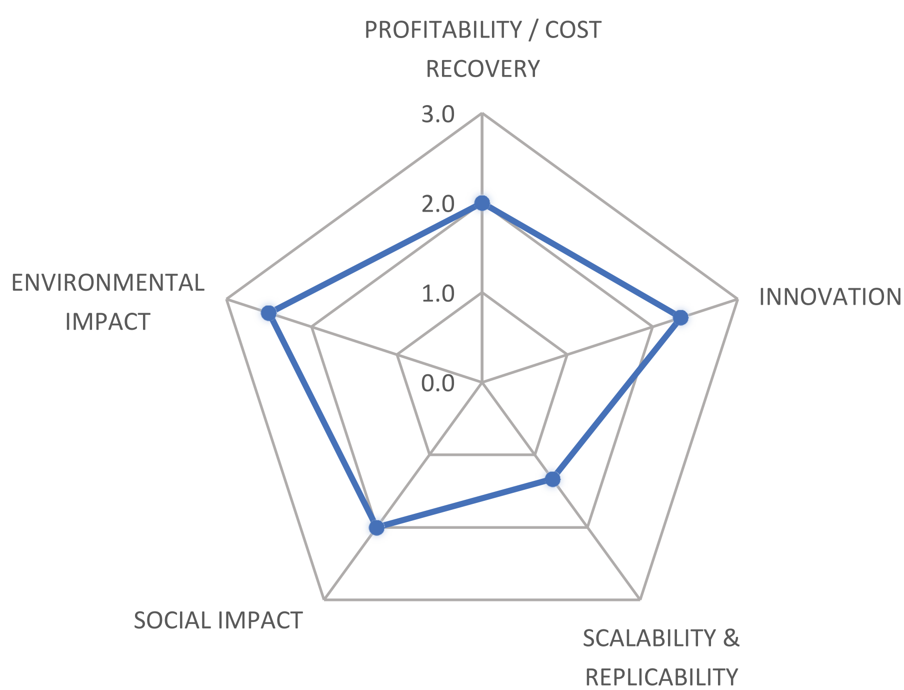
Kala Compost is the first product in Oman produced using an open agitated windrow system on such a large scale. With a capital expenditure of USD 6.25 million, the Kala plant has an in-house laboratory for quality assurance. The equipment was imported from the US and Europe. The capacity of the Kala plant is 40,000 tons of compost per year. Compost is sold for USD 60–100/ton. The company has reported increasing sales over the years (Oman Observer 2017). Kala Compost is a commercial product currently sold to governmental bodies, farmers and landscaping companies. The Kala plant has been accredited by the United Nations Development Program Clean Development Mechanism (UNCDM). It is the first organic fertilizer plant in the Middle East to receive certification. Through the UNCDM program, the Kala Composting Plant is aiming to achieve a total CO_2 emission reduction of 318,000 tons over 10 years.

Haya Water, in collaboration with Sultan Qaboos University, conducted research from 2013 to 2015 to study the effects of Kala Compost on crops. The results showed no accumulation above the normal levels for heavy metals or harmful pathogens in the soil or on the crops. The study indicated that compost derived from sewage sludge increases soil fertility and improves soil water retention retain. It also provides plants with a range of nutrients that increase the quantity and quality of various crops (Jaffar et al. 2017).

[23] Azienda Agri Allevi SRL Home page. https://www.aziendaagricolaallevi.it (accessed on September 15, 2022).

BUSINESS MODEL 4: PRODUCING SLUDGE PELLETS

Brief	**Production of pellets from sewage sludge**
Location	Peri-urban or rural areas based on the location of the WWTPs
Waste input type/stream	Liquid or semi-liquid form of sludge
Value offer	Pelletized sludge for mixing with fertilizer or other soil conditioner
Environmental risk mitigation	Low risk through heat treatment, monitoring of heavy metals needed
Organization type and profit objective	Private, for profit
Major stakeholders	Municipalities, water utilities, fertilizer traders



Business performance of pellet production

- The business model scores high on innovation using advanced technology based on thermal treatment producing organic fertilizer pellets.
- This technology reduces the sludge volume which would have otherwise ended up in landfills adding to disposal costs.
- Scalability requires capital investment in the technology and integration of decentralized WWTPs for achieving economies of scale as the investment costs are high.

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Pelletizing improves sludge transport to locations where sludge is being processed for energy or nutrient recovery. • The smaller the pellets the more options to mix them with other feedstock or later on other fertilizers.	**Weaknesses** • Energy-intensive process that involves high operational costs and high CO_2 footprint to dry sludge.
External origin	**Opportunities** • The use of pelletized sludge for energy recovery allows also the use of contaminated sludge not suitable for farming. • Carbon market for organic fertilzer sludge, storage and disposal costs.	**Threats** • The business model might not be sustainable where agricultural demand for organic fertilizers or refuse-derived fuels is low. • This would lead to a large accumulation of treated.

Business Model Description

This business model involves the production of Class A Exceptional Quality (a category of Class A biosolids), that applies to pellet fertilizers made after thermal drying. Municipalities or public water utilities operating WWTPs contract private service providers to treat and manage sewage sludge. The private service provider operates a combined drying and pelletizing plant to process semi-liquid sludge, usually on the plant premises. The contract might be for design, build, own and operate with full financing of the project or design, build and operate if sufficient public finances are available. The contract is usually for more than 10 years and depends on the infrastructure depreciation period.

The process typically involves transferring dewatered or stabilized sludge to a drying installation combined with a pelletizing facility on-site at the treatment plant. Depending on market conditions and regulatory frameworks, non-contaminated sludge is processed to pellets and sold to organic fertilizer traders who might further refine and blend the pellets with nutrient additives into organic fertilizers for special cultivation applications. Sludge pellets can also be used as dry fuel for combustion in waste-to-energy and coal-fired power plants and the cement industry (Canvas 3). This business model is appropriate for small and medium WWTPs without sludge storage capacities that provide only basic wastewater and sewage sludge treatment and where there is a demand for organic fertilizer. A private service provider can then operate through contractual agreements. Business expansion within a region is determined by sludge transport costs and available agriculture land for reuse near storage and treatment facilities. A schematic representation of the business model producing pellets is provided in Figure 9.

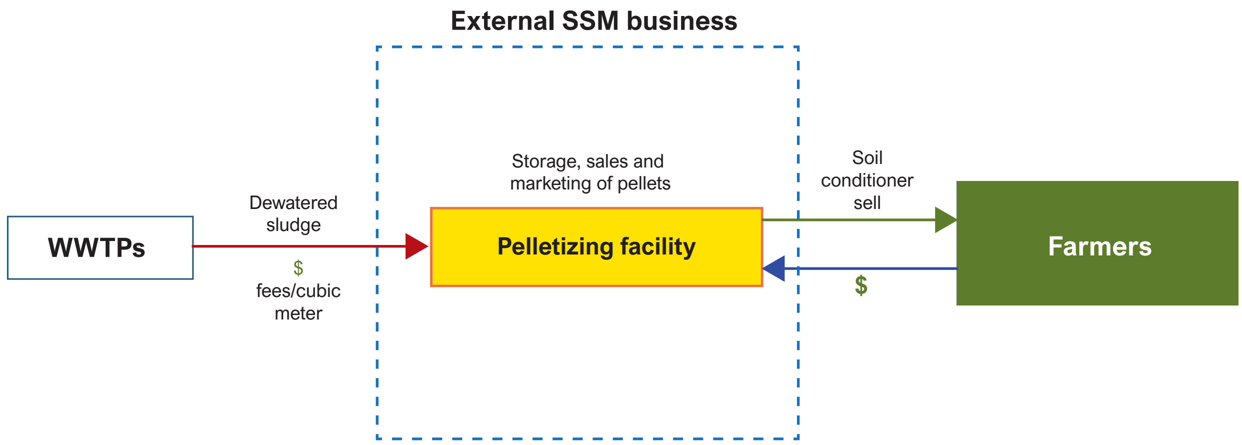


FIGURE 9. BUSINESS MODEL FOR PELLET PRODUCTION.

Source: Author's creation.

<table>
<tr>
<td rowspan="2">Partners
• Urban local bodies, public water utilities and private service providers
• Regulators (environmental, agricultural)</td>
<td>Activities
• Sludge stabilization
• Collection and transportation of sludge for pelletization
• Producing pellets</td>
<td rowspan="2">Value propositions
• Savings from the reduction of sewage sludge to landfills
• Recovery of dry fuel or organic fertilizers for use as a soil conditioner with a slow release of nutrients to the soil
• Option to have product sales and marketing teams handling land application and the required regulatory arrangements</td>
<td>Customer relationships
• Direct interaction with wastewater treatment plant operators to receive sludge
• Direct interaction with the farmers</td>
<td rowspan="2">Customer segments
• WWTP operators and local urban bodies
• Farmers</td>
</tr>
<tr>
<td>Resources
• Dedicated vehicles for collection and transport of dried sludge
• Appropriate technology for heat drying and pelletizing</td>
<td>Channels
• Direct sourcing of sludge from WWTP
• Direct sell sales of pellets to farmers</td>
</tr>
</table>

<table>
<tr>
<td>Cost structure
• Capital costs: mechanical equipment, vehicles
• Salary, wages, rent, interest
• Utility and fuel costs
• Costs associated with marketing and selling fertilizers</td>
<td>Revenue streams
• Revenues generated from fees provided by WWTPs/municipalities
• Revenue generated from sale of pellets (organic fertilizers or dry fuel)</td>
</tr>
<tr>
<td>Environmental and social costs
• Labor health risks might arise due to handling sewage sludge.</td>
<td>Environmental and social benefits
• Reduce pollution in waterbodies and natural habitats as sludge is safely disposed of.
• Reduction of human exposure to untreated and partially treated sludge.
• Reduces land requirements for landfills as treated sludge is not disposed of in landfills.
• Job creation.</td>
</tr>
</table>

CANVAS 4: PELLET PRODUCTION

Case Studies

Synagro, USA[24]

Synagro was founded in 1986 to support biosolids management for municipalities with a wide array of services. It is producing granulite fertilizer and renewable fuel pellets. The fertilizer is produced through an advanced heat drying and pelletizing process in which municipal biosolids are heated and dehydrated to create fertilizer that meets the U.S. Environmental Protection Agency's (EPA) Exceptional Quality standards while reducing the sludge volume by 70% and producing dried biosolids that can be used as (or mixed with other) organic fertilizers and are safe for use even on vegetables.[25] In addition, Granulite fertilizer can be used on flowers, lawns and turf (golf courses, playing fields and sod).

In its Baltimore-Black River Pelletech Facility, Synagro's design, build, own, and operate plant operator promised to process up to 110 dry tons of biosolids per day (20,000 tons of biosolids annually)[26] and management of all disposal operations, producing pellets that are clean, odorless, easy to handle and store, and can be sold as a slow-release fertilizer or soil conditioner. The advanced heat drying method for pelletizing municipal biosolids that meet the US Environmental Protection Agency's Exceptional Quality standards. Granulite has been used successfully on crops such as citrus, corn, cotton, fruits, rice, soybeans, vegetables and wheat. It can also be used on flowers, lawns, golf courses, playing fields, and sod.[27]

Veolia, USA[28]

Veolia produces Nutri-Pel, a biosolids-based commercial fertilizer using sludge from the Ashbridges Bay WWTP.[29] Sludge from the plant is heated at a high temperature and turned into pellets rich in nutrients and organic matter. The fertilizer is sold under the Canadian Fertilizers Act and Regulations. The product has been reviewed by the Canadian Food Inspection Agency for safety, efficacy and label requirements and has a guaranteed minimum nitrogen, phosphorus and potassium ratio (NPK) of 4.5–6–0. The pellets also contain secondary macro-nutrients (calcium, sulfur, magnesium) and micro-nutrients for plant growth. The company claims that approximately 60% of the nitrogen is released in the first year, 30–35% in the second year and the remaining 5–10% in the third year. All the phosphorus is available in the first year, as are all the other nutrients.[30] However, these rates depend on soil temperature and moisture and can fluctuate somewhat.

Today, Veolia produces and sells 25,000 metric tons of Nutri-Pel annually, but in 2007, when the plant had just started, sales were low (5,000 tons per year). Farmers were reluctant to use the product and their cause of concern was the presence of heavy metals. Tests were conducted for eleven metals and the results were used in discussions about the product. The city of Toronto renewed its contract for pellet production for a decade based on the satisfactory results of these tests.

[24] https://www.synagro.com/ (accessed on September 15, 2022)
[25] https://www.synagro.com/wp-content/uploads/2020/03/Services-Heat-Drying-and-Pelletization-2018.pdf (accessed on September 15, 2022)
[26] Synagro. https://www.synagro.com/locations/baltimore-back-river-pelletech-facility/ (accessed on September 15, 2022)
[27] Synagro. https://www.synagro.com/granulite-fertilizer-pellets-2/ (accessed on September 15, 2022)
[28] Veolia. https://www.planet.veolia.com/en/pellet-takes-nutrients-wwtp-field (accessed on September 15, 2022)
[29] Veolia. https://www.veolia.ca/en/case-studies/pelletizer-facility-ashbridges-bay-wastewater-treatment-plant-toronto-ontario (accessed on September 15, 2022)
[30] Veolia. https://nutri-pel.ca/wp-content/uploads/2020/04/Analysis_MV-pp-rev-2020.pdf (accessed on September 15,2022)

3. RECOVERING PHOSPHORUS

Introduction

Phosphorus, an essential element for all life including crops, is extracted from geological deposits of rock-phosphate. The countries with noteworthy phosphorus reserves are only a few: Morocco, China, Egypt, Algeria and Syria. These reserves face an irreversible depletion of their reserves and till then the economic and energetic barriers to their exploitation will increase, calling for investments to recover as much phosphorus as possible from current waste streams (Cordell and White 2011).

Phosphorus is abundant in sewage sludge, however, the quantity recovered depends on its concentration. The choice of technology for phosphorus recovery must be based on technical and financial viability. Phosphorus can be recovered through mono-incinerated sewage sludge or standalone technologies customized for separating phosphorus from sludge.

At municipal WWTPs, phosphorus can be extracted or recovered mainly from three sources (Figure 10):

1. Direct use of sewage sludge with 40–90% phosphorus recovery potential compared to the pre-treatment phosphorus load. (Shown as '1')
2. From sludge, (a) including the aqueous sludge phase before dewatering (5–20% of the initial phosphorus load), and (b) from sludge liquor after dewatering (≤ 25% of the phosphorus load). With forced phosphorus dissolution, the maximal recovery rate can reach 50%. (Shown as '2a' and '2b' respectively)
3. From mono-incineration sludge ash. This has the highest phosphorus recovery potential of over 80% of the pre-treatment phosphorus load. (Shown as '3')

Recovering phosphorus following the thermal treatment of sewage sludge is called downstream recovery. There are different emerging technologies for phosphorus recovery.[31]

In this section we will present two models: one based on phosphorus recovery from incinerated sludge ash (model 5), and one on the recovery of phosphorus from anaerobic digestion (model 6). While model 5 has the advantage of recovering a significant share of phosphorus, model 6 is first of all a cost-saving model as it helps to minimize unwanted (and maintenance cost intensive) struvite crystallization.

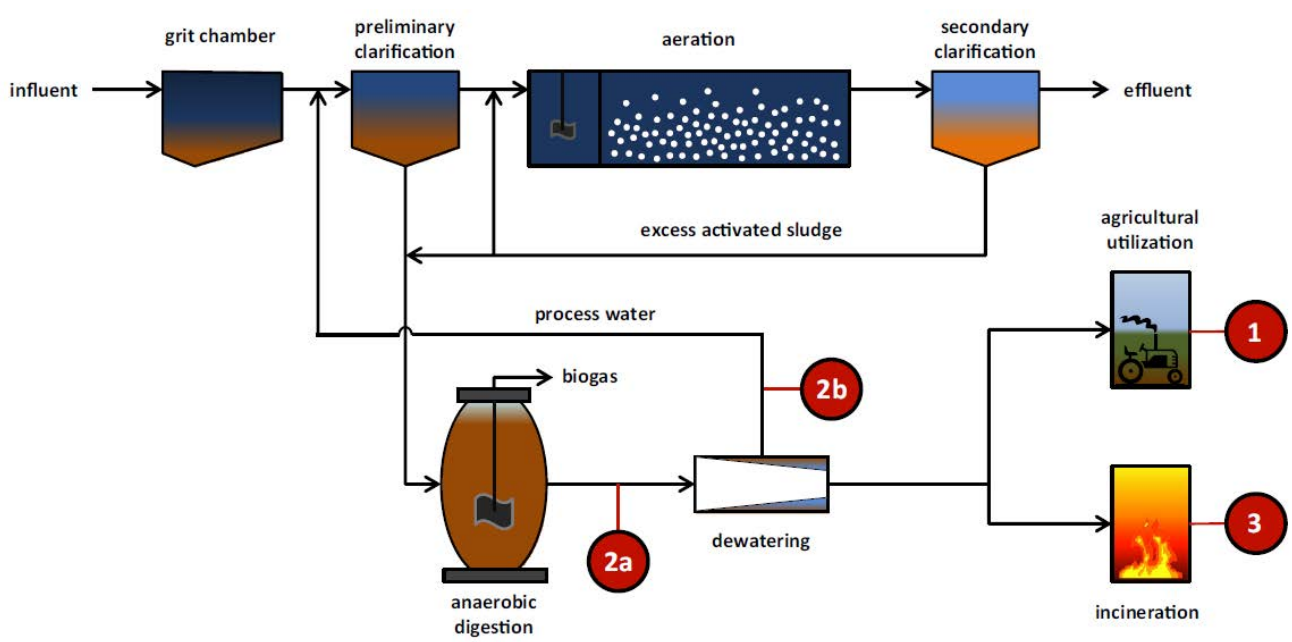


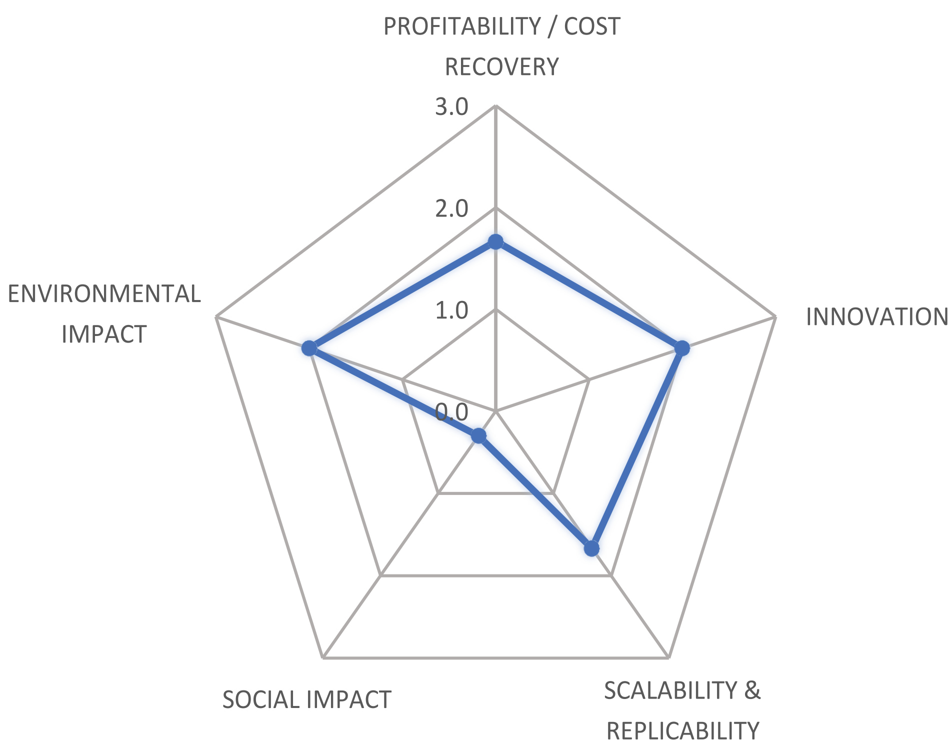
FIGURE 10. PHOSPHORUS RECOVERY AT DIFFERENT STAGES OF SEWAGE SLUDGE TREATMENT.

Source: Kabbe et al. 2015.

[31] There is a regularly updated online catalogue - https://phosphorusplatform.eu/images/download/ESPP-NNP-DPP_nutrient-recovery_tech_catalogue.pdf (last accessed on April 24, 2023)

BUSINESS MODEL 5: RECOVERY OF PHOSPHORUS FROM INCINERATED SLUDGE ASH

Brief	**Recovering phosphorus from sewage sludge ash obtained from incineration**
Location	Urban and peri-urban areas based on the proximity of incineration facilities
Waste input type/stream	Sewage sludge ash
Value offer	Recovery of phosphorus from ash, which is otherwise disposed of, leads to two value propositions: (i) phosphorus is a finite resource, recovery produces a close substitute for agricultural application, and (ii) reduces the cost of disposal for the WWTP operator.
Environmental risk mitigation	Processes needed to separate phosphorus from heavy metals.
Organization type and profit objective	Both public and private operators; the public operator might not operate with a profit motive whereas the private entity would seek profit.
Major stakeholders	WWTP operator, phosphorus recovery plant operator, fertilizer sellers (networks of wholesalers and retailers).



Business performance of recovery of phosphorus from sludge ash.

- The business model scores high on innovation and reduction in environmental impacts.
- The business model includes advanced technology for maximizing phosphorus recovery and hence reduces the risk of environmental pollution.
- The technology can be adapted for WWTPs with an option for incineration and can be scaled to meet demand.

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Modular units for treating sewage sludge ash and recovering significant shares of phosphorus make it easier to upgrade the WWTP. • Scaling up to meet future demand is easier since the installation is modular. • Reduces the volume of sludge ash for disposal.	**Weaknesses** • High investment costs for plant installation. • When a phosphorus recovery plant is installed far from a WWTP or incinerator, transportation of ash leads to increased transportation costs. • Obtaining licenses and permits can be a complex and expensive process.
External origin	**Opportunities** • More research and development to improve the quality of recovered phosphorus. • In some countries. phosphorus recovery is being made mandatory and will require WWTP operators to implement this business model.	**Threats** • Reluctance among farmers and fertilizer traders to accept fertilizer products derived from sludge. • The ash might be contaminated.

Business Model Description

Phosphorus recovery from mono-incinerated sludge ash is usually much greater than that derived from raw sludge or digestate. Phosphorus can be recovered from sewage sludge ash via one of two processes: (i) wet chemical treatment (acid or alkaline ash leaching), and (ii) a thermochemical process. In both cases, a phosphorus recovery unit can be established within a WWTP as a modular plant or elsewhere. However, the latter option would need to consider the cost of transporting the sludge ash to the recovery unit.

This business model can be initiated by a public or private entity based on regulations or the availability of appropriate technology. Publicly initiated phosphorus recovery units can be public-private partnership initiatives where regulations restrict proper disposal of sewage ash or the availability and willingness of private entities as technology providers. A public operator (usually a wastewater treatment plant operator) operating an incinerator needs to dispose of ash according to regulations and hence may seek help from government agencies. Government collaboration can lead to grants for installation. The government may also provide seed grants for research and development and establishing a pilot project which can later be scaled up.

Private technology providers can be contracted by WWTP or incinerator operators for the disposal of sewage sludge. Since sludge ash is considered waste, it is mostly disposed of in industrial landfills since it can be classified as hazardous waste (GWI 2012). A treatment plant or incinerator operator pays the phosphorus recovery unit for ash disposal. A private entity engaged in phosphorus recovery then contacts fertilizer traders for marketing. However, due to recent public discussions on phosphorus recovery, some incineration plant operators think that since sludge ash is an input, they should be paid by the phosphorus recovery unit and technology providers could be looking at higher costs (GWI 2012).

This business model is appropriate when a clustered approach is pursued and there is an economy of scale. Downstream options of phosphorus recovery tend to be costlier and have a longer return on investment (GWRC 2019) and therefore it is important to consider the economics of reaching an optimal scale. Another important consideration is the price of the fertilizers derived from the ash and the revenue stream it can provide for the business entity. A schematic representation of the business model producing pellets is provided in Figure 11.

Nättorp et al. (2017) reported on the cost of two technical processes: (i) leaching with sulfuric acid, solid-liquid separation, pH increase and precipitation of calcium monophosphide and calcium hydroxide; and (ii) leaching ash with phosphoric acid, separation of phosphoric acid and metal ion fractions via staged ion exchange regenerated by hydrochloric acid and yield of concentrated phosphoric acid.

Investment costs include material and energy, personnel, and other costs which can be amortized over 10 years at an interest rate of 3% to find the yearly cost (Canvas 5).

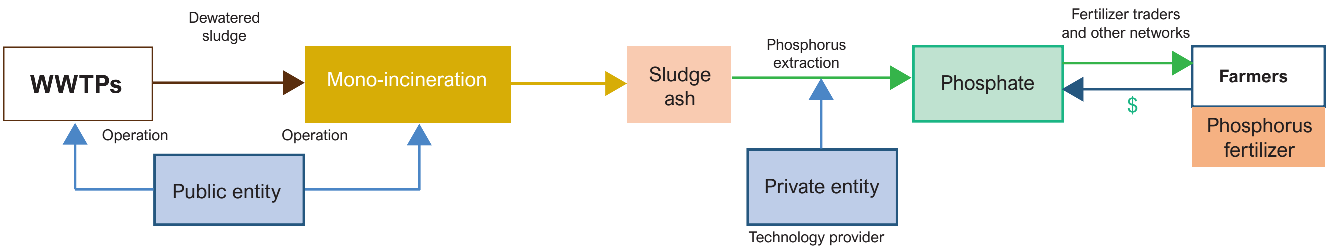


FIGURE 11. BUSINESS MODEL FOR RECOVERY OF PHOSPHORUS FROM SLUDGE ASH.

Source: Author's creation.

Partners
- Technology providers
- WWTP operators and municipalities
- Fertilizer traders

Activities
- Sludge stabilization, and drying, incineration
- Recovering and sale of phosphorus
- Obtaining permits and certifications for fertilizer products

Resources
- Technology for phosphorus recovery
- Existing incineration treatment systems
- Link with fertilizer traders and private entities to market fertilizer products

Value propositions
- Recovering a potentially high-value fertilizer
- Savings in disposal costs to landfills

Customer relationships
- Direct contact with the WWTP operators
- Direct network with fertilizer traders

Channels
- Through bulk and wholesale outlets of private sector entities (sometimes with private-public partnerships)
- May be possible to engage the public sector in marketing and sales

Customer segments
- WWTP operators and incinerator operators
- Fertilizer traders

Cost structure
- Capital costs: installation of modular phosphorus recovery systems, vehicles for sludge transport
- Salary, rent, interest, insurance
- Transaction costs for penetrating fertilizer markets
- Fuel costs and utility charges

Revenue streams
- Revenue generated from fees provided by WWTP and incinerator operators
- Revenue generated from sales of high-value fertilizer
- Cost savings from lower pipe maintenance and disposal costs

Environmental and social costs
- Labor health risks might arise due to handling sewage sludge and other waste streams.

Environmental and social benefits
- Safe sludge application, recovering nutrients and reducing pollution.
- Job creation.

CANVAS 5: RECOVERING PHOSPHORUS FROM SLUDGE ASH

Similarly, the processing costs include improved dewatering and reduced sludge volume to be disposed of, lower demand for polymers in dewatering, and savings in energy consumption for return load treatment in mainstream WWTP since phosphorus and nitrogen content in the return load is reduced due to struvite precipitation in the liquor.

In both these cases, it is assumed there is already mono-incineration and no costs are incurred for the downstream installation except for the phosphorus recovery unit. The estimated cost was USD 5.25 per kilogram (kg) and USD 0.75 per kg, respectively, for phosphorus recovered. Assuming an amortization period of 15 years, the second process results in payback within 10 years and makes some profit due to sales of highly purified phosphoric acid. Similarly, the specific cost per unit of sludge indicates a higher cost for the first technical process (USD 40.7 per ton of sludge compared to USD 7.9 per ton).

Case Studies

Meta Water Company, Japan

Gifu is a city in central Japan that operates four WWTPs generating a total of 29,000 tons of dewatered sludge per annum (Nakagawa and Ohta 2019). Two WWTPs have a mono-incinerator that is fed solely with dewatered sludge. The other plants transport their sludge by road to plants with incinerators. Initially, Gifu City government used the sludge for manufacturing construction bricks for surfacing sidewalks and parks in the city. The demand for bricks gradually declined over the years because of spending cuts for public works. This led to an interest in recovering phosphorus from sewage sludge ash.

METAWATER Company was engaged in a collaborative project for developing the technology supported by the Ministry of Land, Infrastructure, Transport and Tourism. After a project evaluation in 2006, Gifu City acquired a license according to the Japan Sewerage Law in 2007 for the by-product. A full-scale plant was constructed in 2009 at a cost of approximately USD 9.75 million. The plant started operating in 2010 and presently generates 200–300 tons per annum recovering 30–40% of the phosphorus present in the ash.

When the plant started operating, there was no channel for the distribution and sale of Gifu-no-daichi®. Gifu City used advertising campaigns, including free sample offers, a briefing session for farmers, advertisements in a local magazine, and leaflet distribution. Following this, the National Federation of Agricultural Cooperative Associations (JA) launched sales and marketing campaigns for Gifu-no-daichi®. Presently, the product is sold in 20 kg packets through JA branches and has achieved recognition among farmers. Gifu City started selling in bulk in 2011 which has improved the cost recovery of operations. However, the cost recovered is still lower than the operational cost of landfill disposal due to the high cost of chemicals.

METAWATER Co. implemented the same business model in the city of Tottori at Akisato WWTP in 2013 and recovers 150 tons of hydroxyapatite per annum from about 500 tons of sewage sludge ash per annum. The biggest barrier to scaling is the small size of incineration plants which impedes economies of scale. Clustering and cooperation of various ash producers may help lower the operational costs for ash treatment (GWRC 2019).

ICL Amfert, Netherlands

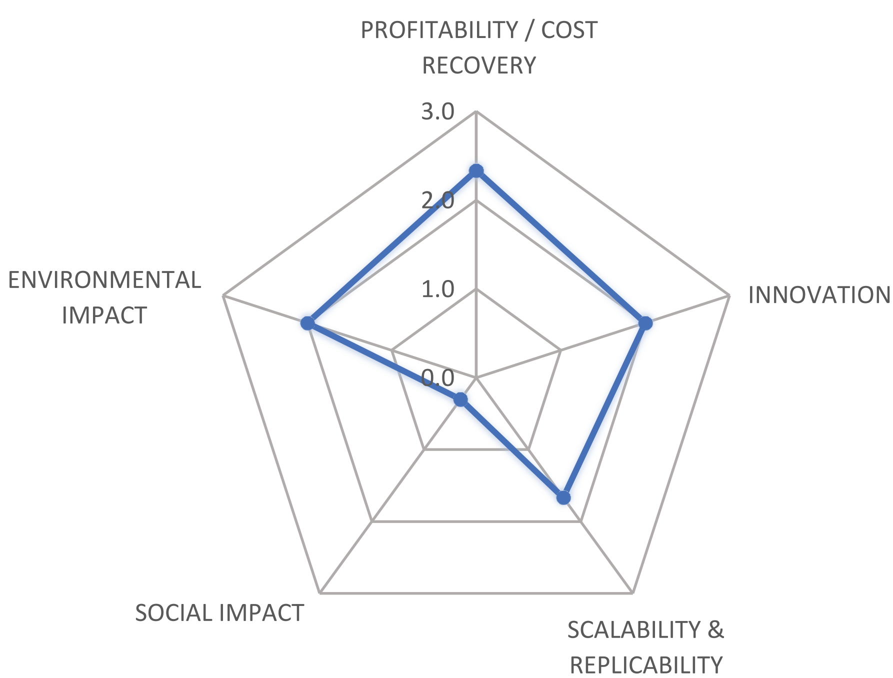
In 2019, ICL Netherlands Amfert (Phosphate BU) initiated its first phosphate recycling project unit aimed at using recycled phosphates from waste streams as a raw material.[32] This project was encouraged by a subsidy of USD 560,000 from the Dutch Province of Noord-Holland. Incinerated sludge ash from WWTPs as well as meat and bone meal ash are the main inputs. ICL Amfert is replacing about 10% of phosphate rock with secondary phosphates in fertilizer products at the pilot recycling unit.

The goal is for ICL Amfert to substitute up to 100% of phosphate rock with recycled sources, depending on market demand and the availability of raw materials. Recovered materials are mixed with phosphate rock or phosphoric acid-based fertilizer, either during acid attack of the rock or later when the product still has some residual acidity. Any contaminants in the ash are diluted in the final product. This is legal under EU regulations on the condition that the ash is not classified as hazardous. The final product is covered by EU Fertilizing Products Regulation STRUBIAS annexes. ICL also has an operation in Germany where ash is processed and has also tested the use of ash in fertilizer production in Fertiberia Spain.

[32] ICL 2021 Corporate Responsibility Report. https://icl-group-sustainability.com/reports/producing-fertilizers-with-recycled-phosphate/ (accessed on September 17, 2022)

BUSINESS MODEL 6: RECOVERY OF PHOSPHORUS FROM ANAEROBIC SLUDGE DIGESTATE

Brief	**Recovering struvite from sludge digestate and dewatered sludge liquor**
Location	Urban or peri-urban area based on the location of the WWTP
Waste input type and stream	Sludge digestate after anaerobic digestion and sludge after dewatering
Value offer	Recovery of phosphorus for use as a green fertilizer; savings in disposal costs; prevention of scaling in digesters and pipes which leads to savings on chemicals and digester maintenance
Environmental risk mitigation	Extracted struvite is without particular environmental risks
Organization type and profit objective	Private entities operating within the WWTP with a profit motive
Major stakeholders	WWTP operators, municipalities, fertilizer dealers and other networks of wholesalers and retailers



Business performance of phosphorus recovery from digestate.

- The business model scores high on innovation with the use of advanced technology.
- The business is profitable with good prospects for cost recovery by the public partner and the possibility for revenue generation from the sale of fertilizer products and treatment fees.
- High positive impacts on the environment due to the reduced risk of eutrophication in waterbodies.
- The business model is scalable and can be adapted to many wastewater treatment processes.

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Upgrading a WWTP is easier since the phosphorus recovery unit is modular and can be scaled to meet demand. • The technology providers share the risk of revenue generation.	**Weaknesses** • High investment costs. • Obtaining licenses and certifications for products can be a complex process and delay the revenue flows from the sale of high-value fertilizer products.
External origin	**Opportunities** • More technology providers as more research and development takes place.	**Threats** • Acceptance among traders and farmers can be low as the product is relatively new and its dissolution different from other phosphorus sources.

Business Model Description

Anaerobic digestion is one of the most common methods used for treating sewage sludge. Using anaerobic digestion, WWTPs can reduce the weight and volume of sewage sludge and recover energy from sludge biomass. After anaerobic digestion, the digestate undergoes solid-liquid separation and dewatering. The high-phosphate liquor (filtrate or concentrate) from sludge dewatering is typically returned to the sewage treatment process. This unnecessarily increases the phosphorus load as well as ammonia, making nutrient removal more difficult. Targeted phosphorus recovery as struvite before it crystallizes where it should not within the system, is an ideal way to simultaneously reduce the internal phosphorus and ammonia maintenance burden and recover them as resources. Struvite can be recovered either from the liquor (filtrate or concentrate) or directly from the digested sludge.

There are two financing models for large investments in struvite recovery: (i) the capital purchase business model, and (ii) the treatment fee model (Drechsel et al. 2018). In the capital purchase model, the WWTP owner (or the client) pays for installation and recovers the cost through savings derived from lower operational and maintenance costs over three to seven years (maximum ten years). Net operational savings are accrued from reduced struvite deposition in the digester which then require less maintenance, improves dewaterability, nitrogen removal, struvite biosolids avoidance, and reduces chemical and polymer consumption (Canvas 6).

In the treatment fee model, the technology provider pays for installation and retains ownership, while the municipality or treatment plant operator pays for operation and maintenance based on the agreed quality of effluent or performance of phosphate removal. In both cases, the technology provider has an off-take guarantee (for the recovered phosphorus) in the contract for several years, which reduces the burden of the WWTP to engage in phosphorus handling, marketing or disposal. The off-take guarantee from the technology provider reduces the involvement of the treatment plant operator in marketing the product and they derive a part of the revenue from sales. In the absence of any guarantee, the treatment plant operator must invest in marketing and create networks and channels for sales. If this capacity is lacking, the operator will likely see a loss. A schematic representation of the business model for recovering phosphorus from sludge is provided in Figure 12.

The business model is appropriate for WWTPs with anaerobic digesters and where the operator is willing to upgrade the phosphorus recovery process. There is also a possibility to integrate two resource, reuse and recovery pathways, i.e., energy and fertilizers. For 190 million liters per day or 50 million gallons per day, a capital investment of around USD 2 to USD 5 million is required (Drechsel et al. 2018). The operational and maintenance costs vary between USD 9 to USD 120 per kg of phosphorus recovered (Bashar et al. 2018).

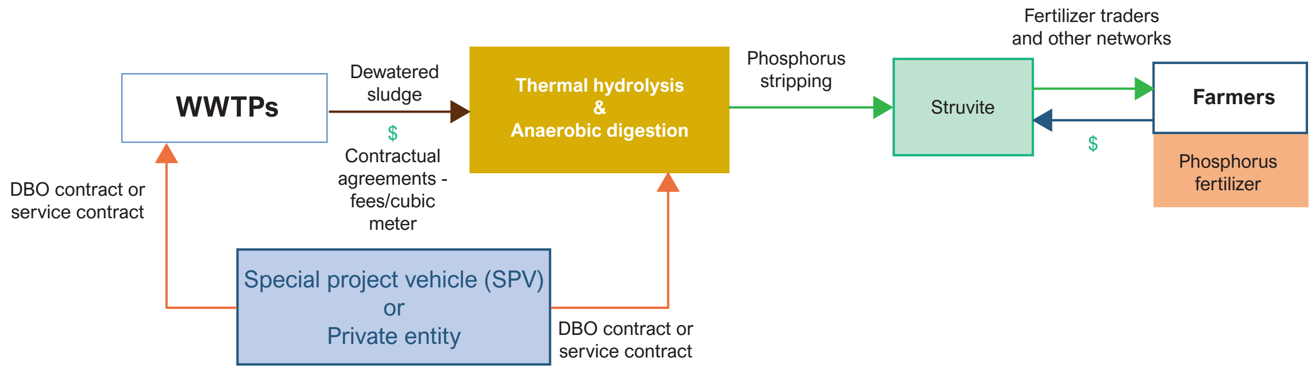


FIGURE 12. BUSINESS MODEL FOR PHOSPHORUS RECOVERY FROM SLUDGE DIGESTATE.

Source: Author's creation.

Partners	Activities	Value propositions	Customer relationships	Customer segments
• Technology provider • WWTP operators and municipalities • Fertilizer traders	• Capturing phosphorus from the treatment process • Marketing and sales of recovered struvite • Obtaining permits and certifications for fertilizer products **Resources** • Technology for phosphorus removal • Existing WWTP with anaerobic digestion • Enabling environment for the sale of struvite (with proper certification)	• Recovering a potentially high-value fertilizer through a modular phosphorus removal systems • Savings in operations and maintenance costs for removing unwanted struvite crystals.	• Direct contact with municipalities and WWTP operators • Direct network with fertilizer traders, associations, wholesalers and retailers **Channels** • Direct technology sales to the client (municipalities, WWTP operators) • Direct sales of phosphorus fertilizer to traders	• WWTP operators and municipalities • Fertilizer markets (traders and networks)

Cost structure	Revenue streams
• Capital costs: modular phosphorus recovery unit • Salary, rent, interest • Struvite collection, storage and marketing costs; transaction costs related to penetrating fertilizer value chains with small phosphorus volumes • Research and development, validation, licensing and certification	• Sales of high-value fertilizer • Savings from lower operational and maintenance costs (less struvite in pipes)
Environmental and social costs	**Environmental and social benefits**
• Uncertain acceptance of the product by traders and farmers. • Need to acquire new technology.	• Environmental benefits from preventing eutrophication. • Supporting circular economy jobs and added-value by phosphorous and nitrogen recovery. • Extended lifetime of a finite resource. • Potentially a cheaper phosphorus resource than rock phosphate.

CANVAS 6: RECOVERY OF PHOSPHORUS FROM ANAEROBIC SLUDGE DIGESTATE

Case Studies

Higashinada WWTP, Japan

The Higashinada WWTP in Kobe City has a sewage treatment capacity of 241,500 m^3 per day. In 2012, Mitsubishi Shoji Corporation Agri-Service and Swing Engineering Corporation (the Japanese technology provider of Rephosmaster®) initiated a two-year demonstration project to test nutrient removal and resource recycling at the plant. In 2014, on completion of the pilot project, a full-scale plant was ready for operation along with registration of the fertilizer. The plant is owned and operated by Kobe City and has the capacity for treating 239 m^3/day of digested sludge. This is equivalent to a quarter of the digested sludge generated at the treatment plant and recovers 360 kg/day (150 tons/year) of struvite. On average, it can recover approximately 40% and 90% of total phosphorus and soluble phosphorus, respectively, from digested sludge. The struvite recovery reduces the volume of dewatered sludge by 3.3% on average and prevents struvite-scaling problems in the sludge treatment process. The recovered struvite has been registered as a chemical fertilizer approved by the Ministry of Agriculture, Forestry and Fisheries of Japan in 2014 and distributed in the Kobe area through fertilizer companies. In 2019, Japan Agricultural Cooperatives Hyogo Rokko started selling it under the brand name Kobe Harvest 10–6–6–2).[33]

OSTARA Nutrient Recovery Technologies Inc.

Ostara Nutrient Recovery Technologies Inc. started its operation in 2005 with headquarters in Canada and has 23 commercial installations across Canada, the USA and Europe. Ostara provides the technology and a fertilizer combined with a marketing strategy. The company has 14 recovery units globally which are using Pearl® and WASSTRIP® and recover struvite sold as a premium fertilizer (tradename Crystal Green®). Their most important strategy is off-take guarantees which reduce the struvite related maintenance risk for water service agencies and WWTPs. Since treatment plant operators are often not familiar with fertilizer marketing and the related bureaucratic burdens, this business model reduces their risk of recovering the costs through the sale of the product. The off-take guarantee provides an income for the WWTP operator since long-term contracts ensure that the struvite produced onsite will be marketed by Ostara and this can pay back the plant operators. Considering a WWTP handling 50 million gallons of wastewater per day, the estimated investment is about USD 5 million (standard installation of two Pearl®2K systems), which would result in a net present value of approximately USD 15 million in 20 years with the total capital investment recovered in five years.[34]

CNP Cycles GmbH, Germany

CNP Cycle GmbH supply process technologies and plants for water and sludge treatment as well as recovery of carbon, nitrogen and phosphorus. CNP developed AirPrex®, a process that improves biological phosphate elimination. The digested sludge is fed into the reactor where it is subjected to CO_2 stripping through aeration. This significantly increases the pH level of the sludge. At the same time, magnesium salts are added, which leads to the precipitation of magnesium, ammonium, and phosphate in the form of struvite. The recovered nutrients can be used as a fertilizer. The patent for the AirPrex® technology was held by Berliner Wasserbetriebe (BWB) and CNP-Technology Water and Biosolids GmbH in Hamburg, Germany obtained the license in 2013. Presently, eight full-scale plants are in operation. In these plants, 80–90% of the phosphate is removed from the liquid phase of the digested sludge. Table 10 summarizes the current operational plants.

At the Amsterdam plant, EUR 3 million was invested using the AirPrex® system. It is estimated that this investment produced benefits of EUR 500,000 (EUR 1.2 million as total benefits while reducing EUR 700,000 from disposal and operational costs) per year resulting in a return on investments of six years (Veltman 2017).

TABLE 10. OPERATIONAL PLANTS OF CNP CYCLES GMBH.

COUNTRY	LOCATION AND OPERATOR	OPERATION SINCE	PERSON EQUIVALENT	CAPACITY OF AIRPREX® (M^3/DAY)	DESIGN STRUVITE PRODUCTION KG/DAY
Germany	MG-Neuwerk, Niersverband[a]	2009	995,000	1,500	1,500
Germany Berliner	Wassmannsdorf, Wasserbetriebe[b]	2011	1,000,000	2,400	3,000
Netherlands	Echten, Drents Overijsselse Delta[c]	2013	190,000	400	500
Netherlands	Amsterdam-West, Waternet[d]	2013	1,000,000	2,500	4,000–5,000

[a] CNP Cycles. https://cnp-cycles.de/en/installations/plants-built-airprexr-license-us/monchengladbach-neuwerk (accessed on September 17, 2022)
[b] CNP Cycles. https://cnp-cycles.de/en/installations/airprexr-installations/berlin-wassmannsdorf (accessed on September 17, 2022)
[c] CNP Cycles. https://cnp-cycles.de/en/installations/plants-built-airprexr-license-us/reest-wieden-nl (accessed on September 17, 2022)
[d] CNP Cycles. https://cnp-cycles.de/en/installations/plants-built-airprexr-license-us/amsterdam-west-nl (accessed on September 17, 2022)

Source: Author's creation.

[33] KOBE Harvest project. https://www.sec.swing-w.com/eng/products/f5e45g00000006pa.html (accessed on September 17, 2022)
[34] Ostara. http://ostara.com/wp-content/uploads/2017/03/Ostara_NRS_BROCHURE_170328.pdf (accessed on September 17, 2022)

Nutrients Recovery Systems (NuReSys), Belgium

NuRESys is a Belgian company founded in 2011 and supplies controlled struvite crystallization technology. The flexibility of the NuReSys process allows it to be adapted in several combinations to resolve critical phosphate issues. Since NuReSys technology can be applied to both digested sludge or post-dewatering, several case-specific approaches are possible, including combined applications. Some combined applications have been designed and are operational at municipal and industrial scales.[35] The price of the BioStru® is between EUR 80–120 per ton.[36]

There are several other examples such as Phosphogreen® at the Marselisborg WWTP in Denmark. This is the largest plant in Nordic Europe, with an operational capacity of 200 tons of struvite per year.[37] Similarly, Veolia (Struvia®) also offers compact installations and has demonstrated struvite recovery in the WWTP of Samoëns, France. The Struvia® solution is appropriate for WWTPs equipped with biological dephosphorylation and plant operators who want to install sludge digestion and for plants equipped with anaerobic digestion and plant operators who want to install biological phosphorus treatment.[38]

4. RECOVERING ENERGY

Introduction

The importance of energy recovery from waste streams is evident from the fact that waste minimization and alternative energy generation can improve resource optimization. The advantages to municipalities and companies include energy cost savings, reduced environmental impact and compliance with stricter regulations. Recovering renewable energy also reduces greenhouse gas emissions and offers the option of earning renewable energy credits. Sludge streams have high calorific values and are rich in energy sources that can be recovered. There are different pathways for generating energy from sewage sludge as briefly described below.

- **Anaerobic digestion:** This is a biological conversion method widely used due to its low cost and ability to use organic waste with high moisture content without reducing the high calorific value of the gas produced (a combination of methane and carbon dioxide).
- **Thermochemical conversion routes:** This includes combustion or mono-incineration, pyrolysis and gasification. These processes require lower moisture levels in the sludge because the energy efficiency of the process is reduced due to the energy consumed for drying the sludge.[39] Incineration is one of the most prominent technologies although not originally meant for energy recovery but to reduce the volume of waste and destroy harmful contaminants. The process of heat recovery converts the traditional incinerator into a combustor where heat is harnessed from flue gas and is used as a heating fluid which can be used directly for heating or for generating electricity via a steam turbine. In pyrolysis, combustion occurs in an inert atmosphere to produce pyrolytic oil, biochar and non-condensable gases. Biochar, non-condensable gases, and bio-oil can be used as solid, gaseous and liquid fuel, respectively, for electricity and heat generation via combustion. Bio-oil can also be reformed as a synthesis gas for energy recovery while biochar can be used as a soil conditioner. Lastly, gasification involves the conversion of organic compounds via partial oxidation at high temperatures for the production of synthesis gas which can be used for heat and electricity generation.
- **Co-incineration and co-processing:** Sewage sludge can be used in co-incineration and co-processing. Co-incineration involves burning municipal sludge in municipal solid waste incinerators. In co-processing, sewage sludge serves as an alternative fuel in cement kilns and coal-fired power plants. This requires additional fuel with a calorific value higher than the sewage sludge. The process replaces 15–20% of conventional fossil fuels.

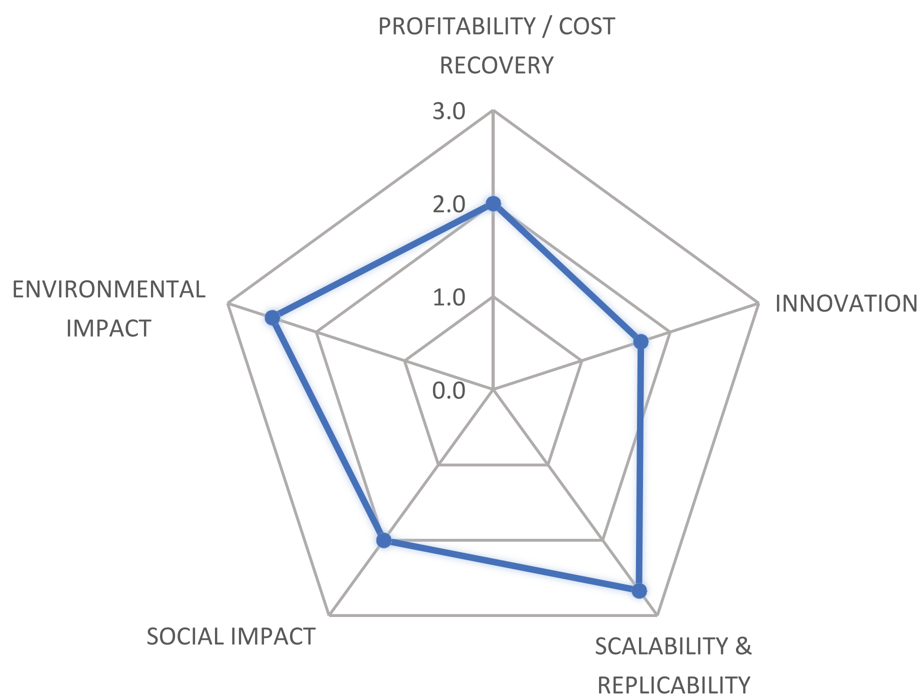
This section will present the following models:

- Biomethane production from anaerobic digestion (business model 7)
- Energy recovery from mono- incineration of sewage sludge (business model 8A)
- Energy recovery from co-incineration (or co-processing) of sewage sludge (business model 8B)
- Energy recovery from gasification and pyrolysis of sewage sludge (business model 9)

[35] NuReSys. http://www.nuresys.be/ (accessed on September 17, 2022)
[36] NUTRIMAN Information Sheet. https://nutriman.net/sites/default/files/2019-12/INFO%20SHEET-PRODUCT-%20Struviet%20Nuresys.pdf (accessed on September 17, 2022)
[37] Phosphogreen brochure. https://www.suez.com/-/media/suez-global/files/dk/brochures/brochure-phosphogreen-marselisborg-case-english.pdf?open=true#:~:text=Marselisborg%20Wastewater%20Treatment%20Plant%20uses,of%20maintaining%20the%20sewage%20works. (accessed on September 17, 2022)
[38] Veolia. https://www.veoliawatertechnologies.com/sites/g/files/dvc2476/files/document/2019/02/3351%2C150354_Mkt_Mun_Brochure_STRUVIA_EN_.pdf (accessed on September 17, 2022)
[39] Solar drying is one of the way to circumvent the use of other forms of energy.

BUSINESS MODEL 7: ENERGY RECOVERY FROM ANAEROBIC DIGESTION

Brief	**Biomethane production from anaerobic digestion**
Location	Peri-urban areas
Waste input type/stream	Sewage sludge with possibilities to include other waste streams and organic waste from households, industry and agriculture
Value offer	Generation of thermal energy and electricity (energy self-sufficiency); savings on disposal costs due to reduction in sludge residue
Environmental risk mitigation	Chemical contaminants of digestates have to be monitored before disposal or reuse
Organization type and profit objective	Public or private based on the size of the operation
Major stakeholders	Municipalities, water utility service providers, energy and electricity transmission agencies, private entities working on landscaping and agricultural soil conditioning



Business performance of energy recovery from anaerobic digestion.

- The business is highly scalable in both developed countries and emerging economies and contributes positively toward environmental and social goals.
- Anaerobic digestion is one of the most applied technologies and the application of thermal hydrolysis increases the efficiency of energy recovery.
- The business allows for the integration of other organic waste streams and small and medium WWTPs can plan for a clustered approach to achieve economies of scale.
- Possibility to recover biosolids (digestate) which adds to the revenue stream.

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Traditional technology with advancements in research and development. • Low operation and maintenance and high revenue.	**Weaknesses** • Demand for considerable capital for investment. • Need for strong institutional arrangements.
External origin	**Opportunities** • Electricity demand is growing. • Integration of waste streams. • Integrating thermal hydrolysis to increase energy recovery. • Option of using digestate as a fertilizer. • Option of participating in carbon markets.	**Threats** • Preference toward upcoming research and development in advanced technologies for energy recovery. • May need high investments to mitigate the risk of gas leaks. • Lack of regional cooperation and support for undertakings and investments toward cluster approaches for small and medium WWTPs.

Business Model Description

The business model involves an operator recovering energy from sewage sludge using anaerobic biodigesters. The operator could be a public or private entity. The operator signs a long-term contract with a municipal or government water agency for a WWTP. The municipality or the public water utility uses the collected sewage tariffs paid by water users (households and commercial hubs) for contracting such services and providing thickened sludge for stabilization and energy recovery.

The input to the digester can be supplemented by including organic waste from industries and households as well as manure and organic waste from agriculture. The management process involves advanced anaerobic digestion followed by traditional anaerobic digestion. Advanced anaerobic digestion generates a larger volume of biogas than traditional anaerobic digestion. During advanced anaerobic digestion, sludge streams are pretreated to break down cells and organic matter in the sludge, making them more easily digestible. This helps reduce the retention time in the digester and makes the biogas generation process more efficient.

Advanced anaerobic digestion pretreatments include: (i) thermal hydrolysis process, (ii) enzymic hydrolysis, (iii) ozonation, and iv) ultrasonic sludge disintegration.

An operator might set up an anaerobic digestion plant within a WWTP or construct and commission a regional plant for energy recovery to benefit from economies of scale. Biogas generated through digestion can be cleaned and upgraded to biomethane as a substitute for natural gas or it can be used in combined heat and power plants to produce heat and energy for boiler systems and dryers or to generate electricity for use at the plant site. The organic material not degraded by the process (digestate) can be composted and sold as organic fertilizer to nearby farmland (Canvas 7).

The contract might be design, build, own and operate with full financing of the project, or design, build, and operate if sufficient public finances are available. The contract is usually for at least 10–15 years and depends on the depreciation period for the infrastructure provided by private service providers.

This business model is appropriate for small and medium WWTPs lacking sludge storage capacity that provides only basic wastewater and sewage sludge treatment and for regional hubs where more than one treatment plant can be served. Sometimes, different waste streams can be combined through such regional hubs where organic wastes from households, agriculture and industries can be co-digested. The private service provider can operate through contractual agreements for using energy for the plant and connecting to a grid for supplying excess heat or electricity. Business expansion within a region is determined by the possibility for economies of scale achieved by integrating treatment plants and transportation costs for the different waste streams. A schematic representation of the business model recovering energy from sewage sludge is shown in Figure 13.

Capital investments for anaerobic digestion for harnessing gas amounts to USD 365/m^3 while recovering electricity requires combined heat and power technology in addition to the digester and therefore requires more investment (e.g., USD 525/m^3) (Mohammed at al. 2017). The associated cost of combined heat and power technology is estimated at USD 4,124/kW (EUR 3,050/kW) (World Bank 2015). The operating cost for extracting gas is USD 3.67/m^3, while the cost for electricity generation is USD 5.30/m^3. The operation and maintenance of a combined heat and power system is reported to be short-term expenses of USD 0.02/kWh (EUR.015/kWh) (World Bank 2015).

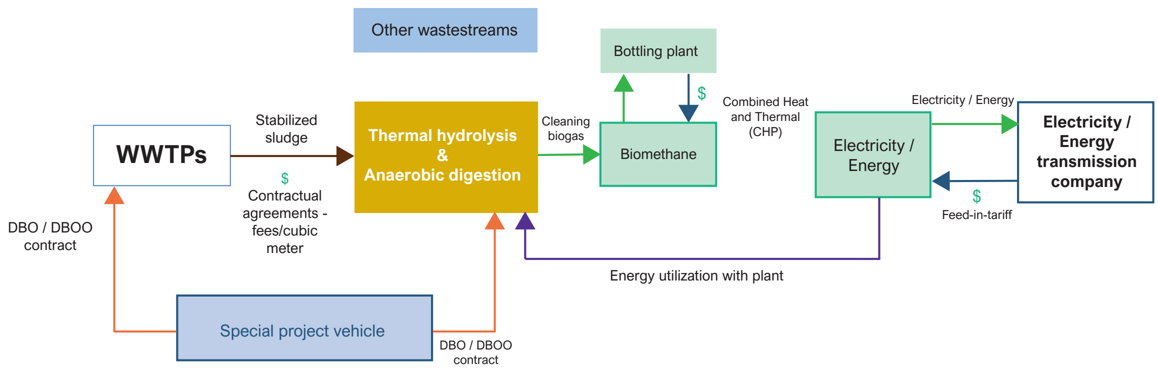


FIGURE 13. BUSINESS MODEL FOR RECOVERING ENERGY THROUGH ANAEROBIC DIGESTION.

Source: Author's creation.

Partners

- Urban local bodies, public water utilities
- Energy and electricity transmission companies
- Private entities engaged in using digestate for landscaping, agriculture and upgrading to fertilizer
- Private and public waste collectors if the other waste streams are integrated
- Local contractors for +-plant construction if required

Activities

- Biological sludge stabilization
- Use of combined heat and power technology for thermal energy and electricity
- Feeding electricity to grid
- Digestate for soil conditioner or fertilizer

Resources

- Establishing and commissioning the plant

Value propositions

- Energy recovered through the recovery process
- Digestate can be used for non-agricultural purposes or can be upgraded to fertilizers for agricultural uses
- Savings from costs incurred for disposing of sludge cake

Customer relationships

- Direct interaction with municipalities, WWTP operators and public water utilities
- Direct interaction with electricity transmission companies

Channels

- Through the operation of a digestion plant
- Heat and electricity fed to grid

Customer segments

- Water utility services or municipalities
- Electricity companies

Cost structure

- Capital costs: mechanical equipment, digester and combined heat and power technology
- Salary, rent, interest, insurance
- Operation and maintenance of WWTPs, composting yards
- Fuel costs and utility charges

Revenue streams

- Revenue from electricity sales
- Revenue generated from fees provided by WWTP operator/waste management company
- An added source of revenue can be the sale of the digestate as organic fertilizer

Environmental and social costs

- Labor health risks might arise due to handling sewage sludge and other waste streams.
- Job creation.
- Low human exposure due to less disposal and contamination.

Environmental and social benefits

- Safe application of sludge, recovering nutrients and reducing pollution.

CANVAS 7: ENERGY RECOVERY FROM ANAEROBIC DIGESTION

Case Studies

Xiangyang City, China

In 2012, Xiangyang City in Hubei Province, China installed a thermal hydrolysis and anaerobic digestion plant in response to the increasing volume of waste caused by rapid urbanization. Anaerobic digestion is used to convert sludge waste into biogas and digested sludge for profit and for reducing greenhouse gas emissions. The facility used a build, operate, and own contracting arrangement between local government agencies (Xiangyang Urban Construction Committee and Xiangyang Urban Management Bureau) to treat sludge and the private sector (Toven Co. Ltd.). Two agreements for sewage sludge and food waste were signed between government agencies and the private entity with a concession period of 23 years, including a construction period of two years). The operator receives a subsidy from the local government and revenues through the sale of compressed natural gas (CNG) to the municipal taxi fleet and the sale of biochar and saplings (Fu et al. 2017).

The facility has a capacity of 300 tons/day (annual capacity of 110,000 tons/day), which includes: (i) sludge (180–220 tons/day), and (ii) kitchen waste (80–120 tons/day). Kitchen waste is crushed at restaurants and transported to the plant. The project operator is responsible for installing the kitchen waste crusher and transporting the waste. The two main products derived from the plant are biogas and digested sludge. Half the biogas produced is used for electricity generation used within the plant, while the other half is purified, compressed, and used to replace 6,000 m^3 or 1,668 gasoline gallon equivalent (GGE) per day of gasoline to fuel 300 municipal taxis. The Xiangyang project also built a CNG fueling station with a storage volume of 6,000 m^3. The digested sludge is further dried to produce 55–60 tons of sludge cake (40% moisture content) each day which serves as a soil amendment.

The project made a total investment of USD 20.7 million comprised of USD 13.8 million for sludge treatment equipment and USD 6.9 million for pre-treatment equipment for kitchen waste, a CNG station and kitchen waste collection trucks. The project used three sources for funding: (i) 30% corporate equity, (ii) 60% from low-interest loans provided by the Export-Import Bank of China and KfW Bankengruppe, and (iii) 10% provided in the form of subsidies from the local government.

Fixed costs for sludge treatment were estimated at USD 16 per ton (80% moisture content). The operating costs are USD 16 per ton (80% moisture). The operation is comprised of these components:(i) labor (27%), (ii) electricity (23%), (iii) chemical agents (23%), iv) equipment (9%), and v) other costs (18%). Costs for the kitchen waste operation include labor, electricity and chemical agents and are estimated to be USD 11 per ton. The main revenue channels include CNG production (6,000 m^3) and sales of digested sludge cake.

The CNG is sold at USD 0.74/m^3 which generates USD 1.41 million annually, while the price of sludge cake with 60% moisture varies between USD 2.9–4.4 per ton and dried sludge cake with 10% moisture at USD 20–22 per ton. Revenue from the sale of dried sludge cake is estimated to be USD 0.12–0.13 million per year. The facility planned for a third source of revenue from the sale of tree saplings grown with the help of dried sludge cake. Estimates showed that using 60 tons of sludge cake each year, 216,000 trees could be planted and sold for USD 29 per tree. This would earn revenue of USD 6.3 million per year. The plant broke even thanks to subsidies of USD 37 per ton and since 2015 increased sales of dried sludge cake have made the operation profitable.

Toyohashi City Japan

Toyohashi City Biomass Utilization Center in Toyohashi City, Aichi Prefecture was completed in 2017. The integrated renewable energy facility for combined anaerobic digestion was planned for the treatment of sewage sludge, septic tank sludge, and food waste. The plant was commissioned by Toyohashi City as a private-public partnership under a build, transfer, and operate contract. The private entity raises funds for construction and on completion, ownership is transferred to Toyohashi City and the private entity operates the plant.

The project to build and operate the facilities comprises:

- Selling electricity generated by the biogas power plant
- Selling fermented sludge to other companies as carbonized fuel
- A large-scale solar power plant using idle land as a subsidiary business

The operating body of Toyohashi City Biomass Utilization Center is Toyohashi Bio Will KK, a special purpose company financed by JFE Engineering Corp, Kajima Corp, Kajima Environment Engineering Corp and Otec. Toyohashi Bio Will KK was contracted to operate and maintain the center for 20 years. Power generated by the facility will be sold using a feed-in tariff scheme.[40]

Aguas Andinas, Chile

Aguas Andinas is Chile's largest water utility company and manages water and sanitation for the Santiago Metropolitan Region. The business case of the La Farfuna wastewater treatment plant and RRR pathway is based on a venture between Aguas Andinas and SUEZ for reclaiming

[40] Bioenergy International. https://bioenergyinternational.com/japans-largest-integrated-food-wastewater-treatment-renewable-power-project-opened/ (accessed on September 21, 2022)

wastewater and Aguas Andinas and Metrogas for biogas generation.

In 2005, Aguas Audinas contracted SUEZ to construct a wastewater treatment plant of 760 million liters per day.[41] The main aim was to treat over 50% of the wastewater generated by the city before discharging it into the Mapocho River. The plant was implemented through a build, operate, and transfer arrangement between Aguas Andinas and SUEZ. SUEZ was entirely responsible for the design, supply, engineering, construction, testing, and commissioning of the treatment plant. The plant is still operated under renewable five-year operation and maintenance contracts.

The treatment plant was further modified for capturing biogas for residential use. Aguas Andinas and Metrogas signed a memorandum of understanding and Aguas Andinas will export the residual biogas generated at the treatment plant to the Metrogas town gas factory. The factory will use the biogas as feedstock to produce town gas and then distribute it to around 30,000 customers in the city of Santiago. This is an important aspect of the business model since the production of upgraded biogas is not considered part of the duties of Aguas Andinas under the water regulations.

La Farfana produces about 800 tons of sludge a day. After the dewatering and drying process, the plant yields about 120 tons a day of dry biosolids. Aguas Andinas has explored alternative uses for its biosolids. About 40% of the biosolids are used in agriculture at no cost to farmers. The total cost of the project was about USD 6 million. The capital investment was divided equally between Grupo Agua Andinas and Metrogas. While Aguas Andinas contributed to expanding the biogas catchment and improving treatment, they later invested in a 13.5-kilometer gas pipeline and the final treatment of biogas. In 2017, Aguas Andinas earned a profit of USD 1 million with revenue from the sale of biogas of USD 3 million and USD 2 million spent on operations and maintenance. Metrogas spent USD 3 million to purchase biogas from Aguas Andinas but saved an estimated USD 1.6 million, which is the price it would have paid for imported biogas. The estimated amount of emission reductions claimed in its first crediting period (2011–2018) was 138,516 tons of CO_2 equivalent (19,788 tons a year), another source of potential extra revenue.

Veolia, China, Germany and US

Among its offerings, Veolia has developed a process for transforming sewage sludge recovery solutions into biogas. This complies with environmental regulations and reduces residual sludge volumes and creates a revenue stream by using the energy on-site or by selling it to the local grid. Veolia offers several technical solutions to treat sewage sludge and recover energy, including Exelys™ and Bio Thelys™. By coupling thermal hydrolysis with anaerobic digestion, Bio Thelys™ and Exelys® offer enhanced performance over conventional digestion and optimize sludge treatment by producing: (i) 25 to 35% less dry solids, (ii) 30 to 50% more biogas, and (iii) a safe and high-quality digestate for land application. This has benefits for the treatment plant operators as there are additional income sources from energy and additional capabilities to process organic waste. Below are some examples where Veolia technologies have been implemented.

The City of Urumqi in China decided to improve its wastewater treatment by modernizing its treatment plant. Under the first private-public partnership signed by the city, Veolia started operating six digesters capable of processing more than 80,000 m^3 of sludge and producing 930,000 m^3 of biogas per month. This biogas is then used to heat the plant and re-injects 800,000 kWh of green electricity per month into the local electricity network.[42]

In Braunschweig, Germany, a wastewater treatment plant is now 100% self-sufficient due to the intervention of BSI Energy, a subsidiary of Veolia which operates the site. It has a population equivalent capacity of 275,000 people. Biological wastewater treatment, thermophilic sludge digestion and co-digestion with organic waste, cogeneration and recovery of biogas have resulted in the plant being energy self-sufficient.[43]

Veolia's solutions have been applied in a wastewater treatment plant in Gresham, the fourth largest city in the state of Oregon in the United States. The plant has undergone a profound transformation. Once the most energy-intensive plant in the city, it is now 94% self-sufficient due to the recovery of biogas from sewage sludge. The plant's electricity costs have dropped by an average of USD 23,100 per month.[44]

[41] World Bank. https://documents1.worldbank.org/curated/en/284951573498126244/pdf/Wastewater-From-Waste-to-Resource-The-Case-of-Santiago-Chile.pdf (accessed on September 17, 2022)

[42] Veolia. https://www.veolia.cn/en/urumqi-wastewater-treatment-project (accessed on September 15, 2022)

[43] Veolia. https://www.veolia.com/en/solution/sewage-sludge-green-energy-biogas-wastewater (accessed on September 20, 2022)

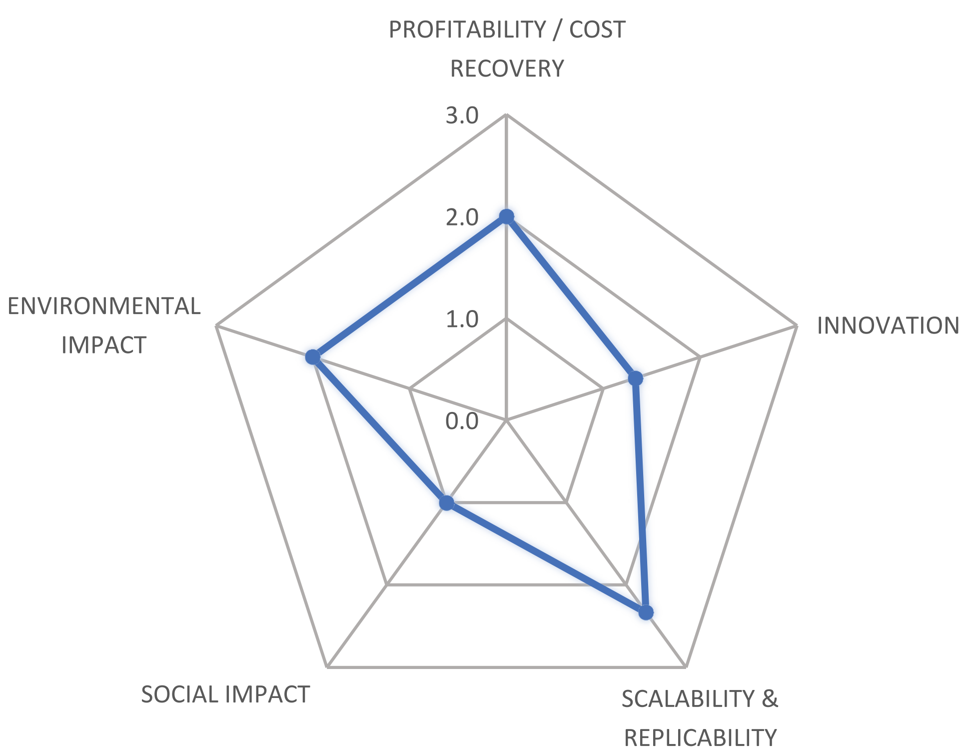
[44] Veolia. https://icma.org/sites/default/files/305996_Veolia%20North%20America%20-%20The%20City%20of%20Gresham%20Oregon.pdf (accessed on September 20, 2022)

BUSINESS MODEL 8: ENERGY RECOVERY FROM INCINERATION

Under model 8 we distinguish between mono-incineration (Model A) and co-incineration (Model B).

Model A: Mono-incineration of sewage sludge

Brief	**Energy recovery from incineration of sewage sludge**
Location	Urban and peri-urban areas
Waste input type/stream	Dewatered and dried sewage sludge
Value offer	Self-sufficiency in energy and the potential for phosphate recovery
Environmental risk mitigation	Pollutant control mechanisms are needed to limit air pollution
Organization type and profit objective	Private entities with a profit motive
Major stakeholders	Urban local bodies, public water utilities, energy and electricity transmission companies, private entities engaged in phosphate recovery, landfill operators for disposing of remaining sludge ash



Business performance for energy recovery from mono-incineration.

- The business uses incineration, which is backed by regulations making the business model more scalable.
- The business model is becoming increasingly relevant in European countries switching over to phosphorus recovery as per regulatory restrictions.
- The incineration produces sludge ash reducing the volume of disposal which helps reduce transaction costs.
- There are multiple sources of revenue that increase the financial feasibility of the business model.

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Traditional technology with know-how and easy integration of pollutant capture technologies. • Energy sufficiency of the operation. • Multiple revenue streams.	**Weaknesses** • Demand for considerable capital for investment • High operational costs. • Requirements for proper handling of sewage sludge ash and flue gas.
External origin	**Opportunities** • Option of recovering and using phosphate from sludge ash. • Opportunities for using sludge ash in cement plants. • Favorable legislation for the incineration of sewage sludge in developed countries.	**Threats** • Lack of support for undertakings and investments. • Environmental laws for the disposal of sludge ash and public acceptability challenges, especially near residential areas.

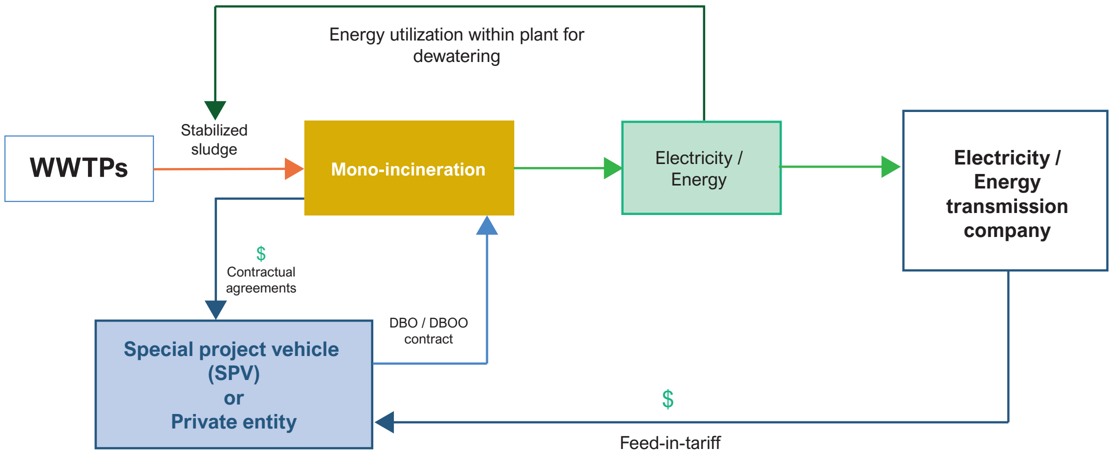


FIGURE 14. BUSINESS MODEL FOR RECOVERING ENERGY FROM MONO-INCINERATION.

Source: Author's creation.

Partners
- Urban local bodies, public water utilities
- Energy and electricity transmission companies
- Private entities engaged in phosphate recovery (potential)
- Landfill operators for disposal of remaining sludge ash

Activities
- Transportation of dewatered sludge
- Recovery of energy efficient thermal energy and electricity from incineration
- Use of electricity within the plant for drying sludge or feeding to the grid
- Sludge ash for phosphate recovery (potential)

Resources
- Establishment and commission of the plant
- Phosphate recovery mechanism (if phosphate is recovered)

Value propositions
- Energy is recovered making the operation
- Savings from disposal costs
- Potential for phosphate recovery from sludge ash

Customer relationships
- Direct relations between sludge producers and incinerator operators

Channels
- Contractual agreements for the operation of incineration plants

Customer segments
- Water utility services or the municipalities
- Farmers (potential)

Cost structure
- Capital costs: mechanical equipment
- Salary, rent, interest
- Operation and maintenance of incineration plants, phosphate recovery technology (if commissioned)
- Fuel costs and utility charges

Revenue streams
- Revenue from electricity sales
- Recovery of phosphate is a potential source of revenue

Environmental and social costs
- Labor health risks might arise due to handling of sewage sludge and other waste streams.
- Flue gas containing furans, dioxins, and heavy metals.

Environmental and social benefits
- Reduction of sludge volume for disposal which is odorless and pathogen free.
- Job creation.
- Potential for phosphate recovery reducing dependence on natural phosphate.

CANVAS 8: ENERGY RECOVERY FROM INCINERATION

Business Model Description

The energy generated by incinerating sewage sludge is used within the plant for dewatering sewage sludge, making this model appropriate for energy efficiency and cost savings in terms of energy recovered and reused. Incineration is an expensive treatment for sludge streams due to high energy requirements. Using incineration as a sludge management process mostly applies to large cities with treatment plants that generate a large volume of sludge. The business is initiated by a private operator contracted by municipal water utility services to reduce the volume of sludge for disposal. There are possibilities for joint ventures with private entities for setting up and commissioning the plant as the investment costs are high.

A regional incineration facility is also an option for smaller and mid-sized plants. These plants share the cost of incineration and transport their sludge streams to a central site for combined processing. In the case of large WWTPs, municipalities or a water utility service provides a long-term contract for the private entity to construct and commission an incineration plant using the sewage sludge and pays private companies through user fees collected from household and commercial establishments. The private entity can also use a public-private partnership model to set up and operate an incineration plant. In such cases, the public authority provides land for the incineration plant and helps with sludge ash disposal contracts with local landfill operators. The municipality or water utility service usually opts for a design, build, own and operate contract with the private entity.

This business model is appropriate for cities with land constraints and large sludge volume generation. Despite the high costs associated with sludge incineration, this approach is expected to grow in the coming years due to stricter regulations affecting landfilling and land application of sludge. Generally, mono-incineration plants have higher investment costs (between USD 250 and USD 450 per ton of dry matter). The operation and maintenance costs for an incineration plant with energy recovery are around USD 200 per ton of dry matter per annum. The model can be boosted in terms of cost savings and opening a revenue source by recovering phosphorus from sludge ash making it available for agriculture as a fertilizer substitute (Canvas 8). Currently, sewage sludge is disposed of in a landfill or used in the production of construction materials and mine filling. All these disposal routes are a cost to the incineration plant as they need to pay for disposal. Figure 14 provides a schematic representation of the business model for recovering energy from incineration of sewage sludge.

Case Studies

Outotec, Switzerland

Outotec sewage sludge incineration plant designs are based on fluidized bed technology which meet air emissions requirements as defined in plant operating permits.[45] The facilities where Outotec had been the service provider were turnkey projects where Outotec was responsible for the design, manufacture, and supply of all equipment, installation and commissioning activities, including all construction work, start-up support, and operator training assistance. The Canton of Zurich, which is the most populous and economically prosperous Canton in Switzerland, has 69 public sewage treatment facilities treating 230 million m^3 of wastewater annually and producing 100,000 tons of dewatered sludge (30% dry solids). Until 2005, agricultural applications of dewatered sludge was a possibility, after which there was a national ban on using dewatered sewage sludge directly in agriculture. This led to the formulation of a disposal plan comprised of 65% to waste-to-energy plants, around 9% dried in cement works, around 25% in two smaller mono-incineration plants with no separate deposition of ash containing phosphorus, and around 1% sludge management in plants outside the Canton. In 2006, some recognized that the existing disposal concept would lead to bottlenecks in capacity starting in 2015. It also became increasingly apparent that phosphorus is a limited resource and the supply of low-pollutant mineral fertilizers is no longer adequately secured. The Canton of Zurich formulated the following clear limiting conditions in 2007 in its decision regarding the Implementation of a Sewage Sludge Disposal Plan (RRB 572/2007). The impetus of the plan was phosphorus recovery and energy use (Morf et al. 2019).

High transport and logistics costs for sludge containing more than 70% water and strict emission restrictions from incineration facilities are common challenges faced by WWTP operators. The technology provided by Outotec is built onsite, is environmentally friendly and is an economically viable solution for treating municipal and industrial sludge without additional fuel consumption. The technology is beneficial in providing self-sustaining thermal energy with minimal emissions and an opportunity of using the residue ash for phosphorus recovery.

Transformation Park, Hong Kong

Transformation Park in Hong Kong is the region's first sludge treatment facility and operates the world's largest incinerator.[46] The facility is designed for incinerating 2,000 tons of sewage sludge per day. It collects sludge from all 11 wastewater treatment works in Hong Kong, 70% via

[45] Outotec. https://www.energy-xprt.com/downloads/outotec-waste-to-energy-plants-brochure-1004000 (accessed on September 17, 2022) Presently Metso Outotec. https://www.mogroup.com/corporate/media/news/2012/11/outotec-to-build-the-largest-and-most-advanced-sewage-sludge-thermal-treatment-plant-in-switzerland/ (accessed on September 17, 2022)

[46] T. Park. https://www.tpark.hk/en/ (accessed on September 20, 2022)

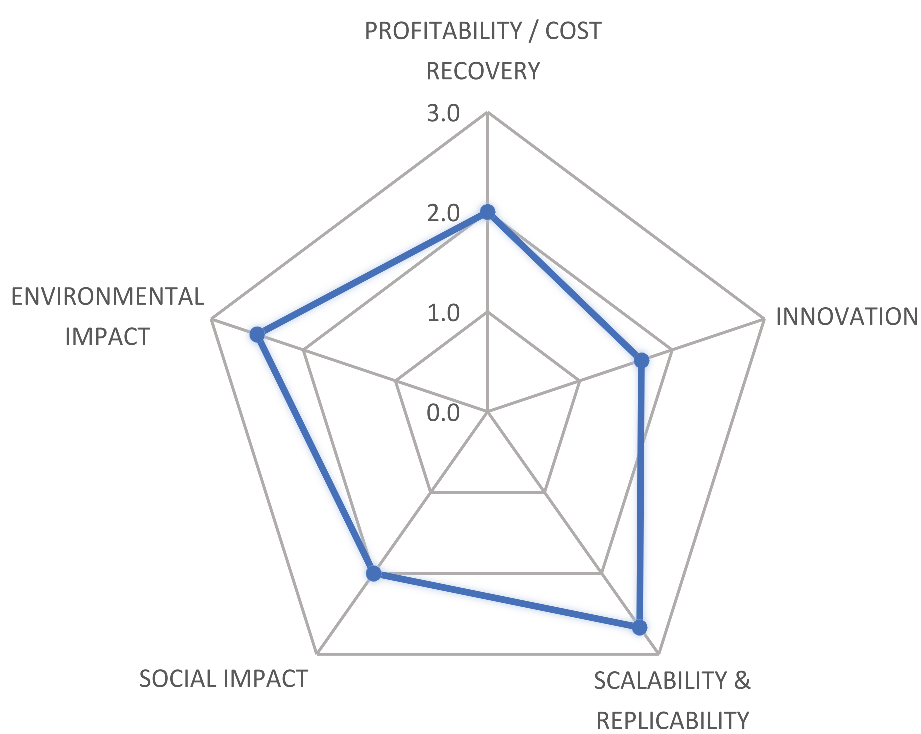
vessel and 30% via truck. Phase 1 (1,600 tons/day) has been in operation since April 2015 and Phase 2 (400 tons/day) started in April 2016. The current management and operation of the facility is contracted to VW-VES(HK) Ltd., a wholly-owned subsidiary of Veolia. The facility is a joint venture between the Environment Protection Department of the Hong Kong Government (Special Administrative Region) in 2010. A long-term contract for design and build and 15 years of operation was offered to Veolia. Presently, the facility handles 1,200 tons of sewage sludge which is estimated to increase to 2,000 tons by 2030.[47] The incinerator uses fluidized bed incineration technology coupled with a series of treatments for flue gas. These treatments are comprised of multi-cyclones, dry reactors and bag filters where large and fine particles are removed and acidic gases, organic pollutants and heavy metals are neutralized or captured. The cleaned flue gas is constantly monitored by a continuous emission monitoring system to ensure full compliance with stringent international emission standards.

The facility is self-sufficient in terms of the thermal energy produced and generates a surplus of 2 MW of electricity when operating at full capacity. This meets the electricity demand of 4,000 households. Incineration also results in a reduction of 90% of the original sludge volume to be disposed of in the landfill. Therefore, it not only reduces disposal costs but also reduces the emission of greenhouse gases by up to 237,000 tons a year. The treatment facility is unique in design and generates revenue from recreational and educational complexes in the park.[48]

[47] T. Park. https://www.tpark.hk/en/story/ (accessed on September 20, 2022)
[48] T. Park. https://www.tpark.hk/en/process/ (accessed on September 20, 2022)

Model B: Co-incineration of sewage sludge

Brief	**Energy recovery from co-incineration or co-processing of sewage sludge**
Location	Peri-urban areas based on the location of waste-to-energy plants, thermal plants and cement kilns
Waste input type/stream	Dewatered and dried sewage sludge
Value offer	Energy recovered from co-incineration, reduction in disposal costs
Environmental risk mitigation	Pollutant control mechanisms needed to limit air pollution
Organization type and profit objective	Public water utilities wanting to dispose of sludge
Major stakeholders	WWTP operators, partnerships with waste-to-energy plants, thermal powerplants and cement kilns



Business performance of co-incineration of sewage sludge.

- The business model supports disposal of sewage sludge generated at WWTPs through the co-incineration of dried sludge in waste-to-energy plants, thermal power plants and cement kilns.
- The business is scalable since cement plants are willing to accept dried sludge as an alternative fuel source and disposal fees are usually lower than landfill fees.

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Elimination of potential environmental risks through burning sludge at temperatures up to 1,450° C • Reduction in the volume of sludge disposed • Fuel cost reduction and additional income through tipping fees for the cement industry and thermal power plants • Support sewage waste management if co-incinerated with municipal solid waste • Energy sufficiency	**Weaknesses** • No recovery of phosphate possible • Additional investments for modifying incinerators to accept different fuel sources
External origin	**Opportunities** • Option of using sludge ash in manufacturing Portland cement or brick production.	**Threats** • Restrictive regulations based on mandatory phosphorus recovery through mono-incineration can be a limitation. • Co-feedstock might contain additional pollutants.

Business Model Description

The co-incineration process involves incinerating dried sludge with other waste and fuel sources and can be in one of the following forms to derive energy from the process.

Co-incineration with municipal solid waste. This involves the combustion of dried sludge with municipal sludge in municipal solid waste incinerators. The process provides more potential for energy recovery than mono-incineration. However, the ash produced is not suitable for phosphate recovery as in mono-incineration. In some cases, where sludge drying facilities are not available within the WWTP, waste-to-energy plants can provide energy for drying.

Co-incineration in coal-fired thermal power plant. Coal-fired thermal power plants in developed countries are interested in reducing their fossil fuel footprints by mixing dried sludge thereby reducing costs to sustain operations.

Co-incineration in cement plant. Common where regulations restrict the use of sewage sludge in agriculture or disposal in landfills or where disposal fees are high. Co-incineration in the cement industry is a possibility when conventional fuels are expensive. The sludge is used as a fuel source in cement kilns along with fossil fuels, which have a higher caloric value. Sludge can substitute for 15–20% of the conventional fossil fuels used in cement kilns (Box 2).

The sludge is typically dried and made into pellets, which makes it easier to use as fuel. The drying process is necessary to ensure that the cement kilns reach the required temperatures of up to 1,450° C. The high temperatures destroy any organic pollutants in the sludge. The cost for a multi-fuel kiln with a capacity of 5,000 tons of clinker a day amounts to USD 250,000 to USD 300,000. The cost for corresponding drying equipment that uses process heat to dry sewage sludge ranges from 25% to 90% and is USD 10 to USD 15 million.[49]

This business model is driven by: (i) regulations that prohibit or limit the disposal of sewage sludge in landfills and agriculture and mandates resource recovery and reuse through alternative fuels, and (ii) the presence of waste-to-energy plants using municipal solid waste for incineration, coal-fired power plants or cement kilns in nearby areas, (iii) the availability of combustion

[49] Information provided by Mr. Werner of Schwenk Cement industries (telephonic interview)

BOX 2. ADAPTATIONS OF THE BUSINESS MODEL

Two beneficial uses of cement kiln sludge ash are directed toward material recovery and can create a new value chain. These options for material recovery include using sludge ash for Portland cement and brick production. Cement kiln sludge ash generated through co-incineration in the cement plant can be integrated into clinker production. The clinker is cooled, mixed and ground with gypsum for the production of Portland cement. Adding sludge ash saves the cost of conventional raw materials used for cement production. The heavy metal pollutants in sludge ash are stabilized in the clinker and there are no further sludge residues or hazardous materials left over.

Similarly, sludge ash has the potential to replace clay in brick production. However, the quality of the bricks produced depends on two factors: (i) 20–40% by weight of sludge ash should be added to the clay, and (ii) the firing temperature for baking the bricks should be 1,000 °C.

Source: GWI 2012.

technologies that allow for incineration of waste-derived alternative fuel sources with various dry matter, and iv) a suitable tariff structure of tipping and disposal fees paid by the WWTPs to coal- and waste-to-energy power plants. In the last case, the WWTP and the waste-to-energy plant might be operated by the same private entity contracted through the municipality, which leads to easier disposal and use of sewage sludge for co-incineration. Most waste-to-energy, coal-fired thermal power and cement plants in high- and mid-income countries have adjusted combustion equipment according to the regulations, especially those related to emissions.

Typically, WWTPs deliver dewatered or dried sludge to the waste-to-energy or coal-fired thermal power plants where it is stored and further dried and processed so its physical properties match the requirements of the burners and combustion equipment. The treatment plant operator needs to pay for disposal and tipping. This payment is necessary to justify the capital and operating costs in modifying incinerators to be acceptable for co-incineration.

This business model is appropriate for large WWTPs disposing of sewage sludge in a manner that enhances a circular economy and reduces disposal costs (Canvas 9). This applies where RRR in agriculture is not a feasible option and co-incineration as an alternative fuel in the cement industry provides a tested and sustainable solution at scale. Scaling up the business requires co-incineration plants to have storage and drying capacities for sewage sludge to increase the calorific value. As a source of alternative fuel, the sludge should not exceed 20% in a fuel mixture.[50] A schematic representation of the business model recovering energy through co-incineration is shown in Figure 15.

For co-incineration in a waste-to-energy or coal-fired thermal power plant, the investment costs for smaller plants (40,000 tons/annum) amounts to about USD 41 million and USD 1,026 per ton respectively. The investment costs for larger plants (250,000 tons/annum) amount to USD 169 million and USD 680 per ton. For co-incineration in cement plants, investment in equipment for storage, drying, processing, delivery and feeding sludge into multi-fuel kilns for medium-sized factories with production capacities of 5,000 tons of clinker/day can be up to USD 10 million. However, solar drying sewage sludge will significantly reduce the investment needed for drying equipment at WTTPs or cement industries. The annual operational costs for co-incineration in waste-to-energy or coal-fired thermal power plants are estimated at 5–7% of the investment cost, i.e. USD 2.05 to 2.87 million for 40,000 tons/annum plant and USD 8.45 to USD 12 million for the larger plant respectively.

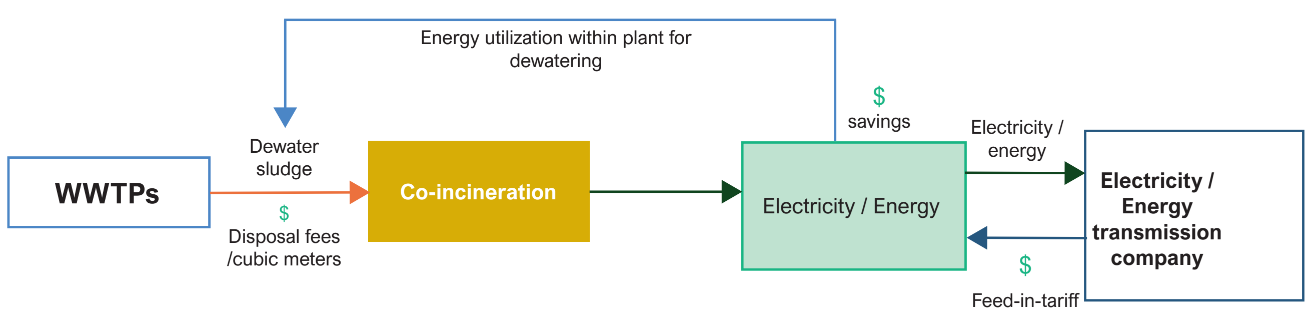


FIGURE 15. BUSINESS MODEL FOR CO-INCINERATION.

Source: Author's creation.

[50] Personal communication with manager of waste-to-energy plants in Bremen.

Partners
- Urban local bodies, public water utilities
- Energy recovery plants, waste-to-energy plants, thermal/cement plants
- Power transmission companies in the case of waste-to-energy and thermal plants

Activities
- Transportation of dewatered and dried sludge
- Recovery of thermal energy and electricity from incineration
- Use of electricity within the plant for drying sludge or feeding to the grid as cost recovery

Resources
- Establishing and commissioning incinerators that accept multiple fuel types

Value propositions
- Energy is recovered through the process making it energy efficient and a cost-effective alternative fuel for cement and thermal power plants
- Savings from lower disposal costs

Customer relationships
- Direct relations between the WWTP operators and energy recovery units (i.e. waste-to-energy, plants and cement plants)

Channels
- Contractual agreements for use of sewage sludge at incineration plants

Customer segments
- Waste-to-energy plants
- Thermal power plants using coal
- Cement plants

Cost structure
- Capital costs: mechanical equipment, incinerator and combined heat and power
- Salary, rent, interest
- Operation and Maintenance of incineration plants, mechanized equipment
- Fuel costs and utility charges

Revenue streams
- Cost savings from using alternative low-cost fuel
- Revenue generated from feed-in-tariff
- Disposal fees paid by WWTP operators

Environmental and social costs
- Labor health risks might arise due to handling sewage sludge and other waste streams.
- Flue gas containing furans, dioxins and heavy metals.

Environmental and social benefits
- Reduction of the sludge volume for disposal which is odorless and pathogen free.
- Creation of jobs.
- Potential of phosphate recovery reducing the dependence on natural phosphate.

CANVAS 9: ENERGY RECOVERY FROM CO-INCINERATION OF SEWAGE SLUDGE

Case Studies: Co-incineration in Cement Plants

Cementos Molins Group, Spain

Cement manufacturers worldwide strive to increase alternative fuel use such as sewage sludge. The activity of Cementos Molins (2020) focuses on manufacturing, distributing and selling cement, concrete, mortar, aggregate and concrete prefabricates, and running activities and production. Molins operates plants in Spain, Argentina, Uruguay, Mexico, Bolivia, Columbia, Bangladesh, India and Tunisia. As dried sewage sludge is an ideal fuel for the main burner in cement kilns, Cementos Molins is using this fuel plus biomass.[51, 52] Since one supplier usually cannot supply all the alternative fuel needed by a cement plant, homogeneous feed is an important consideration. Every supplier or treatment plant is producing alternative fuel with sometimes slightly, sometimes markedly different material properties, Cement industries are interested in uniformly drying sewage sludge to achieve a homogenous final product. Cementos Molins is dealing with different batches of granulated dry sludge humidity ranging from 10–15%.

Schwenk, Germany

Schwenk has long-term contracts with several WWTPs for the co-incineration of 30 tons of dewatered sewage sludge per day in its cement kilns. Costs for technical upgrading of the cement plant amounted to USD 10 million, 90% of which

[51] The renewable fuels used were agricultural waste, biomass, wood and sawdust, sewage sludge, and paper and cardboard. Cementos
[52] Molins, Annual Sustainability Report. 2020.
Cementos Molins https://sostenibilidad.cemolins.es/en/pilares/economia-circular/ (accessed on September 22, 2022)

was used for the installation of drying equipment that uses the thermal energy of process heat, and 10% for installing a multi-fuel kiln.[53] Dried sewage sludge is regarded as a CO_2 neutral fuel. As the cement industry generally has difficulty cooling its kilns and clinker products, they welcome the use of excess heat for drying dewatered sewage sludge with special heat exchange technologies. If dried sewage sludge is used, the recommended dry sludge is > 90% to allow for pneumatic feeding of dried sewage sludge particles into the kilns. The plant is a leader in using secondary fuel in Germany.[54]

In Germany, cement production facilities are designed to receive only dewatered sludge as this is most profitable for the industry due to the high disposal fees paid by WWTPs and utilities. On the other hand, this payment covers the capital and operating costs of modifying incinerators at cement plants to use alternative fuel and high investments in drying equipment to reduce the sludge water content before it can be fed into the kilns. Typically, the lower the disposal fees paid by the sludge producers, the higher the dry matter content demanded by the cement plants.

Case Studies: Co-incineration with MSW

Bamberg, Germany

The Bamberg waste-to-energy plant has been operating for more than 30 years and serves the district of Bamberg, Forchheim, Erlangen and Erlangen- Höchstadt. The plant treats 144,000 tons of household, commercial, and bulk waste as well as dewatered sewage sludge per year.[55] The sewage sludge is mixed with other waste and subjected to thermal treatment. The plant treats approximately 126,000 m^3/year with 3% dry residue content (about 30% dry residue after dewatering).[56] The plant owner, the Association of Waste-to-Energy Plants in the city and district of Bamberg invested EUR 50 million in 2007–2009 to upgrade the plant, which now produces 11.3 MW of electricity and 51 MW of heating output. This is mainly used for district heating and electricity for the Bamberg public utility. The electricity generated is approximately 80,000 MWh per year with 75,000 MWh used for district heating.[57] The plant produces 35,000 tons of bottom ash per annum (250 kg from one ton of waste). This is used as a filling and sealing material in mining or for road and landfill construction. The major savings come from less use of fuel (250 liters of heating oil or 250 cubic meters of natural gas per ton of residual waste.

Case Studies: Co-incineration in Coal-Fired Thermal Power Plant

Frechen, Hürth-Knapsack, Heilbronn, and Lippendorf Germany

Schmitz (2009) in Wiechmann et al. (2013) indicates the authorized volume of sewage sludge used in different thermal power plants adds up to 716,000 tons, only 500,000 tons can be used from a technical standpoint. Roskosch and Heidecke (2018) report that in 2016, the amount of sludge used by the plant was 401,000 tons considering co-incineration in both lignite and hard coal-fired power plants. The report mentions that in most coal-fired thermal power plants, the sewage sludge used is up to 5% of the fuel mass and the current use rate of the approved co-incineration capacity is just under 50%. As reported by Schmitz (2009), RWE Power Ag has the largest authorized capacity of 213,700 tons of sewage sludge. Weber et al. (2020) report that eight coal-fired power plants are authorized to co-incinerate sewage. RWE Power Ag and EnBW use sewage sludge in different power plants along with lignite and hard coal (Table 11).

Although using sewage sludge in coal-fired thermal power plants is one mechanism for disposal for the WWTP operator, using sewage sludge is becoming more difficult due to the increasing cost of complying with regulations and meeting standards. The heavy metal load entailed by sewage sludge use is significant when it comes to emission values. Therefore, using larger amounts of sewage sludge requires the installation of waste gas scrubbing equipment and hence additional investment and operational costs. Additionally, fly ash generated after co-incineration is recycled for use in construction materials and needs to comply with the applicable construction materials standards, which further limits its use.

[53] Information provided by Mr. Werner of Schwenk Cement industries (telephonic interview).
[54] Schwenk. https://www.schwenk.de/en/company/sustainability/ (accessed on September 22, 2022)
[55] Bamberg. https://www.hz-inova.com/files/2014/11/hzi_ref_bamberg_en.pdf (accessed on September 22, 2022)
[56] The feedstock used in the plant comprises of 133,000 tons of waste along with 12,000 tons of sewage sludge per year.
[57] MHKW Bamberg. https://www.mhkw-ba.de/index.php/nachhaltigkeit-umwelt.html. (accessed on September 22, 2022)

TABLE 11. RWE POWER AG AND ENBW USE OF SEWAGE SLUDGE.

Businesses	Installations	Description
RWE Power Ag	Frechen, North Rhine-Westphalia[a]	Founded in 1902, the plant co-fires sewage sludge and lignite to generate electricity.
	Hürth-Knapsack, North	Founded in 1992, this plant uses lignite-fired power with process
	Rhine-Westphalia[b]	steam extraction. The plant co-incinerates sewage sludge and generates 40 MW for district heat.
EnBW	Heilbronn thermal power plant	With an electrical output of 1,000 MW and an extractable thermal output of 320 MW, this t is one of EnBW's largest coal-fired power plants.
	Lippendorf power plant[c]	The plant started operation in 1999 and EnBW, along with Vattenfall. Europe Generation Ag, operates the plant producing 1840 MW. Sewage sludge has been co-incinerated in Lippendorf since 2004.

[a] RWE. https://www.rwe.com/en/our-portfolio/our-sites/frechen-factory

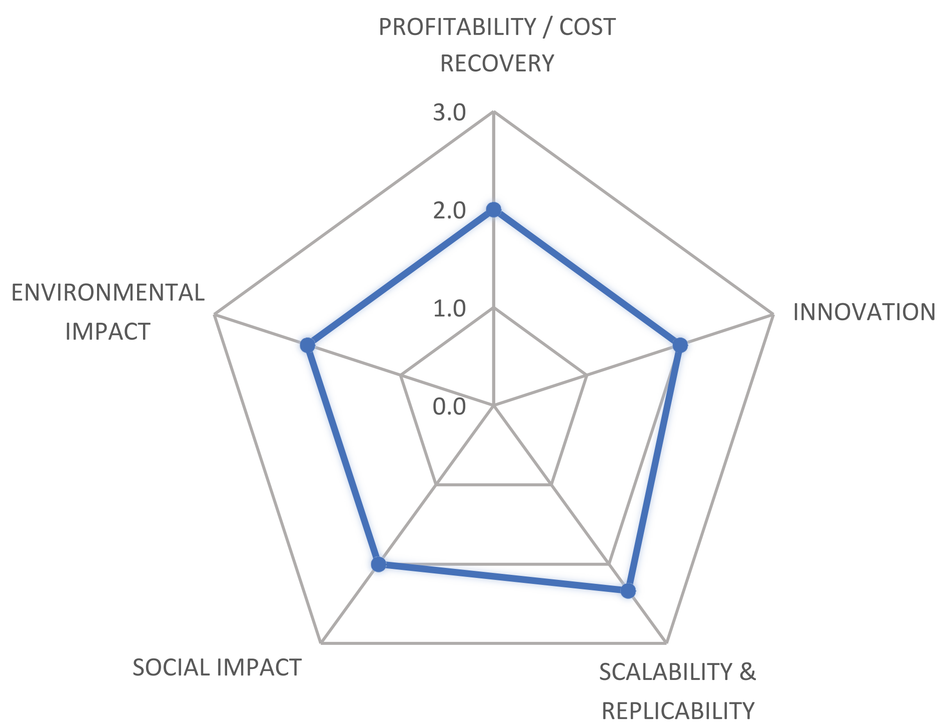
[b] RWE. https://www.rwe.com/en/our-portfolio/our-sites/knapsacker-huegel-power-plant/

[c] ENBW. https://www.enbw.com/company/the-group/energy-production/fossil-fuel/locations.html

Source: Author's creation.

BUSINESS MODEL 9: ENERGY RECOVERY FROM GASIFICATION AND PYROLYSIS

Brief	**Energy recovery from gasification and pyrolysis of sewage sludge**
Location	Peri-urban areas. The plant can be located at the WWTP
Waste input type/stream	Sewage sludge and other biomass as feedstock
Value offer	Energy recovery and reduced disposal costs
Environmental risk mitigation	Lower emissions than incineration but requires monitoring, especially for chemical contaminants in residue, although the risk is lower for biochar than sludge
Organization type and profit objective	Private operations with a profit motive, private-public partnerships between WWTP and technology providers
Major stakeholders	Municipalities, water utility services, private companies and technology providers



Business performance of energy recovery from gasification and pyrolysis.

- The business model scores evenly across the parameters used to determine performance primarily because of innovative technology and scalability.
- The technology developed can be used in a modular form, customized for a large operation or in a decentralized manner and thus helpful for small -and medium-sized WWTP.
- The operations are energy self-sufficient and save both energy and disposal costs.

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Higher efficiency of energy recovery. • Reduced emissions and ability to handle most inorganic compounds in sludge. • Production of biochar. • Reduced disposal costs.	**Weaknesses** • Sludge dewatering and drying are needed. • Complex technology and hence few commercial applications. • Extensive gas cleaning is needed for syngas applications. • High investment and operation costs, economies of scale and automation favor large-scale operations.
External origin	**Opportunities** • Niche market and energy self-sufficiency in WWTPs. • Potential for co-feeding with other types of biomass. • Development of by-products (bio-oil and biochar) for promoting circularity.	**Threats** • Legislation favoring the recovery of soil nutrients might lead to a shift toward other processes. • Markets for bio-oil, and biochar is not well-developed. The market needs development for the promotion of pyrolysis.

Business Model Description

This business model is appropriate for a private entity contracted by a WWTP operator who wants to manage sludge volume and reduce disposal costs. Wastewater facilities represent the largest energy consumers in the public sector and energy-self-sufficient treatment plants are the key to cutting costs. Gasification and pyrolysis for energy recovery are still in the nascent stage of application and are mainly found in developed countries.

Gasification: A process that converts sludge into fuel gas which is called synthesis gas or syngas for short. Syngas fuel can be used on-site to generate electricity for plant use or can be used in applications such as thermal drying systems. Syngas can be converted to liquid fuel for offsite applications and use in the chemical industry. Ash is a by-product of the gasification process. The ash can be sent for disposal at landfill sites, or it can be sent for resource recovery.

Pyrolysis: A thermal process that decomposes sludge by heating it (usually above 500-600ºC) in the absence of oxygen. The process converts sludge into a high-carbon solid called biochar. Other products of the pyrolysis of biomass are a mixture of syngas and bio-oil. The process can be tailored to produce different ratios of biochar to bio-oil. While biochar is pathogen-free, it can still contain heavy metals, but largely immobilized.

Both processes begin with thickening and dewatering the sludge which is then dried up to 90% dry solids content. These are necessary steps to improve energy efficiency. The installation and operation of the plant can be of two types: (i) a private entity installs the plant as a turnkey project financed by a WWTP operator, and (ii) a public-private partnership between a treatment plant operator and a technology provider. In the first case, the treatment plant operator might obtain financing from donors or through their own public finance mechanisms and contract a technology provider to commission the plant. In the second case, long-term contracts are prepared between public utilities and technology providers for a design, build, and operate system. The private entity designs, builds, and operates the plant while ownership remains with the public utility service. Figure 16 illustrates the business model for recovering energy from sludge through gasification or pyrolysis.

Gasification

The capital investment, including the dryer, varies between EUR 6 to EUR 12 million (USD 7 to USD 14 million) for handling 4,000 to 6,000 tons per annum. The operating expenses are USD 350,000 to USD 830,000 per annum which provides a return of 15–25% per annum. The payback period is four to seven years. The costs for gasifying sewage sludge significantly exceed the costs of incineration and pyrolysis due to both the high cost of equipment and the complexity of maintaining the gasification process.

Pyrolysis

Mills (2015) indicates the capital expenditure for a thermal hydrolysis plant with a dryer and a pyrolysis plant of 100 tons/day is USD 76 million. Adding a thermal hydrolysis plant and dryer increases the efficiency of electricity generation.

The same author calculates operational and maintenance costs as USD 2.15 million per ton per annum. The operating and maintenance costs also include disposal costs. Considering electricity generated and tipping fees as the revenue sources (USD 3.8 million per ton of sludge per annum), the study projects a net present value of USD 48 million and an internal rate of return of 18.6% with a payback of 5.2 years.

Table 12 provides a detailed estimate of a plant capacity of 2.1 tons/hour operational for 8,000 hours per annum. The study highlights that revenue from the sales of the biochar and tipping fee for the sewage sludge are important revenue sources for the financial sustainability of the model (Canvas 10).

Most plants creating sewage sludge biochar are in the United States or Australia, with a few in Europe. Those already operational are reaping the benefits of reduced disposal costs and new revenue streams. The Loganholme example from Australia (see below) shows how spending AU$1.8 million annually on bio-solid hauling contractors can be turned around into returns of almost AU$1 million per year through reduced disposal costs and revenue from carbon credits (GWI 2023a).

Due to the high carbon content of biochar and its ability to sequester carbon, it can also create revenue from the voluntary carbon market. IPCC (2018) highlighted biochar as a central carbon dioxide removal technology (negative emission technology, NET) and estimates by the European Biochar Industry Consortium suggest that approximately 300-500 kg of CO_2 could be permanently stored per ton of dried sewage sludge. This is a stark contrast to the incineration of sewage sludge which releases CO_2 into the atmosphere. Compared to other carbon sinks, biochar is an extremely cost-effective option and creates a viable business model (GWI 2023a). Although biochar can contain heavy metals, the potential risk of biochar on soil and groundwater contamination is lower than for sewage sludge as some are volatilized (Hg, Cd) and the bio-availability of others is reduced (Lu et al. 2016; Zangh et al. 2021).

TABLE 12. ESTIMATES OF PLANT CAPACITY.

Equipment Section	Purchase costs (USD)[a]
Belt dryer	486,943
Char storage	220,706
Pyrolysis gas burner	376,590
Rotary kiln burner	1,157,550
Scrubber	116,527
Direct capital costs[b]	4,784,540
Indirect capital costs[c]	2,700,950
Working capital	524,756
Total capital expenditures	**10,332,472**
Annual total operating costs	**1,018,644**

[a] 1 CDN = 0.7717 USD in 2018.

[b] Includes installation, piping, instrumentation and control, electrical installation, building and services, land and site development, utilities and service facilities.

[c] Includes engineering and supervision during construction, construction expenses, contractor's fees and contingencies.

Source: Barry 2018.

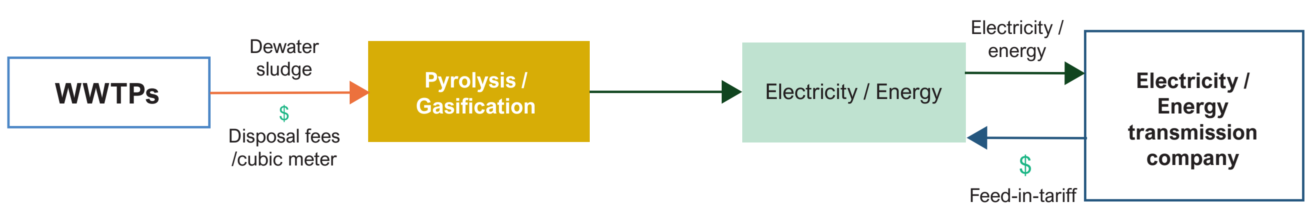


FIGURE 16. BUSINESS MODEL FOR ENERGY RECOVERY THROUGH PYROLYSIS AND GASIFICATION.

Source: Author's creation.

Partners
- Urban local bodies, public water utilities
- Energy and electricity transmission companies
- Local contractors

Activities
- Dewatering and drying sludge
- Transportation of dried sludge in case of regional plants
- Recovery of thermal energy and electricity
- Use of electricity within the plant for drying sludge or feeding to the grid

Resources
- Establishing and commissioning the plant
- Dewatered and dried sludge

Value propositions
- Energy is recovered through the process making it energy efficient
- Savings from disposal costs
- Potential for using other by-products in case of pyrolysis

Customer relationships
- Direct

Channels
- Contractual agreements for establishing and operating the plant

Customer segments
- Water utility services and municipalities

Cost structure
- Capital costs: mechanical equipment, combined heat and power technology, thermo hydrolysis and pyrolysis and drying units, gasification and pyrolysis units
- Salary, rent, and interest
- Operation and maintenance of all units
- Fuel costs, chemical costs and utility charges

Revenue streams
- Revenue from selling electricity
- Tipping fees
- An added source of revenue can be the recovery of bio-oil and biochar in the case of pyrolysis
- Carbon credits
- Savings on disposal costs

Environmental and social costs
- Labor health risks might arise due to handling sewage sludge and other waste streams

Environmental and social benefits
- Near or close to zero disposal required
- Job creation
- Fewer health issues

CANVAS 10: ENERGY RECOVERY FROM GASIFICATION AND PYROLYSIS

Case Studies: Gasification

SÜLZLE KOPF SynGas, Germany

SÜLZLE KOPF SynGas offers comprehensive and innovative solutions for decentralized sewage sludge use with energy recovery. On-site energy recovery and use not only use a CO_2-neutral energy source, but also significantly reduce pollutant emissions from sewage sludge disposal. SÜLZLE KOPF designs and implements these solutions based on a patented method that constitutes an economical and proven alternative to the standard processes.[58] The company has commissioned three plants in Germany in Balingen, Koblenz and Mannhein. The details of the three plants are shown in Table 13.

The examples above of small WWTPs that are not financially viable, can implement such technologies with high efficiency in energy recovery. Due to reduced energy costs, the payback period for installing such plants are relatively short.

Kiyose Water Reclamation Center, Japan

The Bureau of Sewage (Tokyo), Tokyo Metropolitan Sewerage Service Corporation and METAWATER Co. conducted a demonstration test in the Tobu Sludge Plant and established a wastewater sludge gasification process. The plant has been in operation since 2010 as a public-private venture where the 20-year design build and operate contract covers design, construction and operation and maintenance of the system as a single entity. The plant produces 150 kW of electric power which accounts for approximately 30% of the entire power consumed in the sewage sludge gasification process. The gasification process also provides heat for sludge drying.[59]

Loganholme Wastewater Treatment Plant, Australia

Sludge gasification is an emerging technology and there are examples where local authorities are taking the initiative and implementing this business model. The Loganholme WWTP in Australia is upgrading its treatment plant and investing

[58] Koph Syngas. https://kopf-syngas.de/en/start-2/ (accessed on September 23, 2022)
[59] Kiyose Bureau of Sewerage. https://www.gesui.metro.tokyo.lg.jp/english/news/r_and_r08/index.html (accessed on September 23, 2022)

USD 17.28 million to commission a gasification plant to generate renewable energy and sustainably produce biochar for agricultural purposes. The Loganholme plant services 300,000 people in the Logan region, producing 34,000 tons of biosolids per annum (an average of 90 tons a day).[60] This requires a 300 kilometer trip to Darling Downs agricultural area where it is used as soil improver costing USD 1.8 million (30% of the WWTP operating costs).[61] Biosolids treatment and disposal costs are increasing due to rising electricity prices, an increasing population, and the likely tightening of regulations associated with carbon footprint reduction and managing persistent organic pollutants in soils. The gasification plant would reduce the volume of biosolids by 90% and produce a safe, environmentally friendly biochar. The plant would be energy neutral and reduce carbon dioxide output by 4,800 tons per year. It is estimated that accounting for all these changes would save operating costs of USD 0.38 million. The project is a private-public partnership between the City of Logan Water and Sewage and Downer Group, with a USD 6.2 million grant from the Australian Renewable Energy Agency awarded to Logan City Council. The initiative is estimated to save ratepayers around USD 20 million in operating costs over the next 20 years.[62]

Case Studies: Pyrolysis

Eisenmann, Germany

Case 1. Thermal sewage sludge treatment in the Central Puster Valley [63]

In 1998, ARA Tobl GmbH (presently ARA Pustertal AG) procured a sludge drying plant. Drying achieved a reduction in sludge weight from 17,000 tons of wet sludge (20–22% dry matter) to 4,000 tons per annum with a residual moisture of approximately 10%. However, the weight reduction was not satisfactory as the sludge pellets formed after drying needed to be transported to the Po River valley about 300 km away. Following this, EISENMANN proposed thermal treatment of the sludge using the Pyrobuster® process. The Pyrobuster® plant was installed for the incineration of dried sludge pellets (calorific value of 12,000 kJ/kg) operating at a capacity of 550 kg/hour for 7,500 operating hours a year. The heat recovered from thermal treatment was used to heat the thermal oil which in turn heats the sewage sludge dryer. This process saves 70% of the energy required for drying and produces less carbon dioxide. The accumulated ash can be disposed of in landfills taken by a recycling company and further processed for reuse.

Case 2. Biomass-fueled power plant combined with sewage sludge [64]

KSV GmbH, at Dinkelsbühl, a special-purpose sewage sludge company, was formed under the management of the public utility Stadtwerke Crailsheim GmbH. Stadtwerke Crailsheim GmbH serves 27 municipalities and approximately 200,000 inhabitants. This special-purpose sewage sludge company disposes of regional sewage sludge along with biomass using the Pyrobuster® process. The plant receives about 18,000–22,000 tons of mechanically dewatered sewage sludge annually. The sludge contains approximately 25% dry matter which is transformed into a granulate with a dry matter content of about 88% before it is pyrolyzed. The energy required for drying is generated from the pyrolysis process which is capable of producing up to 72 million kilowatt hours (kWh) per annum. The plant is energy self-sufficient and the remaining ash is used for further processing.

TABLE 13. SÜLZLE KOPF SYNGAS PLANTS.

Item	Balingen[a]	Koblenz[b]	Mannhein[c]
Year established	2001 upgraded in 2011	2017	2010–2011
Operating capacity sludge 75–85%)	2,000 tons/annum (dry dry sludge)	4,000 tons/annum (80–85% (dry sludge 80%)	5,000 tons/annum
Power generation	215 kW	425 kW	530 kW
Heat generation	265 kW	535 kW	665 kW

[a] Koph Syngas. https://kopf-syngas.de/en/syngas-sewage-plant-in-balingen/ (accessed on September 23, 2022)

[b] Koph Syngas. https://kopf-syngas.de/en/syngas-sewage-plant-in-koblenz/ (accessed on September 23, 2022)

[c] Koph Syngas. https://kopf-syngas.de/en/syngas-sewage-plant-in-mannheim/ (accessed on September 23, 2022)

Source: Authors' creation.

[60] Australian Renewable Energy Agency. https://arena.gov.au/news/wastewater-treatment-plant-to-use-gasification-for-waste-disposal/ (accessed on September 23, 2022)

[61] Australian Renewable Energy Agency. https://arena.gov.au/projects/logan-city-biosolids-gasification-project/ (accessed on September 23, 2022)

[62] Downer Group. https://www.downergroup.com/downer-commences-100-million-upgrade-of-logan (accessed on September 23, 2022)

[63] Eisenmann. https://cdn2.hubspot.net/hub/133998/file-1576391265-pdf/PDF/Pyrobustor_en.pdf (accessed on September 23, 2022)

[64] Op.cit.

5. HYBRID MODELS

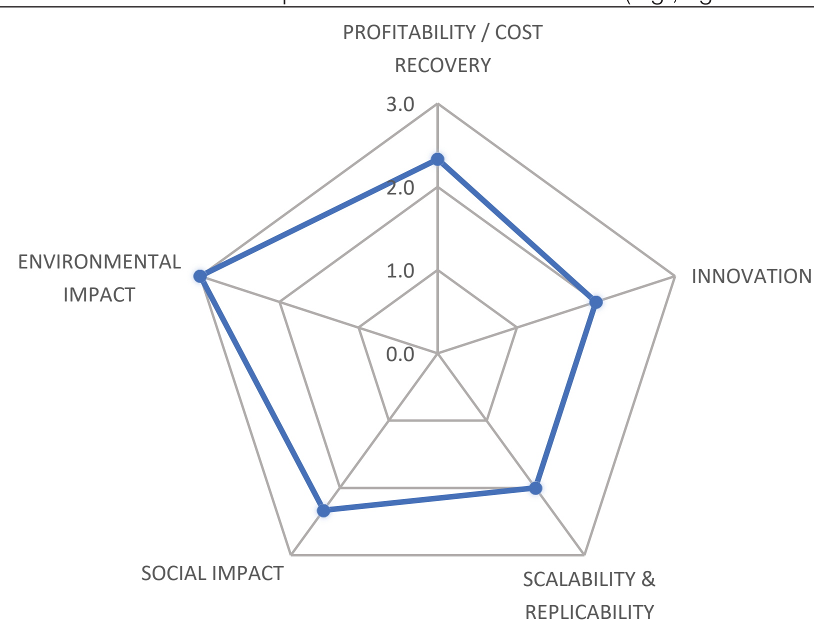
Introduction

This section describes business models where more than one resource recovery pathway is included. It includes the following models:

- Recovery of biosolids, biomethane and electricity from sludge digestion (model 10)
- Recovery of energy/electricity from sludge incineration and phosphorus from the ash (model 11)
- Recovery of phosphorus and energy from anaerobic digestion (model 12A)
- Recovery of phosphorus, biochar and energy through pyrolysis (model 12B)

BUSINESS MODEL 10: RECOVERY OF BIOSOLIDS, BIOMETHANE AND ELECTRICITY FROM SLUDGE DIGESTION

Brief	**Recovering biosolids from digestate and biogas from anaerobic sludge digestion**
Location	Urban and peri-urban areas
Waste input type/stream	Sewage sludge and other waste such as farm and food waste, agricultural and industrial waste can be integrated
Value offer	Recovered energy makes the plant self-sufficient and provides a revenue source; digestate is a Class A quality biosolid and can be used as organic fertilizer for land application; reduction in disposal costs; upgrading existing treatment systems to make the profitable
Environmental risk mitigation	Heavy metal concentrations in the digestate require monitoring
Organization type and profit objective	Public-private partnerships with a profit motive
Major stakeholders	Sludge producers, water boards, utility service agencies, private technology providers, construction companies, electricity transmission companies and other line ministries (e.g., agriculture and forestry)



Business performance of recovery of biosolids and energy.

- The business model uses traditional technology for harnessing energy and organic soil ameliorants thereby reducing dependence on fossil fuels.
- The model scores high on environmental and social measures.
- In recent installations, technological improvements such as thermal hydrolysis show that system efficiency can beincreased and scaled to achieve economies of scale.
- Centralized systems with integrated waste management systems, including sludge from wastewater, food waste and agro-waste or clustered treatment for small and medium WWTPs in a district can enhance profitability.

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Known technology used and hence operation and maintenance is easier. • Using thermal hydrolysis adds to the efficiency of the digester process.	**Weaknesses** • Requirement for regional collaborations or strong institutional partnerships for scaling up and achieving economies of scale.
External origin	**Opportunities** • Potential for co-feeding with food waste and a agro-waste. • Possibilities for job creation across sectors in case of integrated waste streams. • Clustered approach for small to medium wastewater treatment plants can lead to economies of scale.	**Threats** • Quality of waste from other waste streams. • Legislation favoring incineration and recovery of soil nutrients may lead to a shift.

Business Model Description

This business model is suitable for regional sludge centers that connect multiple WWTPs, usually 3–4 with a capacity ranging from 100,000–500,000 m^3/day, and run by private or public entities contracted by a municipality or water utility. The digestion process is enhanced by integrating thermal hydrolysis. The business model can be implemented through a private-public partnership model where the private entity can design, build, own and operate the digester plant along with energy recovery. The dewatered digestate could be marketed as a Class A biosolid as it is pathogen free and can be used on agricultural or non-agricultural land (Canvas 11). Apart from feeding electricity to the grid, another aspect of the business could be the production of upgraded biogas for household and commercial establishments. The service provider operating the digester plant can contract another provider for distribution to households.

In a clustered regional operation, the digester and the electricity recovery plant can initially be in one of the treatment plants and other plants can join in the recovery process. Wastewater treatment plants usually provide thickened sludge for advanced anaerobic digestion followed by thermal hydrolysis. This model requires economies of scale to be financially sustainable and hence setting up regional collaborations among treatment plants is an important step. The sludge-to-energy process is estimated to cost USD 52 million considering a 100 tons dry solid/day plant (Rus et al. 2017).[65] This includes pre-treatment and thickening, thermal hydrolysis, combined heat and power technology and electrical installations. The net present value after 20 years is approximately USD 31 million with an internal rate of return of 13.6% and a payback of approximately seven years.[66] Figure 17 provides a schematic representation of the business model.

[65] Considering GBP 1 = USD 1.289 with inflationary factor of 1.21. The dollar had an average inflation rate of 3.86% per year between 2017 and the present, producing a cumulative price increase of 20.83%.
[66] Similar conversion as above.

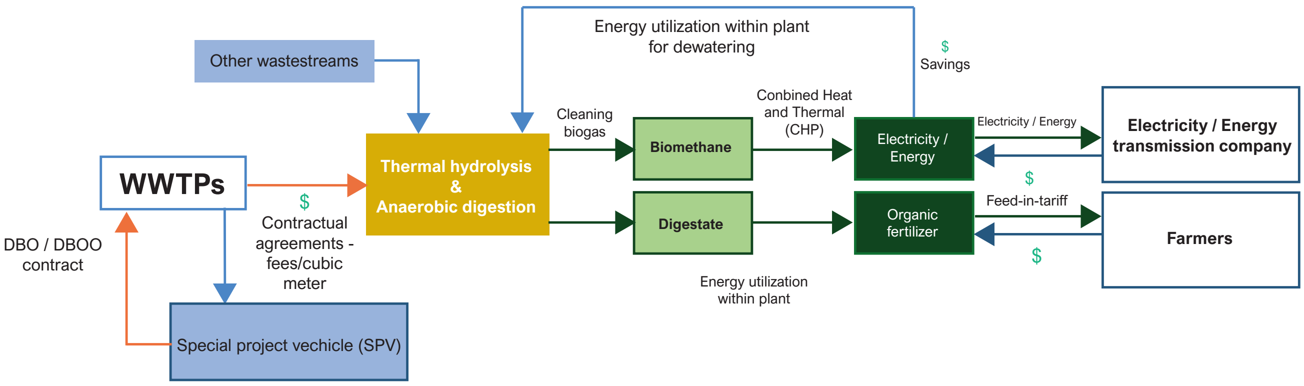


FIGURE 17. BUSINESS MODEL FOR RECOVERY OF BIOSOLIDS AND ENERGY (BIOMETHANE AND ELECTRICITY).

Source: Author's creation.

Partners
- Urban local bodies, public water utilities
- Biogas, energy and electricity transmission companies
- Local contractors
- Regulating bodies

Activities
- Pre-treatment and thickening of sludge at WWTP
- Transportation of sludge from other WWTPs in case of regional plants
- Recovery of biogas for energy and electricity
- Use of electricity within the plant for dewatering and drying sludge or feeding it to the grid

Resources
- Establishing and commissioning the plant
- Pre-treatment and thickening sludge
- Use of thermal hydrolysis

Value propositions
- Energy is recovered making the operation more energy efficient
- Savings from disposal costs incurred from lower sludge volume
- Potential of using the biosolids from digesters as an agricultural soil conditioner or upgrade it as a fertilizer for subsequent use

Customer relationships
- Direct relationship with the municipality/ WWTP operator

Channels
- Contractual agreements for establishing and operating plants
- Connection to energy grids

Customer segments
- Sludge producers, water utility services and municipalities
- Energy, electricity transmission companies
- Farmers

Cost structure
- Capital costs: mechanical equipment, combined heat and power technology, thermo hydrolysis and pyrolysis and drying units, biogas scrubbers
- Salary, rent, and interest, insurance
- Operation and maintenance of thermo hydrolysis, pyrolysis and digester units
- Fuel costs, chemical costs and utility charges

Revenue streams
- Revenue from electricity, energy (heat) and biogas sales
- Tipping fees
- Cost savings from disposal fees
- Sale of biosolids and organic fertilizers

Environmental and social costs
- Labor health risks might arise due to handling sewage sludge and other wastes.

Environmental and social benefits
- Near or close to zero disposal required.
- Job creation of jobs across sectors.
- Fewer health issues from reduced sludge to waterbodies and groundwater.

CANVAS 11: RECOVERY OF BIOSOLIDS AND ENERGY

Case Studies

Gaoantun Sludge Treatment Centre, Beijing, China

Gaoantun Sludge Treatment Center Is the largest in China and treats sewage sludge from four WWTPs, Gaoantun (200,000 m^3/d), Qinghe II (500,000 m^3/d), Jiuxianqiao (200,000 m^3/d), and Beixiaohe (100,000 m^3/d).[67] This amounts to the daily treatment of 4.5 million population equivalent with a capacity to treat 146,000 tons of sewage sludge dry matter per year. In 2014, Beijing Drainage Group decided to upgrade and expand existing treatment plants as water reclamation plants and recover resources from sludge.[68] This entailed treatment using anaerobic digestion and thermal hydrolysis to enhance digestion efficacy and convert the organic matter to recovery biogas and biosolids to meet Class A quality standards. A private-public partnership model was initiated between Beijing Drainage Group and Cambi™ to implement the project with a long-term design, build, and operate contract.

The sludge treatment line was equipped with pre-treatment (thickening and centrifuge dewatering), sludge silos, the Cambi thermal hydrolysis pre-treatment process which operates at 39° C, anaerobic digesters, a chamber filter press for final dewatering and a filtrate treatment system before it is sent back to the head-works of the wastewater treatment plant nearby. The total digester capacity of the plant amounts to 88,000 m^3 per day.

After installation of Cambi™ thermo hydrolysis and pyrolysis units in 2017, biogas production reached 350 m^3 per ton of dry matter. The final sewage sludge cake after dewatering has a dry matter content of 40% and is a Class A biosolid (pathogen and odor free.)[69] The sludge cake is transported offsite by the treatment plant operator and is used as a soil conditioner on forestry land in the surrounding areas of Beijing. Based on this application, advanced anaerobic digestion using thermal hydrolysis pre-treatment has gained strong interest both in academic institutes and in several industrial suppliers within China. We therefore expect to see a considerable increase in the use of advanced digestion of sludge and food waste in China in the next five to ten years.[70]

Billund Biorefinery, Denmark

Billund Biorefinery combines new technologies to process raw materials comprised of wastewater, organic household waste and organic waste from agriculture and industries. The outputs are purified water, energy (in the form of heat and electricity) and organic fertilizer for agricultural use. The project was initiated in 2015 and started operation in 2017 as a public-private partnership between the Danish Utility company Billund Vand A/S and Krüger A/S, a Veolia Water Technologies subsidiary with a payback of only nine years.[71]

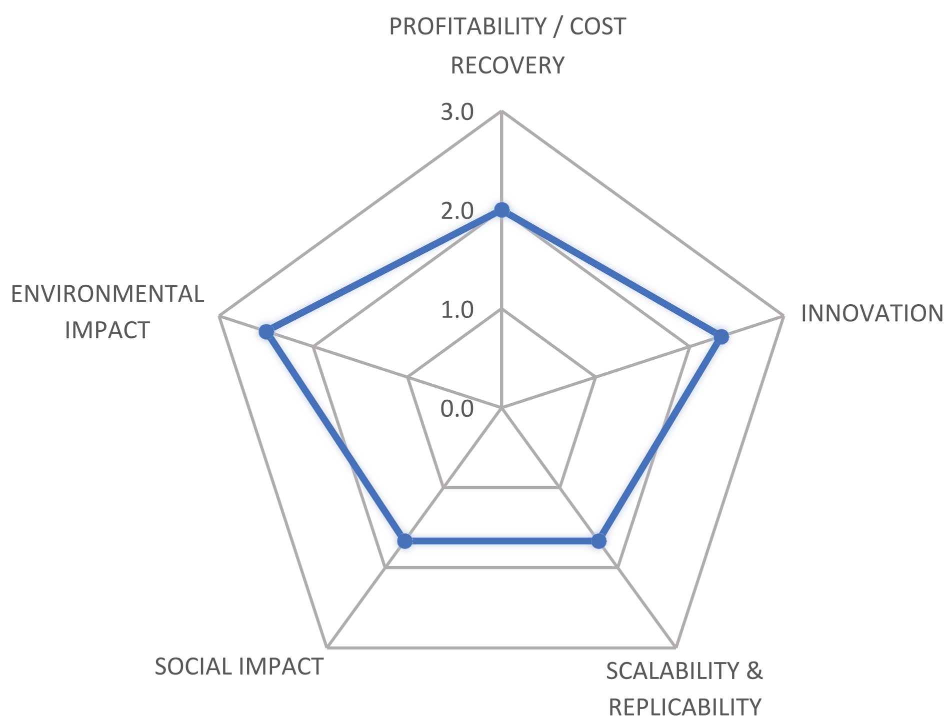
The plant size of 70,000 population equivalent is a fine example of how urban waste streams can be turned into profitable resources with environmental and health benefits. The total budget for upgrading the project was EUR 9 million with a grant of EUR 2 million from the Danish Eco-innovation Program and the Vandsektorens Teknologiudviklingsfond.[72] Upgrading the existing treatment system resulted in:

- An increase in energy production by more than 160% from approximately 8.5 million kWh to about 22 million kWh per year. The energy is used within the plant and the rest is converted to electricity and sold to the grid.
- Expenses for sludge treatment were reduced by 30–40%.
- Plant capacity to receive approximately 40,000 tons of waste from the food industry.

[67] Cambi. https://www.cambi.com/resources/references/asia/china/beijing-gaoantun/#:~:text=Gaoantun%20Sludge%20Center&text=Gaoantun%20 treats%20400%20tDS%20of,put%20into%20operation%20in%202017 (accessed on September 25, 2022)
[68] Aquaenviro. https://www.aquaenviro.co.uk/proceedings/advanced-digestion-of-sludge-enhances-shift-of-biosolids-management-strategy-in-beijing/liao-et-al_-advanced-digestion-enhances-shift-of-biosolids-management-in-beijing/ (accessed on September 25, 2022)
[69] Aquaenviro. https://www.aquaenviro.co.uk/proceedings/advanced-digestion-of-sludge-enhances-shift-of-biosolids-management-strategy-in-beijing/liao-et-al_-advanced-digestion-enhances-shift-of-biosolids-management-in-beijing/ (accessed on September 25, 2022)
[70] Aquaenviro. https://www.aquaenviro.co.uk/proceedings/advanced-digestion-of-sludge-enhances-shift-of-biosolids-management-strategy-in-beijing/liao-et-al_-advanced-digestion-enhances-shift-of-biosolids-management-in-beijing/ (accessed on September 25, 2022)
[71] Billund Biorefinery. https://www.billundbiorefinery.com/ (accessed on September 25, 2022)
[72] Veolia. https://www.veoliawatertechnologies.com/sites/g/files/dvc2476/files/document/2019/06/170324_VWT_NA_WAVE_Sludge_web%20%281%29.pdf (accessed on September 25, 2022)

BUSINESS MODEL 11: RECOVERY OF ENERGY/ELECTRICITY FROM SLUDGE INCINERATION AND PHOSPHORUS FROM THE ASH

Brief	**Recovering electricity through sludge incineration and phosphorus from sewage sludge ash**
Location	Peri-urban areas close to WWTPs where incinerators and phosphorus recovery can be integrated
Waste input type/stream	Dewatered and dried sewage sludge
Value offer	Recovering phosphorus which can be used as a green fertilizer; electricity generation contributes to plant energy self-sufficiency; savings in disposal costs
Environmental risk mitigation	Processes are needed to separate phosphorus from heavy metals; pollution control mechanisms are needed to limit air pollution
Organization type and profit objective	Public utility services operating for social motives; possibility of private entities as technology providers and marketing fertilizers
Major stakeholders	WWTP operators, incinerator operators, phosphorus recovery unit operators, fertilizer marketing agencies



Business performance of phosphate and energy recovery.

- The business model scores high on innovation by using advanced technology. The proportion of phosphorus recovery from sewage sludge ash is substantial which makes the operation of more energy self-sufficient.
- Potential for cost recovery and positive environmental impacts with reduced disposal in landfills.

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Modular units are more easily installed and scaled. • Cost recovery through different revenue streams.	**Weaknesses** • Horizontal and vertical links among and between partners across the value chain are required, which implies agreements and strong institutional management.
External origin	**Opportunities** • More technology providers as more research and from development is undertaken. • Favorable regulations for using sludge ash for phosphorus recovery.	**Threats** • Public perception risks and strong competition phosphate fertilizers. • Lacking regulations to promote recovered phosphorus fertilizer products.

Business Model Description

This business model extends the mono-incineration process through which energy is recovered. The incineration of municipal sewage sludge concentrates nutrients in sludge ash, which contains high concentrations of phosphorus. Ash generated from mono-incineration is more suitable for phosphorus recovery than ash generated from co-incineration. Sludge ash is typically sent to a landfill due to the presence of heavy metals, which make it unsuitable for agriculture. Recovering phosphorus from sludge ash provides opportunities for the beneficial use of sludge streams.

This model is therefore driven by a desire to reduce disposal fees for incinerated ash. Mandatory regulations to recycle and reuse phosphorus are another prominent driver. Typically, private operators are contracted by WWTP operators to construct and operate incinerators. Phosphorus recovery is a separate business provided by companies with phosphorus recovery technologies (Canvas 12).

There are two technology streams to recover phosphate from incinerated ash, wet chemical and thermo chemical. Wet chemical approaches (Leachphos®, TetraPhos®, EasyMining™) leach phosphate from the ash through acidic dissolution. The wet process retains impurities of iron and aluminum and hence sometimes the thermochemical process is preferred. The thermo-chemical process allows for the removal of heavy metals and increases the bioavailability of the phosphate. However, in the wet chemical process, there is a possibility to recover concentrated phosphoric acid which adds to the revenue stream.

This model is appropriate for WWTPs where regulations have restricted treated sewage sludge disposal in landfills or incineration facilities and municipalities are willing to upgrade their systems to reduce the disposal of ash in landfills. Figure 18 provides a schematic illustration of the business model for recovering energy and phosphorus from sewage sludge. Scaling up a project requires partnerships among WWTP operators, municipalities, technology providers, and private agencies with experience in agronomic advisory services and fertilizer marketing as well as local contractors and suppliers. Investment costs are high and to benefit from economies of scale, cooperation between municipalities for sludge treatment is a necessity.

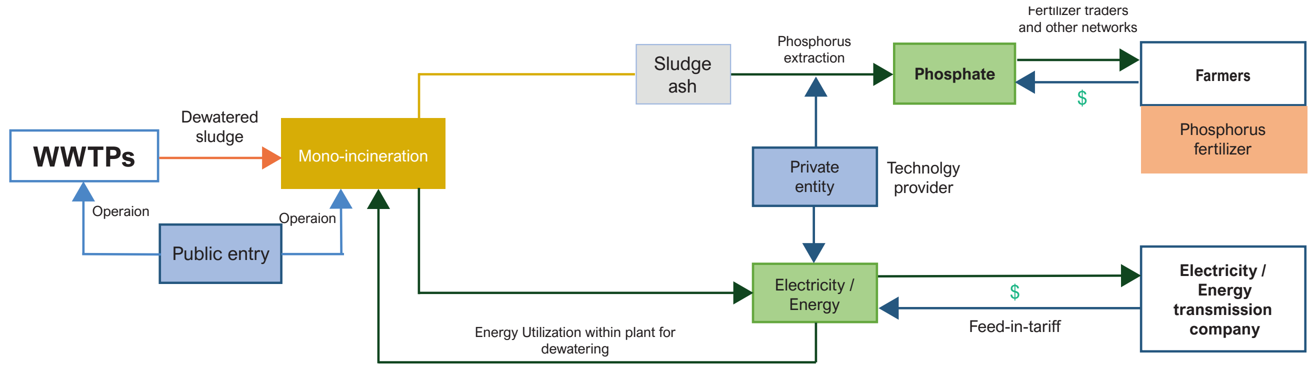


FIGURE 18. BUSINESS MODEL FOR RECOVERING ENERGY AND PHOSPHORUS.

Source: Author's creation.

Partners
- Urban local bodies, public water utilities
- Incinerator plant operators
- Energy and electricity transmission companies
- Local contractors
- Regulating bodies
- Companies dealing with fertilizers sales

Activities
- Pre-treatment and thickening sludge at WWTP
- Transportation of sludge from other WWTPs in case of regional plants
- Drying sludge
- Incineration of sludge
- Phosphorus recovery

Resources
- Technology for incineration and phosphorus recovery
- Permits and licenses
- Capacity for the sale of phosphorus-

Value propositions
- Energy is recovered through the process making it energy efficient (especially for sludge drying)
- Phosphorus recovery for making high-value fertilizer products
- Savings from disposal costs

Customer relationships
- Direct contact with municipalities, public utility companies, / WWTP operators
- Direct networking with the fertilizer trading companies
- Direct links with energy distribution companies

Channels
- Contractual agreements establishing and operating plants
- Connection to energy grids

Customer segments
- Water utility services, municipalities
- Energy, electricity transmission companies
- Fertilizer traders (networks and associations)

Cost structure
- Capital costs including phosphorus recovery units
- Salary, rent, interest
- Operational costs including phosphorus recovery units
- Transaction costs to penetrate fertilizer value chains with small phosphorus volumes
- Research and development, validation, licensing and certification

Revenue streams
- Revenue from electricity and energy sales
- Sale of green fertilizer
- Tipping fees

Environmental and social costs
- Labor health risks might arise due to handling sewage sludge and other waste streams.
- Uncertain acceptance of phosphorus fertilizer recovered.

Environmental and social benefits
- Near or close to zero disposal required.
- Energy recovery.
- Fewer health issues from reduced exposure of sludge to waterbodies and groundwater.

CANVAS 12: RECOVERY OF ENERGY AND PHOSPHORUS BY INCINERATION

Case Studies

ZVK – Zweckverband Klärwerk Steinhäule, Germany

ZWK is a corporation under public law and a special purpose association for sewage treatment in Steinhäule. The association comprises 31 cities, municipalities, municipal companies and special purpose associations with a primary aim to recycle sewage sludge in Steinhäule.[73] The Steinhäule wastewater treatment plant is designed to treat wastewater from 440,000 inhabitants in the region. The plant generates 1,000,000 m^3 of sewage sludge annually with 10,000 tons of dry matter. Another 10,000 tons of sewage sludge accumulates in the treatment plants of the other association members. The incineration plant was initiated following the updated Sewage Sludge Ordinance (AbfKlärV) and Fertilizer Ordinance (DüMV) in 2017. Until 2012, the plant was limited to treating wastewater and using the biosolids produced for agriculture.[74] To ensure regulatory compliance, thermal treatment and phosphorus recovery were initiated by ZWK.

This sewage sludge is dewatered enough to be thermally recycled in a fluidized bed furnace and achieves dry solid content of 25–30%. The flue gas is cooled in a heat recovery boiler and the steam created in the process is used to generate electricity via steam turbines. The plant generates 6.1 million kWh/annum, which is fed to the grid and used in the plant for dewatering sludge. Thermal treatment destroys contaminants in the sludge and about 99% of the phosphorus remains in the ash. Phosphorus recovery is estimated to be 580 kilograms daily (about 650 tons per year). The phosphate ash is enriched with nutrients and other additives. Since 2014, SePura GmbH markets the ash as a phosphate fertilizer for use in agriculture.[75] The residues from the fabric filter are used as fill materials in mining operations.

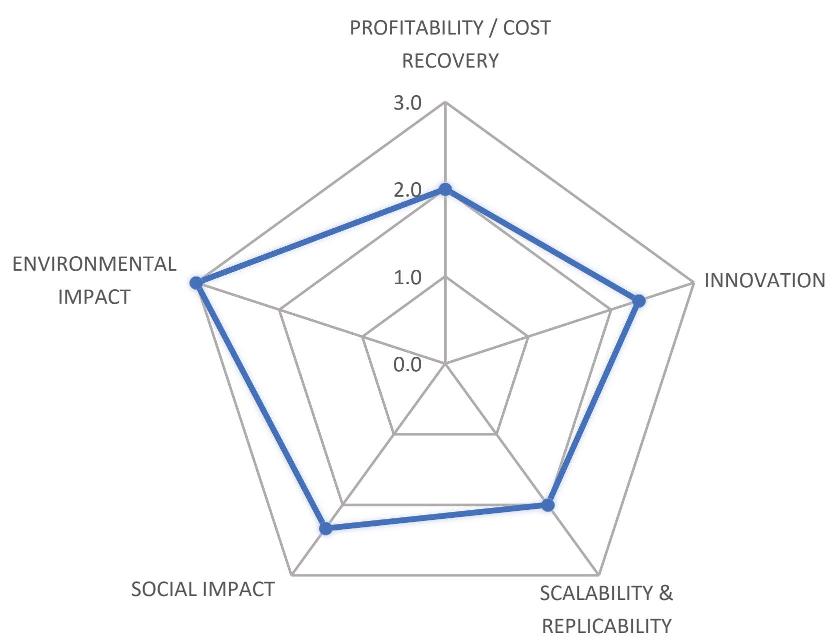
[73] Zweckverband Klärwerk Steinhäule. https://www.zvk-s.de/en/administrative-union-zvk/?lang=en (accessed on September 25, 2022)
[74] Zweckverband Klärwerk Steinhäule. https://www.zvk-s.de/en/treatment-plant/sludge-treatment-and-recycling/?lang=en (accessed on September 25, 2022)
[75] IWAM Interactive Water Management. http://www.iwama.eu/sites/iwama/files/12_recycling_sewage_sludge_ash_for_agricultural_application_in_germany_plank.pdf (accessed on September 25, 2022)

BUSINESS MODEL 12: RECOVERY OF PHOSPHORUS AND ENERGY FROM SEWAGE SLUDGE

Under model 12 we distinguish between the recovery of phosphorus and biomethane from anerobic digestion (Model A) and through pyrolysis (Model B).

Model A: Recovery of phosphorus and energy from anaerobic digestion

Brief	**Recovering energy and phosphorus from anaerobic digestion in large-scale WWTPs**
Location	Peri-urban areas, usually through regional energy and nutrient plants
Waste input type/stream	Sewage sludge
Value offer	Energy recovery makes the plant self-sufficient and generates electricity generated households and commercial establishments Recovered phosphorus sold through commercial arrangements Cost savings from reduced maintenance
Environmental risk mitigation	Extracted struvite is without particular environmental risks
Organization type and profit objective	Public-private partnership seeking financial viability of operations
Major stakeholders	Water and wastewater utility services, private operators (designing and operating plant, technology providers, subcontractors, suppliers), electricity transmission companies, local companies selling fertilizers



Business performance of energy recovery (biomethane) and phosphorus.

- The business model is suitable for most WWTP operators using anaerobic digestion, which is widely used.
- The scalability of the business depends on the willingness of different WWTPs to cooperate for establishing a centralized regional facility.
- The phosphorus recovery unit is modular and uses advanced technology.
- Digester efficiency can be increased through advanced technologies such as thermal hydrolysis.
- The business provides risk sharing for revenue generation and has a strong positive impact on the environment and society.

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Known technology used to make operation and maintenance easier. • Using thermal hydrolysis increases digester efficiency.	**Weaknesses** • The business model needs to achieve economies of scale and is therefore suitable for large WWTPs and regional collaborations. • Strong institutional links are required for efficient operation.
External origin	**Opportunities** • More technology providers as more research and from development is undertaken. • Favorable regulations for using sludge ash for phosphorus recovery.	**Threats** • Public perception risks and strong competition phosphate fertilizers. • Lacking regulations to promote recovered phosphorus fertilizer products.

Business Model Description

These business models are mostly public-private partnerships between water utility services and technology providers. Sometimes, the private entity is a partnership between a technology provider and a design, build, and operate organization. The private-public partnership contracts are mainly for design, build, and operate for 10 to 20 years. These business models are often initiated by stringent environmental regulatory frameworks that prohibit direct disposal and application of sewage sludge in controlled landfills and agricultural use and mandates resource recovery. These models are also possible where water utility agencies consider upgrading for energy recovery and plan to reduce the cost of chemicals, labor and maintenance from struvite deposition in pipes and digesters through phosphorus removal and recovery with a potential reuse market.

Electricity generated through anaerobic digestion is improved through thermal hydrolysis, which can make the plant operation energy self-sufficient and generates revenue by feeding additional electricity to the grid (Canvas 13). Phosphorus recovery offers another source of revenue for the water utility service. The long-term contract offers revenue sharing from fertilizer sales for the technology provider who is also the off-taker. The water utility service agency need not participate in downstream product sales, which become the responsibility of the technology provider. The associated marketing and off-take risks are transferred to the technology provider and therefore this business model offers an opportunity for spreading risk and a more sustainable operation. The payback period of these businesses varies between three to ten years. Figure 19 provides a schematic diagram of the business model for recovering biomethane and phosphorus from sewage sludge.

This business model is suitable for WWTPs with treatment facilities serving 200,000–300,000 population equivalent and willing to upgrade the plant for nutrient recovery and make it more energy efficient. Sometimes, regional hubs for sludge management are effective ways for promoting such businesses.

The acceptance within the fertilizer industry for blending their phosphorus sources with struvite might still be low, with reasons related to low quantities and limited solubility than alternative phosphate sources (Drechsel et al. 2018). Moreover, in many countries legislation is lacking, unclear, or prohibits the reuse of resources recovered from waste.

More progressive legislation is needed that allows penetrating conventional phosphorus markets by mandating a certain mix-ratio of recovered phosphorus. Additionally, certification of plants recovering phosphorus through periodic monitoring should be made a necessary condition for reuse and hence this might be one way of reducing barriers. The capital expenditure of a phosphorus recovery plant (e.g., 50 tons/day) is USD 7 million. The investment costs can be recouped in five (3-10) years through savings from reduced cost of the unwanted crystallization of struvite in pipes, complemented by additional revenues where the recovered phosphorus can be sold as fertilizer.

The net present value of a 50-ton a day plant over 20 years is about USD 16 million, of which net savings on the operations provide about 80% of the net present value and the remaining from fertilizer revenue.

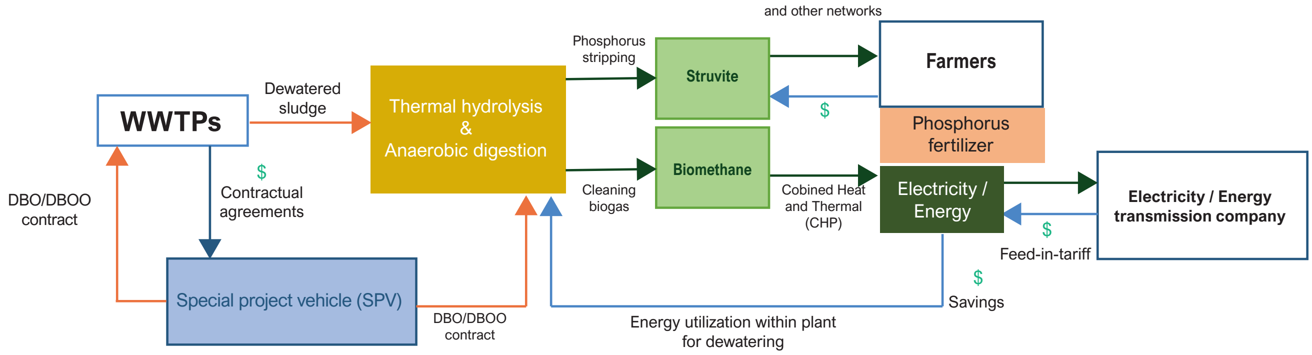


FIGURE 19: BUSINESS MODEL FOR ENERGY AND PHOSPHORUS RECOVERY THROUGH ANAEROBIC DIGESTION.

Source: Author's creation.

Partners	Activities	Value propositions	Customer relationships	Customer segments
• Urban local bodies, public water utilities • Biogas, energy and electricity transmission companies • Local contractors • Regulating bodies	• Pre-treatment and thickening sludge at WWTP • Transportation of sludge from other WWTPs in case of regional plants • Recovery of biogas for energy and electricity • Use of electricity within the plant for drying sludge or feeding to the grid **Resources** • Establishing and commissioning plants • Pre-treatment and thickening sludge • Use of thermal hydrolysis	• Energy is recovered making the operation more energy efficient • Phosphorus recovery • Savings from disposal costs incurred from lower sludge volume • Potential to use biosolids from digesters as an agricultural soil conditioner or upgrade it as a fertilizer	• Direct relations between sludge producers and technology providers **Channels** • Contractual agreements for establishing and operating plants • Connection to energy grids	• Water utility services and the municipalities • Energy and electricity transmission companies • Farmers

Cost structure	Revenue streams
• Capital costs: mechanical equipment, combined heat and power technology, thermo hydrolysis and pyrolysis and drying units, biogas scrubbers • Salary, rent, and interest • Operation and maintenance of thermo hydrolysis and pyrolysis and digester units • Fuel costs, chemical costs and utility charges	• Revenue from electricity, energy (heat) and biogas sales • Sale of fertilizers • Tipping fees • Savings from reduced pipe maintenance
Environmental and social costs	**Environmental and social benefits**
• Labor health risks might arise due to handling sewage sludge and other waste streams	• Near or close to zero disposal required • Job creation • Reduction in health issues from reduced sludge to waterbodies and groundwater

CANVAS 13: RECOVERY OF ENERGY AND PHOSPHORUS FROM SEWAGE SLUDGE

Case Studies

Amersfoort, Netherlands

Amersfoort WWTP in the Netherlands is owned and operated by the Dutch Water Board Vallei en Veluwe. In 2013, the board awarded a project to Eliquo Water and Energy (Eliquo Group) to upgrade the existing wastewater and sludge processing facilities into a regional hub for recovering energy and nutrients using innovative commercially tested technologies. The sludge produced from the treatment of wastewater from communities in Amersfoort, Soest, Nijkerk and Woudenberg (315,000 population equivalent) is approximately 50,000 m^3/day. All the sludge is digested at the Amersfoort treatment plant. Digestion is enhanced with thermal pressure hydrolysis using LYSOTHERM® to increase biogas yield and produce green electricity. The entire WWTP and sludge facilities are energy self-sufficient. A surplus of approximately 2,000,000 kWh is supplied to the national power grid and this is sufficient to provide 600 households with green electricity annually.[76]

Amersfoort WWTP uses a biological phosphorus removal process by Ostara, where phosphorus is retained in activated sludge and recovered thereby producing a high-quality commercial fertilizer called Crystal Green®. Phosphorus is extracted from the activated sludge before anaerobic digestion by applying a patented waste-activated sludge stripping process (WASSTRIP®). Phosphorus-rich filtrate from the WASSTRIP® is treated with the rejected water from the sludge dewatering in a Pearl® reactor, producing Crystal Green® pellets. The pellets are dried, classified and bagged for transport. The reactor can produce two tons of Crystal Green® per day.[77] The combination of the WASSTRIP® and Pearl® processes reduces the amount of chemical sludge formed when phosphorus is removed from wastewater by chemical dosing via conventional removal methods.[78] It also improves dewatering of digested sludge. The uncontrolled deposition of struvite is avoided, saving the water board significant ongoing costs associated with the maintenance and replacement of pipes and other mechanical equipment.

Water board revenue is generated through a long-term agreement for the off-take of the fertilizer produced by the technology provider. The water board does not have to participate in the downstream product sales as all the associated marketing and off-take risks are transferred to the technology provider. The combined application of energy and nutrient recovery with a guaranteed long-term off-take agreement results in a payback period of just under seven years. Marketing the fertilizer is easier since this fertilizer is European Certified in the same category as the highest quality fertilizers and marketed exclusively by Ostara.

Chicago, USA

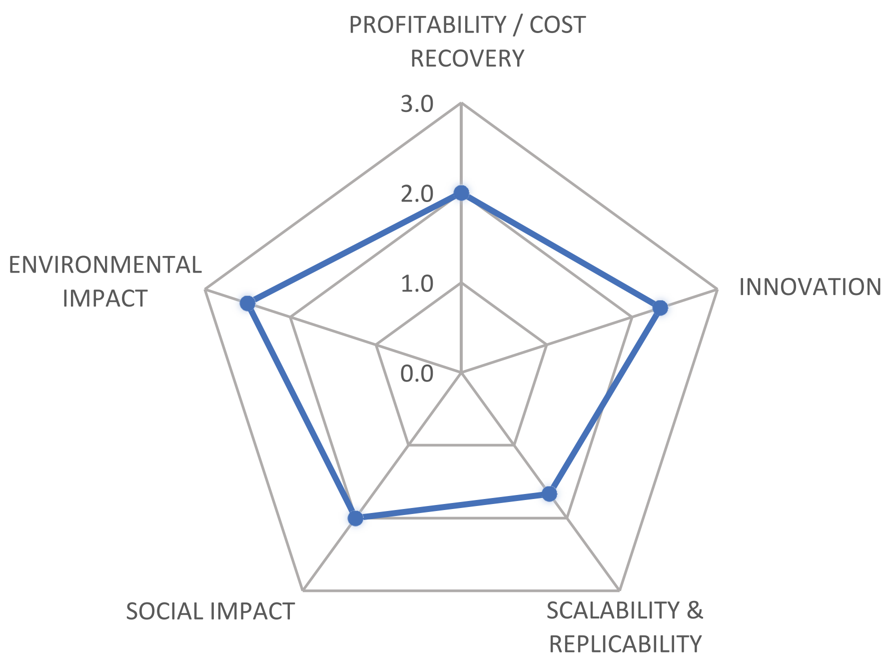
The Chicago-Stickney WWTP is one of the largest wastewater treatment plants in the world and is designed to treat up to 550,000 m^3/day. The Metropolitan Water Reclamation District of Greater Chicago (MWRDGC 2019) wanted a closed-loop and cost-effective phosphorus management strategy to meet the challenge of more stringent regulatory limits for effluent discharge in addition to a wastewater system that was experiencing an unwanted accumulation of minerals in struvite form. In 2013, MWRD selected Black & Veatch and Ostara Nutrient recovery technologies to design and build a nutrient recovery system at its Stickney Water Reclamation Plant in Cicero, Illinois.[79] The objective was to capture the phosphorus before it creates problems within the pipe system which would be costly to address, while helping to exceed the environmental regulation target of 1 mg/liter total phosphorus in the treated effluent.[80]

The Ostara process for nutrient recovery is based on a closed-loop process whereby phosphorus and nitrogen in wastewater are recovered to form a commercial fertilizer marketed by Ostara. The Stickney treatment plant has installed three Pearl® reactors with an installed production capacity of up to 9,000 tons of pelletized phosphate fertilizer per year (Ostara 2023). As the plant operator, the district pays Ostara as it saves on every ton of phosphorus removed by Ostara's technology before it can damage the system. On the other hand, Ostara buys back the recovered struvite produced by plants utilizing its technology (municipal plant operators are usually not in the fertilizer business), providing in this way a guaranteed revenue stream for the treatment plant. Depending on regulations for end-of-waste products and market acceptance Ostara can then earn revenue for every ton of fertilizer sold.[81]

[76] Eliquo Technologies. https://www.eliquo-tech.com/en/references-details.html?articles=omzet-amersfoort-4983 (accessed on September 27, 2022)
[77] Eliquo Technologies. https://www.eliquo-tech.com/en/references-details.html?articles=omzet-amersfoort-4983 (accessed on September 27, 2022)
[78] Ostara. https://ostara.com/nutrient-recovery/nutrient-recovery-solutions/ (accessed on September 27, 2022)
[79] Koch Lefler Britton. https://www.mi-wea.org/docs/Koch_Lefler_Britton-Phosphorus_Recovery.pdf (accessed on September 27, 2022)
[80] Ostara. http://ostara.com/wp-content/uploads/2016/05/Ostara_MWRD_CaseStudy_web.pdf (accessed on September 17, 2022)
[81] Ostara. http://ostara.com/wp-content/uploads/2017/03/Ostara_NRS_BROCHURE_170328.pdf (accessed on September 17, 2022)

Model B: Recovery of phosphorus, biochar and energy through prolysis

Brief	**Recovery of phosphorus, biochar, and energy from sewage sludge**
Location	Peri-urban areas
Waste input type/stream	Sewage sludge; other organic wastes; pyrolysis can handle both digested and undigested sludge
Value offer	Energy sufficiency; reduction in disposal costs; biochar production as a soil conditioner
Environmental risk mitigation	Pyrolysis efficiently degrades organic toxins but enhances heavy metals in the biochar. However, these are largely immobilized resulting in a much lower risk than for sewage sludge
Organization type and profit objective	Mainly private entities and for-profits
Major stakeholders	Water utility services, municipalities and urban local bodies, regulatory organizations, especially those related to the use of biochar as a soil conditioner or fertilizer



Business performance of energy and phosphorus recovery or biochar though pyrolysis.

- The business model scores high on innovation by using advanced technology to recover phosphorus.
- Phosphorus recovery through pyrolysis can be adapted and integrated by WWTPs to upgrade their systems.
- The business model provides opportunities for cost recovery and reduces the risk of the WWTP as there are off-take guarantees.
- The business model provides positive environmental impacts and the use of the generated biochar has been approved for agriculture so far in three EU countries (Sweden, the Czech Republic, and Denmark) which is an important signal for other countries.

Strengths, weaknesses, opportunities, and threats (SWOT)

	Helpful	Harmful
Internal origin	**Strengths** • Upgrading a WWTP is easier since the units are modular and can be scaled to meet licenses and expensive which can delay revenue • Technology providers share the risk of revenue generation.	**Weaknesses** • High investment costs. • Obtaining and permits can be difficult demand.
External origin	**Opportunities** • Little competition in niche markets. • Regulations by local governments in certain areas favor the marketing and use of biochar.	**Threats** • Acceptance from traders and farmers is low as the product is relatively new.

Business Model Description

These business models are decentralized and blend two technologies for recovering energy and phosphate from sewage sludge. The technologies are often complimentary and technology providers usually form partnerships to recover energy and soil nutrients. Although the technologies are advanced, these businesses have completed pilot stages in most cases and are running at full scale. However, the enterprises might be still small scale and decentralized, primarily because marketing biochar requires regulatory approval before being scaled up.

WWTPs or water utility providers form joint ventures, which might be private-public partnerships for design, build, and operate arrangements for 10 to 20 years. Sometimes these begin as pilot projects and gradually grow to full-scale operations complying with regulatory norms. The business model is driven by environmental regulatory frameworks that prohibit direct disposal and application of sewage sludge in controlled landfills and for agricultural use and mandate resource recovery. Since these are emerging technologies, setting up and commissioning a plant requires significant investment. WWTPs need to ensure there are adequate water tariffs and public subsidies that allow for financing additional investments for improved sewage sludge treatment and resource recovery.

The pyrolysis process produces syngas, bio-oil and biochar. This model is oriented toward making the business energy self-sufficient. The energy generated through pyrolysis is used within the plant for dewatering sludge. Figure 20 shows a schematic diagram of the business model dependent on pyrolysis for energy and biochar production. The plethora of end-uses for sewage sludge biochar make it an exciting opportunity, especially with the bonus of carbon sequestration (Canvas 14). Nevertheless, supporting regulations are needed to fully exploit its value and consolidate off-take markets. Until then biochar also provides a desperately needed alternate avenue for a safe and compact bio-solid disposal (GWI 2023a).

These business models are suitable for WWTPs serving 200,000 to 300,000 population equivalent or more with basic wastewater and sludge treatment facilities and without sludge storage capacities. These treatment plants incur higher operating and maintenance costs for transportation and sludge disposal and sludge treatment and recovering fertilizers provides additional revenue.

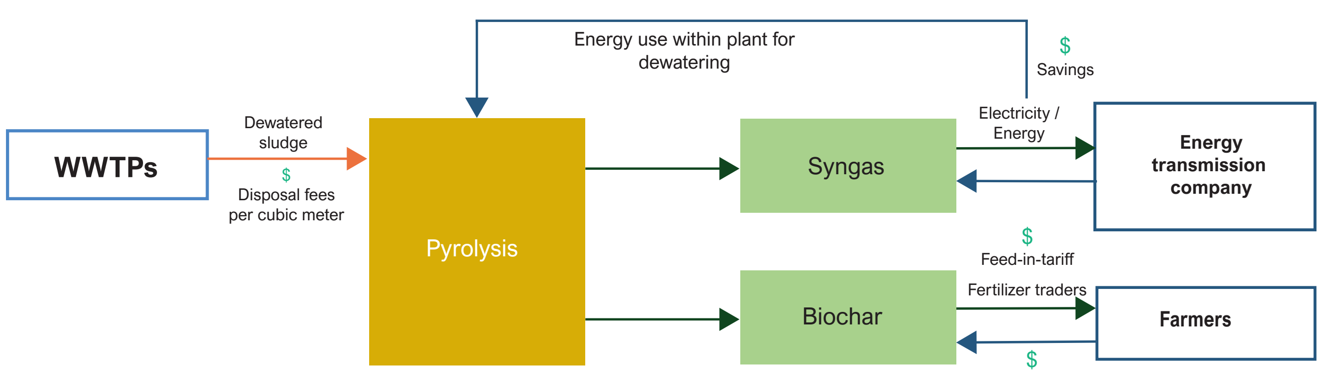


FIGURE 20. BUSINESS MODEL FOR RECOVERING ENERGY AND PHOSPHORUS (AND OTHER NUTRIENTS VIA BIOCHAR).

Source: Author's creation.

Partners
- Urban local bodies, public water utilities, WWTP operators
- Biogas and electricity transmission companies
- Local contractors
- Regulating bodies
- Fertilizer traders

Activities
- Pre-treatment and thickening sludge at WWTP
- Transportation of sludge from other WWTPs in case of regional plants
- Capturing phosphorus or biochar
- Using electricity within the plant for drying sludge or feeding to the grid
- Marketing and sales
- Obtaining permits and certifications for fertilizer products

Resources
- Establishing and commissioning plants
- Pre-treatment and thickening sludge
- Use of thermal hydrolysis

Value propositions
- Energy recovered making plants more energy efficient
- Savings from disposal costs
- Recovering potentially high-value fertilizers and biochar
- Cost recovery in terms of maintenance of the WWTP

Customer relationships
- Direct contact with municipalities and WWTP operator
- Direct networking with fertilizer traders

Channels
- Contractual agreements for establishing and operating plants
- Connections to the power grids

Customer segments
- Water utility services and municipalities
- Energy companies
- Fertilizer traders and their networks of wholesalers and retailers

Cost structure
- Capital costs: modular phosphorus recovery units
- Salary, rent, interest
- Struvite collection, storage and marketing costs
- Transaction costs related to penetrating fertilizer value chains with small phosphorus volumes
- Research and development, validation, licensing and certification

Revenue streams
- Revenue from electricity, energy (heat), biogas and fertilizer sales
- Tipping fees
- Cost savings from disposal fees
- Carbon credits

Environmental and social costs
- Labor health risks might arise due to handling sewage sludge and other waste streams
- Uncertain acceptance of products by traders and farmers

Environmental and social benefits
- Near or close to zero sludge disposal required
- Fewer health issues from reduced sludge to waterbodies and groundwater
- Bioavailability of micro-nutrients for soil amendment using biochar

CANVAS 14: RECOVERY OF PHOSPHORUS, BIOCHAR AND ENERGY THROUGH PYROLYSIS

Case Studies

Homburg and Linz, Germany

The Eliquo Water Group and PYREG formed a partnership for recovering energy and valuable fertilizer substrates (biochar) from sewage sludge in two WWTPs in Homburg and Linz-Unkel. Eliquo provides the technology for thermal energy (ELODRY®) while PYREG is the technology provider for recovering phosphorus via pyrolysis. Both have patented technologies that are complementary and support an autothermic process generating phosphorus of superior quality. A brief description of the two plants in operation is provided in Table 14.

TABLE 14. OPERATION PLANTS OF ELIQUO AND PYREG IN GERMANY.

	Homburg wastewater treatment plant[a]	**Linz-Unkel wastewater treatment plant**[b]
Client and design capacity	EVS - Saarland Waste Disposal Association Capacity of 75,000 PE up to 60,000 m^3/day of wastewater, creating around 1,400 t/a dry residue of MSS	Linz-Unkel Joint Waste Management Association Capacity of 30,000 PE
Contract value	EUR 1.5 million	EUR 1.4 million
Project description	The PYREG® module reduces the volume of sewage sludge by 90% and converts it into a high-quality fertilizer raw material with a high proportion of plant-available phosphorus. In this project, ELIQUO STULZ GmbH was the subcontractor to PYREG GmbH providing EloDry® NT32 for low-temperature belt drying and was responsible for implementing the treatment facility	PYREG® module used reduces the volume to around 40% of the original volume with simultaneous full conversion to a high-grade fertilizer material. Same as with Homburg WWTP, Eliquo STULZ GmbH has provided the EloDry® and operates the plant.
Process flow	In general, thermal hydrolysis processes help to improve the anaerobic digestion of sewage sludge, which is required to sanitize the sludge, while increasing gas yield, reducing residual biosolids (and relate digestate management costs), and improving dewaterability. The high ammonium and phosphate release into the liquid phase (digestate) from anaerobic digestion can be valorized through pyrolysis resulting in (nutrient rich) biochar. The need for digestate valorization is important because the application potential of digested sewage sludge as such in agriculture is limited due to concern regarding the potential presence of organic contaminants, pathogens, microplastics, etc. which processes like (dry) pyrolysis or hydrothermal carbonization (wet pyrolysis) can eliminate at high temperatures. In the PYREG PX 750 process, for example, the sewage sludge is dried using an (energy self-sufficient) drying belt system which feeds the sludge into the PYREG reactor where it is carbonized within a few minutes at temperatures of 500°C to 700°C. Phosphorus recovery can reach over 90%. The generated biochar (phosphorus content of about 15%) can be monetized on carbon markets as a Negative Emissions Technology (NET).[c]	

[a] Eliquo. https://www.eliquo-tech.com/en/references-details.html?articles=homburg (accessed on September 28, 2022

[b] Eliquo. https://www.eliquo-tech.com/en/references-details.html?articles=linz-unkel (accessed on September 28, 2022)

[c] https://pyreg.com/ (accessed on June 6, 2023)

Bioforcetech, California, USA

Based in California, Bioforcetech (BFT) partnered with PYREG GmbH, Germany in 2016 to initiate a full-scale installation to recover phosphorus and energy in a WWTP managed by Silicon Valley Clean Water).[82, 83] In 2017, operations were initiated and in 2019 they received a US pyrolysis permit.

The BFT system is comprised of a biodryer and a phosphorus series pyrolysis unit which can individually handle both dry and wet material and produce biochar from sewage sludge. The biodryer patented by BFT is necessary to reduce the moisture content and requires 50% less energy than traditional processes. Heat from thermophilic bacteria cultivated within the biodryer dries biosolids from 80% moisture content to 10–20% moisture content. The dried sludge complies with Class A biosolid standards. The second step is a phosphorus series pyrolysis system that transforms biosolids and organic waste streams such as food waste and green waste and converts them into biochar and renewable energy. The self-sustained and automated process ensures a high-quality biochar output without the need for fossil fuels.[84]

[82] Pyreg biochar (from sewage sludge) is registered as a fertilizer in Sweden (PYREGphos generated from Hammenhög wastewater treatment plant). Although sewage sludge biochar has received European Biochar Certification (EBC a voluntary standard), it is yet to be included in current EU Fertilizing Products Regulation STRUBIAS proposals.

[83] Bioforcetech. https://www.bioforcetech.com/pyrolysis.html (accessed on September 28, 2022).

[84] Bioforcetech. https://www.bioforcetech.com/biodryer.html (accessed on September 28, 2022)

6. OVERVIEW OF BUSINESS MODEL ATTRIBUTES

Table 14 shows the different requirements and attributes for successfully implementing these business models. The table indicates that investments and operating and maintenance costs required for nutrient and soil amendments recovery are low compared to energy recovery models. The applicability of these models for emerging and developing countries depends on the country's context (ADB 2012). Energy recovery models through sludge digestion and co-incineration are highly applicable. Land application is also feasible using sludge digestate and composting. The ADB study suggests that coal substitution, composting and gasification are feasible in China, provided the necessary regulations and infrastructure are in place. Careful consideration of these attributes is important when planning resource recovery and reuse pathways. Another key factor can be public perceptions. Despite numerous biochar projects being operational globally, only a few use biosolids as feedstock thus far – primarily due to regulatory barriers and a negative public perception of the feedstock (GWI 2023a).

6.1 Drivers for sewage sludge recovery and reuse pathways in Europe and USA

While there are sludge management facilities in Europe, the sector is still developing as numerous companies are developing improved solutions. Regulatory drivers, renewable energy incentives and government agendas promoting improved technologies are supporting these innovations (GWI 2012). Landfill bans, restrictions on direct use and inappropriately treated sludge in agriculture are landmark regulations forcing industries to look for alternatives or face significant fees. Denmark, Germany, the Netherlands, the Scandinavian countries and Switzerland have imposed restrictions on agricultural applications and these countries are switching to alternatives or implementing innovative technologies. For example, mono-incineration, advanced digestion, co-incineration in the cement industry and phosphorus recovery are among the disposal routes local authorities are planning for or have already implemented.

Local authorities in Germany are restricting the use of sewage sludge in agriculture (Box 3) while supporting alternative sludge treatment through an increase in sludge storage facilities, improved dewatering, and scaling up anaerobic digestion and mono-incineration. The move from land application to incineration will entail a higher cost for farmers to replace the sludge and the taxpayer (ca. Euro 7-8/household/year; see also Table 5) but not reduce the emphasis on resource recovery. In contrary, the 2017 amendment of the Sewage Sludge Ordinance (AbfKlärV) provides for the first-time comprehensive specifications for phosphorus recovery from sewage sludge or sewage sludge incineration ash, and set as target a phosphorus content reduction of at least 50 % (based on sewage sludge TS) or of at least 80 % from sewage sludge incineration ash (Roskosch and Heidecke 2018). Figure 21 shows the 2032 phosphorus (P) recovery obligations and possible recovery methods for wastewater treatment plants serving more than 50,000 capita. According to this, sewage sludge must undergo phosphorus recovery if the phosphorus content in the sewage sludge reaches or exceeds 2% of the total solids matter (TS). Estimates show that, depending on regional conditions, wastewater charges may increase through mandatory phosphorus recovery by around Euro 3 to 11/person/year. Soil application will no longer be permitted for plants of this size, but remain an option for smaller plants, e.g., in more rural settings where co-incineration capacities are lacking.

TABLE 15. REQUIREMENTS AND ATTRIBUTES FOR SUCCESSFULLY IMPLEMENTING BUSINESS MODELS.

RRR-Pathways for Sewage Sludge	Main attributes									
	Technology	Investment costs	O & M costs	Land requirement	Volume reduction	Technical complexity	Energy recovery	Nutrient recovery	Carbon foodprint	Pathogen reduction
BIOSOLIDS/ORGANICS										
Stabilized sludge (liquid/solid)	Chemical stabilization	Low	Medium	Medium	Low	Low	None	High	Medium	Medium
Dewatered/dried biosolids	Sand drying beds/mechnanical process	Low	Low	High	Low	Low	None	Medium	Low	Low
Co-composted sludge	Composting	Low	Low	High	Low	Low	None	Medium	Low	Medium
Pelletized sludge	Pelletizing	Medium	Medium	Low	Medium	Medium	None	Medium	Medium	Medium
NUTRIENTS										
Phosphorus	Anaerobic digestion	Medium	Low	Low	Medium	Low	None	Low	Low	Medium
	Incineration	High	High	Low	High	Medium	None	High	Medium	High
ENERGY										
Bio-methane	Anaerobic digestion	Medium	Low	Low	Medium	Medium	Medium	Low	Low	Medium
Thermal energy	Mono-incineration	High	Medium	Low	High	High	High	High	Low	High
Alternative fuel	Co-incineration with solid waste	High	Medium	Low	High	Medium	High	None	Low	High
	Co-incineration in thermal power plant	High	Medium	Low	High	Medium	High	None	Low	High
	Co-incineration in cement plant	High	Medium	Low	High	Medium	High	None	Low	High
Electricity	Gasification/Pyrolysis	High	High	Low	High	High	High	None	Low	High
FERTILIZER & ENERGY										
Organic fertilizer & energy recovery	Anaerobic digestion, dewatering, drying	Medium	Medium	Medium	Medium	Medium	Medium	High	Low	Medium
Phosphate & thermal energy	Mono-incineration, P-extraction	High	High	Low	High	High	High	Medium	Medium	High
Struvite & energy recovery	Anaerobic digestion, P-stripping	High	High	Low	High	High	High	Medium	Medium	High
Phosphorus/biochar & energy recovery	Pyrolysis, P-extraction	High	High	Low	High	High	Medium	High	Low	High

Source: Author's creation

BOX 3: SEWAGE SLUDGE APPLICATION ON SOILS ACCORDING TO THE GERMAN SEWAGE SLUDGE ORDINANCE

The amount of sewage sludge that may be used in Germany in agriculture for fertilization purposes is limited to prevent the transmission of pathogens (like salmonellae) and chemical contaminants. Thus, according to the 2017 amended Sewage Sludge Ordinance (AbfKlärV), sludge, sewage sludge mixtures or sewage sludge compost are only allowed to be applied on or introduced into soils if certain heavy metal and organic contaminants threshold values are not exceeded. According to the Sewage Sludge Ordinance, up to 5t of sewage sludge dry matter per hectare may be applied within three years, or 10t once. In principle, only sewage sludge originating from municipal wastewater treatment plants may be used, not industrial or smaller plants if the type of sludge differs. The application of sewage sludge is generally prohibited in organic farming, in forests, gardens, on grassland and arable land, in fruit and vegetable cultivation as well as in water conservation areas and nature reserves, but can be used e.g., for maize grown for biogas production. Rules and quantities can differ slightly depending on the frequency of application as well as for sewage sludge mixtures and sewage sludge composts.

Source: http://www.bgbl.de/xaver/bgbl/start.xav?startbk=Bundesanzeiger_BGBl&jumpTo=bgbl117s3465.pdf

In the North American sludge management market, the main drivers are costs, regulations and public perceptions associated with sludge management. The price of sludge disposal in landfills is high and therefore municipalities are looking for technologies that can reduce the volume of sludge, increase biogas production and reuse energy for sludge drying. Regulations are continuously influencing treatment and disposal routes. For example, regulations related to sludge incineration might have a marked effect on sludge movement. Similarly, 50% of the sludge reuse in the US is for land applications, which is possible due to both stringent regulations that local authorities monitor and public opinion on abiding by these regulations.

Although there are many beneficial uses for biochar, for the European market the unfavorable regulatory landscape has historically been a significant constraint. Changes to the regulatory climate could help the market to open up. Although the EU's Fertilizer Regulation update (implemented in July 2022) excluded sewage sludge as an acceptable biochar feedstock, various EU member states such as the Czech Republic, Denmark and Sweden have recently taken matters into their own hands, each introducing regulation which allows sewage sludge derived biochar to enter as fertilizer their markets (GWI 2023a).

Up until recently the drivers for phosphorus or ammonium recovery have been maintenance costs, pollution control and regulatory compliance. The potential for contributing to economics, greenhouse gas mitigation, carbon and nutrient neutrality are now additional incentives making ammonia recovery for reuse more economically attractive, especially as the current process of generating ammonia, the Haber-Bosch process, is wholly dependent on a fossil fuel input (GWI 2023a).

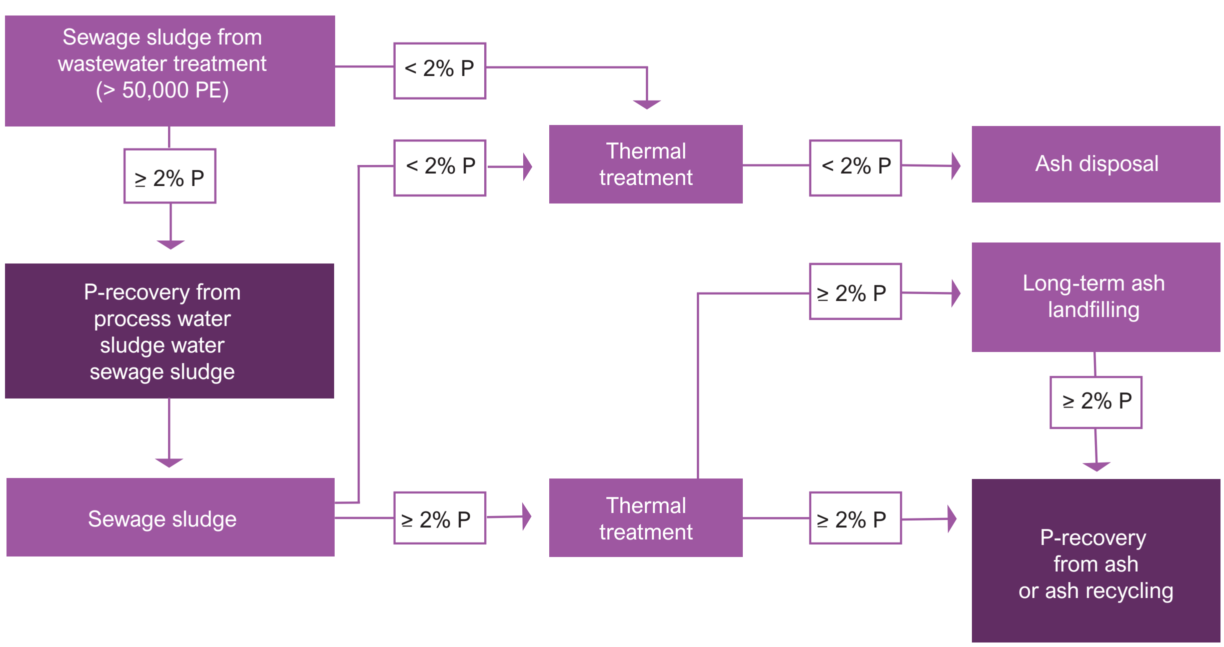


FIGURE 21: GERMAN SEWAGE SLUDGE TREATMENT TARGETS FOR 2032 DEPENDING ON PHOSPHORUS CONTENT

Source: AbfKlärV (Roskosch and Heidecke 2018)

6.2 Requirements for adaptation to and in the Global South

The cases analyzed in this study are from existing businesses operating in Europe and North America and some in the Global South. The main drivers in Europe and North America are regulatory frameworks, public opinion and environmental risk awareness, technological innovations for cost reductions, and the need to increase the efficiency of resource recovery. In the Global South, lower awareness about technological options and business models, and limited willingness to regulate the sector (positive and negative incentives) are often cited reasons for limited progress and business development.

Business models related to recovering soil nutrients and organic fertilizers require stringent regulations and positive public perceptions before there is wider acceptance and use of recovered products for soil amendment. The transferability of phosphorus recovery or thermal treatment of sewage sludge for producing pellets requires access to technology. Access to technology is a key requirement once public awareness and basic infrastructure can be facilitated before it will be attractive to technology providers. Emerging economies in the Global South have started investing in wastewater management infrastructure for treatment, for example, in China, India and Latin American countries. However, the basic infrastructure for wastewater treatment is still lacking in big cities which is quite essential for establishing businesses.

The critical step for emerging economies is to develop a wastewater management strategy and link it to a circular economy framework. Treatment of wastewater and reuse of the reclaimed water, followed by sewage sludge treatment and management, should be integrated into the strategy. To drive wastewater management, economies need to plan for the following:

- **Supporting policies and regulations.** Policies and regulations are critical to positively (or via punitive fees) incentivize alternative sludge management options and favor establishing utilities for wastewater management with resource recovery and reuse pathways (as in Singapore and Mexico).

- **Access to finance.** Upfront investments and professional operation and maintenance of treatment plants are the two main challenges of WWTPs. Municipalities and public agencies should integrate a costrecovery framework into the implementation of their WWTPs.

- **Determine the scale of intervention**. Plan for centralizedordecentralizedmscale of operations based on which RRR operations can be proposed.

- **Define an institutional framework and management strategies by establishing organizations**. Along with policies and regulations, suitable organizations to manage projects are of utmost importance. For example, public sector agencies that took the lead in managing projects include the Public Utilities Board (Singapore), Mekorot Water Company (Israel), South Australian Water (Australia), eThekwini Water Services (South Africa), Water Development Department (Cyprus), City of Stockholm and Stockholm Vatten (Sweden), Orange County Water and Sanitation District (California), and CONAGUA (Mexico).

- **Mechanisms to enhance public perception.** Government agencies, NGOs and community-based organizations have a major role to play in improving public perceptions of wastewater systems. International experience shows that including politicians and public figures, targeted interventions through subsidies, mass media campaigns, and positive messages from successful projects help win public confidence and ensure acceptance.

Although countries in the Global South are working toward renewable energy, access to technology and capacity to manage it, can be a determining factor in business implementation. Similar to the situation with nutrient recovery, infrastructure is a necessary condition for upgrading wastewater treatment plants with the necessary energy recovery technologies. For example, opening waste-to-energy plants would allow for co-incineration, and regulations for the use of sewage sludge in cement plants would allow for the transferability of business models.

We identified three important potential drivers/obstacles toward energy recovery and recovering soil amendments: regulations, public awareness, and access to technology. These three are complemented by another three, namely existing infrastructure, skilled labor, and access to finance. In some countries, existing infrastructure and the availability of skilled labor can be a challenge, while for some emerging economies, there is infrastructure and skilled labor which bodes well for establishing new and upgrading existing businesses. Since technology is a strong requirement, countries need to regulate technology procurement with long-term agreements. Long-term contracts would further help governments and local authorities provide more infrastructure for scaling up a business. Table 15 shows a heat map of these six parameters applied to the discussed business models.

TABLE 16. HEAT MAP OF TRANSFERABILITY OF THE BUSINESS MODELS TO THE GLOBAL SOUTH.

Hierarchy	Business Model	Regulations	Existing Infrastructure	Public Awareness	Access to Technology	Access to Finance	Skilled Labor
Recovering biosolids from sewage sludge	**Business Model 1:** Formal sludge collection and treatment for use	High	Not decisive	High	Not decisive	Not decisive	Not decisive
	Business Model 2: Informal sludge collection and treatment for use	High	Somewhat	High	Somewhat	Not decisive	Not decisive
	Business Model 3: Producing co-compost	High	Not decisive	High	Not decisive	Not decisive	Not decisive
	Business Model 4: Producing sludge pellets	High	High	High	Very high	Very high	Somewhat
Recovering phosphorus from sewage sludge	**Business Model 5:** Recovery of phosphorus from incinerated sludge ash	High	High	High	High	Very high	Not decisive
	Business Model 6: Recovery of phosphorus from anaerobic sludge digestate	High	High	High	High	Very high	Somewhat
Recovering energy from sewage sludge	**Business Model 7:** Energy recovery from anaerobic digestion	Very high	Very high	Very high	Somewhat	Very high	Very high
	Business Model 8A: Mono-incineration of sewage sludge	Very high	High	Very high	High	Very high	Very high
	Business Model 8B: Co-incineration of sewage sludge	Very high	High	Very high	High	Very high	Very high
	Business Model 9: Energy recovery from gasification and pyrolysis	Very high	High	Very high	High	Very high	High
Hybrid models	**Business Model 10:** Recovery of biosolids, biomethane and electricity from sludge digestion	High	Somewhat	High	High	Somewhat	High
	Business Model 11: Recovery of energy/electricity from sludge incineration and phosphorus from the ash	High	High	High	High	Somewhat	Very high
	Business Model 12A: Recovery of phosphorus and energy from anaerobic digestion	High	High	High	High	Somewhat	Very high
	Business Model 12B: Recovery of phosphorus, biochar and energy through pyrolysis	High	High	High	High	Somewhat	Very high

Legend: Increasing transferability challenges

Not decisive · Somewhat · High · Very high

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ANNEX 1. BUSINESS MODEL CANVAS (GUIDANCE)

Partnerships

Who are the main partners?

What resources are derived from the partners?

Which activities do the partners perform?

Activities

Which activities are required for creating the value proposition?

What are the channels required and how would partners develop customer relationships?

Which activities would generate revenue for the business?

Resources

What resources are needed for creating the value of the goods and services?

What are the resources needed for developing customer relationships and channels?

What are the resources needed for revenue generation?

Value propositions

What bundle of products and services are you offering to each customer segment?

What is the value added for the customer?

What are the problems solved through the business?

Which customer needs are satisfied?

What is unique about the product or service compared to others in the market?

Customer relationships

What type of relationships does each of our customer segments expect to establish and maintain?

How are they integrated with the rest of our business model?

Channels

What are the channels we use to reach customer segments?

How are the channels integrated with customer routines?

Customer segments

For whom are we creating value?

Which goods and services are customers looking for?

Who are the most important customers?

Cost structure

What are the most important costs in the business model?

Which elements derive the costs?

How much does each cost item contribute to the overall costs?

Revenue streams

What are customers willing to pay?

How much are the customers currently paying, how are they paying and for what?

How much does each revenue stream contribute to the overall revenue if there are different products and services?

Social and environmental costs

What are the potential environmental risks of doing business?

What are the potential risks to the health of workers and society?

Social and environmental benefits

What are the potential benefits the business can bring to the environment and what health benefits for society?

Can the business model improve health and reduce health hazards?

Does it create new jobs?

Source: Otoo and Drechsel 2018

ANNEX 2. BUSINESS PERFORMANCE POTENTIAL (KEY TO SCORES)

INDICATOR	GUIDING QUESTIONS	PARAMETERS	SCORE
Profitability and cost recovery	What is the level of operational profit and cost recovery achieved by the business model on an annual basis?	Loss-making	1
		Break-even	2
		Profit	3
	How many revenue streams does the business model depend on and how strong are these revenue line items?	One strong revenue source	1
		Two or more revenue sources with one strong revenue line	2
		Two or more revenue sources with two strong revenue lines	3
	How many of these factors represent a risk of increased costs to the business model? Factors are: 1) high worker and managerial skill requirements, 2) diverse customer base, 3) diverse products, 4) need for R&D and 5) self-distribution of product to end customer	More than 3 factors applicable	1
		2–3 factors applicable	2
		0–1 factor applicable	3
Social impact	How many jobs are created by the business model compared to the range of all the business cases within the same section (energy or nutrients or water)?	Low	1
		Medium	2
		High	3
	Number of people with increased positive health impacts from the business model compared to the range of all the business cases within the same section (energy or nutrients or water).	Low	1
		Medium	2
		High	3
	On how many of these factors does the business model have an improved or increased positive impact? Factors are: 1) water security, 2) food security, 3) energy security, 4) improved living standards, 5) reduced government costs for waste management services (sanitation), health services and 6) gender	Meets 0–2 factors	1
		Meets 2–4 factors	2
		Meets more than four factors	3
Environmental impact	What quantity of waste is being processed and reused compared to the range of all the business cases within the same section (energy or nutrients or water)?	Low	1
		Medium	2
		High	3
	On how many of these factors does the business model have an improved or increased positive impact? Factors are 1) health of water bodies, 2) reduced greenhouse gas emissions, 3) soil fertility, 4) renewable sources of raw material and 5) reduced deforestation	Meets 0–1 factor	1
		Meets 2–3 factors	2
		Meets more than 3 factors	3

INDICATOR	GUIDING QUESTIONS	PARAMETERS	SCORE
Scalability and replicability	How many of these factors limit the replication potential of the business model elsewhere? Factors are 1) new technology, 2) policies and regulations, 3) strong institutional capacity, 4) specific waste availability 5) market demand and 6) ambiguity of product acceptance	Meets more than four factors	1
		Meets 3–4 factors	2
		Meets 0–2 factors	3
	What is the ease of scaling the business model vertically and horizontally?	Low potential for vertical AND horizontal scaling	1
		High potential for either vertical OR horizontal scaling	2
		High potential for vertical and horizontal scaling	3
	How easy is it to finance the business model elsewhere?	Investment is HIGH and financing is UNIQUE	1
		Investment is HIGH and financing is COMMON	2
		Investment is LOW and financing is UNIQUE	2
		Investment is LOW and financing is COMMON	3
Innovation	How innovative is the technology or process?	Known technology or process	1
		Relatively new to developing countries (technology transfer)	2
		New to the world	3
	How innovative are the partnership arrangements?	No partnerships required	1
		Partnerships within the same sector	2
		Partnerships crosscutting different sectors (PRIVATE-PUBLIC PARTNERSHIP, R&D, finance)	3
	How innovative is the product or value proposition?	Standard product and value proposition	1
		Relatively new product or value proposition	2
		New to the world	3

Source: Otoo and Drechsel 2018

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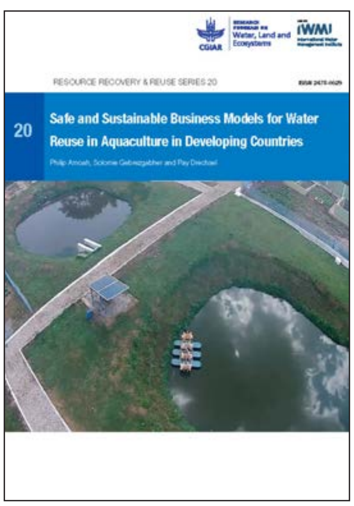

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