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CURRENT STATUS, CHALLENGES AND PROSPECTS OF SEWAGE SLUDGE VALORISATION FOR CLEAN ENERGY IN POLAND

AKTUALNY STAN WIEDZY, WYZWANIA I PERSPEKTYWY WYKORZYSTANIA OSADÓW ŚCIEKOWYCH W PRODUKCJI CZYSTEJ ENERGII W POLSCE

Abstract: The valorisation of sewage sludge (SS) is a practical approach for the production of chemicals, fuels and clean energy. In the past, sewage sludge disposal and management in the European Union (EU) typically involved landfilling, incineration, agricultural application, or bulk storage. With the prohibition of these techniques, novel processes are urgently required to address the growing stockpiles of sewage sludge particularly in nations with high demographics such as Poland. The most promising technologies for SS valorisation are the thermal conversion; pyrolysis, gasification, combustion and co-firing. However, SS valorisation is beset by numerous challenges. Consequently, this paper seeks to examine the current status, challenges and prospects of SS valorisation in Poland. The findings demonstrated that the treatment of municipal and industrial wastewater generates substantial quantities of sewage sludge (SS) each year. Currently, the SS is mostly utilized for agriculture, landfilling and bulk storage. The paper reports that municipal SS is the mostly utilized SS for agriculture, compost production, thermal conversion, bulk storage; whereas industrial SS is used for land reclamation and landfilling. However, the bulk of Polish SS is still not effectively and efficiently utilized. Therefore, the authors proffered prospective technologies such as co-firing and direct utilization of SS for future green electricity production as possible solutions. However, it is pertinent to state that the application of novel SS valorisation technologies will require adapting and adopting low carbon strategies and legal frameworks in the future.

Keywords: sewage sludge valorisation, clean energy, sustainability developement

Introduction

Sewage sludge (SS) is the heterogeneous residue produced from the processing of industrial or municipal waste water effluents in treatment plants [1, 2]. The treatment of SS involves several physical (mechanical), chemical, biological or various combinations [3] resulting in the production of large quantities of solid, semi-solid or liquid residues [4]. Consequently, the effluent sources and the physico-chemical or biochemical composition of treated SS is significantly determined by the selected treatment technique. In view of this, SS potentially consists of harmful inorganic, biodegradable, chemical constituents such as heavy metals, pharmaceuticals, pesticides, hormones and dioxins [5-7]. However, the biological fraction contains nutrient rich organic matter with potential applications in agriculture. Based on its constituents, SS is predominantly disposed, managed or utilized through traditional technologies such as landfilling, incineration, and bulk storage [8].

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Conversely, European Union (EU) regulations prohibit the proliferation of these methods due to their potential threats to human health, safety and environment (HSE) [9]. The protocols are largely targeted at reducing biodegradable wastes landfills, agricultural application, environmental accumulation of chemicals and costs of off-site disposal solutions for sewage sludge. Furthermore, increased population, high living standards and rising processing costs have geometrically increased sewage sludge production in Poland 540 thousand Mg [10]. Additionally, increased pressure on sewage treatment infrastructure has resulted in the search for more cost effective, efficient and environmentally friendly methods for SS disposal and management.

Hence, novel sewage conversion technologies are urgently required to address the current challenges encountered by wastewater treatment plants (WWTPs) in Poland [11]. One of the most promising approach for the valorisation of SS is the use of thermal conversion processes such as pyrolysis, gasification, combustion and co-firing technologies [10, 12]. This has the potential to create a circular economy from SS valorisation in sustainable chemicals, fuels and energy for future applications. However, the transition to the circular economy will require identifying and addressing potential challenges due to socio-economic, environmental and technological factors.

Therefore, the main objective of this paper is identify and examine the current status of SS valorisation for clean energy generation in Poland. It will also present an overview of the various challenges that will potentially hamper the valorisation of SS for clean energy generation. Lastly, the study will outline the future prospects of SS valorisation through various thermal conversion technologies.

Current status of sewage sludge in Poland

The Republic of Poland is a central European nation located east of Germany on the geographical coordinates 52°N 20°E with a total land mass of 312,685 km^2. The land mass comprises 2.71% water and 97.3% land with 3,070 km^2 of territorial boundaries shared with Belarus, Czech Republic, Germany, Lithuania, Russia, Slovakia and Ukraine. The land terrain consists of flat plains and mountains along the borders in the south which account for its temperate climate. The seasonal weather is typically characterized by moderate to severely cold, cloudy winter conditions with regular rainfall whereas summer conditions are mild with periodic showers and thunderstorms.

According to year 2016 estimates, Poland is inhabited by 38.5 million people comprising 96.90% Polish, 1.10% Silesian, 0.20% German, 0.10% Ukrainian, and others 1.70%. The economy of Poland is dominated by the Services sector with 55.60%, Industrial Manufacturing 41.10% and 3.30% Commercial Agriculture. The three sectors jointly account for USD$ 1.005 trillion of Poland’s Gross Domestic Product (GDP, Purchasing Power Parity). Consequently, the per capita income of the average Pole is estimated at USD$ 26,000 which buttresses the nation’s high living standards [13]. According to empirical studies, higher livings standards have significantly influenced the generation of municipal and industrial waste around the globe [14]. Similarly, Hoornweg et al. [15] posit that rising urban population has increased solid waste generation by tenfold around the globe. In addition, global estimates indicate solid waste generation will double from 3.5 million to 6 million Mg/day by 2025 exceeding environmental pollutants and greenhouse gases (GHGs) [15]. In corroboration, Matsunaga et al. [14] assert that rising solid waste generation prompted by rising wealth and population dynamics will increase pressure on current waste management systems. In addition, this will result in significant socio-economic, environmental, technological and geopolitical implications globally.

Consequently, it stands to reason that sewage sludge production in Poland is set rise to 706 thousand Mg (dry matter) in the future [10]. Table 1 presents data on the disposal, management and utilization of the total industrial and municipal sewage sludge produced from over 4,255 waste water treatment plants (WWTP) operating in Poland for the year 2014.

Table 1

Sewage sludge [Mg d.m.] production in Poland for 2014 [16]

Sewage sludge utilization	Industrial SS	Municipal SS	Total SS
Agriculture	20,940	107,222	128,162
Land reclamation	95,034	21,961	116,995
Compost production	1,707	46,330	48,037
Thermal conversion	80,184	84,237	164,421
Landfilling	103,736	31,503	135,239
Bulk storage	17,042	62,192	79,234
Other uses	92,789	202,537	295,326
Accumulated*	6,280,853	226,034	6,506,887
Grand Total	6,692,285	782,016	7,474,301

* Total annual SS accumulated on the WWTP on landfill areas

According to the data in Table 1, the treatment of wastewater in Poland resulted in 7.5 million Mg of municipal and industrial SS. As can be observed the amount of industrial SS (89.54%) is significantly higher than from municipal sources (10.46%). The marked difference may be due to the high volume of waste water generated from industrial manufacturing or service industry processes which account for approximately 96.7% of Poland's GDP. However, the low SS from municipal sources could also be due to the lack of extensive sewerage network, waste management systems or low sewage sludge per capita around municipal areas in the country. Lastly, the enforcement regulations from the government agencies require higher HSE standards in WWTP in the industry. This ultimately results in high volume, specialized treatment of waste water in SS.

Furthermore, Table 1 presents the sectorial utilization of treated SS in Poland. As can be observed, SS in Poland is utilized for agriculture, land reclamation, compost production, thermal conversion, landfilling, bulk storage, and other uses. The data indicates that municipal SS is mostly utilized for agriculture, compost production, thermal conversion, bulk storage, and other uses than industrial SS. However, land reclamation and landfill applications are the most predominant applications of industrial SS. Overall, the data indicates that municipal SS is more widely applied or utilized than industrial SS in Poland. This may be due to strict regulations on industrial SS due to harmful chemical based compounds such as pharmaceuticals and metal compounds [5-7].

Figures 1 illustrates the proportions of SS from municipal and industrial WWTPs utilized for various applications in Poland as deduced from Table 1. The data in Figure 1 indicates that the highest proportion or 29% of municipal SS is reserved (accumulated) on

WWTPs on landfill areas. Conversely, 13% is used as agricultural input for use as fertilizer while 11% is thermally converted for energy or energy related applications. In addition, the use of municipal SS also includes bulk storage (8%), compositing (6%), landfilling (4%), and land reclamation (3%). Lastly, the remainder (26%) of the SS has no clearly defined use. In summary, 71% of all SS produced from municipal WWTP in Poland is valorised for various applications. In contrast, the industrial SS is sparingly utilised for any applications. The data indicates that only 6% of all SS produced is utilised for utilized for agriculture, land reclamation, compost production, thermal conversion, landfilling, or bulk storage. The highest proportion (2%) of the SS is used for landfilling and land reclamation. Agriculture and compost production account for less than 1% in each case. This may be due either strict regulations on its usage or lack of incentive from legislation to valorise the large proportions of industrial SS.

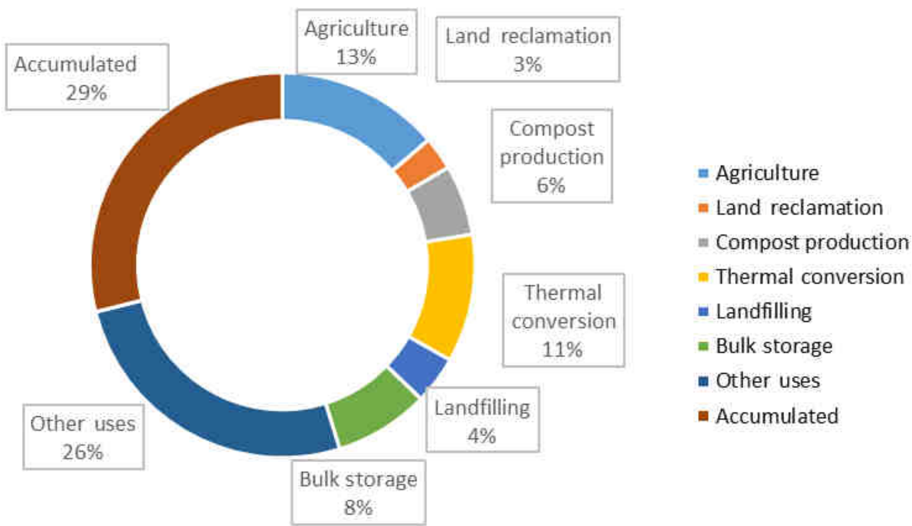

Fig. 1. Sectorial utilization of municipal SS in Poland

In view of this, Poland and the EU have enacted and instituted the legislative framework to not only monitor potential emissions and harmful substances from SS. It is envisage this will stimulate SS valorisation into useful chemicals, fuels and energy in the future. Table 2 presents an overview of the major legislative framework for SS disposal, management and utilization on the continent.

Based on these laws, the Polish government has established modalities to ensure the definition of wastes streams such as SS, recycling, reuse, recovery and safe disposal. Figure 2 presents an illustration of the approach as described in the Waste Framework Directive (WFD) (2008/98/EC) [17].

Table 2

Overview of major legislation on SS Management in the EU [17-29]

Law/Act	**Code**	**Date of enactment**	**National or EU**	**Summary of goals and objectives**
Sewage Sludge Treatment Directive	86/278/EEC [21]	12th June 1986	EU Directive	To determine rules for the use of sewage sludge as a fertiliser or agricultural purposes by farmers. To regulate and set limits for heavy metal concentrations in SS. To prevent adverse effects of SS human health, water and environment.
Urban Waste Water Treatment Directive	91/271/EEC [22]	21st May 1991	EU Directive	To protect the environment from the effects of urban waste water and industrial discharges. To determine guidelines for the collection, treatment and discharge of domestic, and industrial waste water effluents.
Landfill Directive	99/31/EEC [23]	26th April 1999	EU Directive	To prevent or reduce the negative effects of landfilling waste on the environment. To define the different categories of waste for landfills. To define wastes accepted in landfills, establish systems and operating permits. To introduce stringent technical requirements for landfills.
Waste Incineration Directive	2000/76/EC [24]	4th December 2000	EU Directive	To impose strict operating conditions and technical requirements on waste incineration plants and waste co-incineration plants in the European Union. To prevent or reduce pollution of the air, water and soil due to emissions form incineration or co-firing of waste. To set limits for pollutant emissions in air or water.
Implementation Directive on Landfills	2000/738/EC [25]	17th November 2000	EU Directive	To establish questionnaire for Member States to file reports on directive 1999/31/EC on the landfill of waste. To serve as implementation directive for the landfill directive and create modalities for effective implementation by EU Member states.
6th Community Environment Action Programme	EAP [26]	10th September 2002	EU Directive	To define the objectives of EU on the environment. To establish policy guidelines for the implementation of sustainable development strategies. To prioritize the efficient disposal, management and utilization of waste streams among EU Member states.
National Programme for Municipal Waste Water Treatment	NPMWWT [27]	16th December 2003	Polish National Directive	To establish the Polish national legal framework for the implementation of Directive 91/271/EEC of the EU. To create environment for the construction of sewage management systems, sewerage networks, and waste water treatment plants (WWTP).
Waste Framework Directive	2008/98/ECC [28]	12th December 2008	EU Directive	To establish legal framework for the treatment of waste in the EU. To define the basic concepts associated with waste management (WM). To determine principles for WM in the EU. To enact legislation for defining waste streams, responsibilities and penalties for Member States.
National Waste Management Plan 2014	NWMP [29]	31st December 2010	Polish National Directive	To establish a National Programme for waste reduction. To control pollutant emissions in the air, waters and soil. To establish mechanisms for recycling, reuse, landfilling or incineration of waste streams within the safety limits. To ensure implementation of Municipal Waste Water Treatment (NPMWWT) scheme.

Fig. 2. Schematic for Waste Management [17]

The “polluter pays principle” and “extended producer responsibility” described in the Waste Framework Directive requires novel sustainable technologies for waste valorisation. In addition, the directive mandates Member States to implement waste management plans and prevention programmes [17].

Prospects of sewage sludge valorisation

Based on WFD, there is an urgent need to explore technologies for the valorisation of SS in Poland. The use of thermal conversion technologies is considered one of the most effect methods for valorising organic wastes streams [30-34]. The most commonly used techniques are presented in Table 3.

Table 3

Potential routes for thermal valorisation of SS

Conversion technologies	**Process definition, Reaction conditions, and effects**	**Reaction products**	**References**
Pyrolysis	Thermal conversion (400-600°C) of carbonaceous feedstock in oxygen deficient conditions. Process ensures size reduction, increase in calorific value and energy density.	Biochar, activated carbons, bio-oil, biogas	[30-35]
Torrefaction	Mild pyrolysis process (200-300°C) for thermal pretreatment of carbon based feedstock. Process improves grindability, hydrophobicity, calorific value, and energy density	High heating value torrefied fuel, pellets	[36-38]
Hydrothermal carbonisation	Thermochemical process for converting organic feedstock into carbonaceous products under mild temperatures (180-350°C) and pressures (2-10 MPa)	Hydrochars, and aqueous by-product	[39-41]
Gasification	Conversion of feedstocks into clean synthesis gas (Syngas) at temperatures 650-1000°C. The syngas is used for producing chemicals, fuels or clean energy	Synthesis gas (syngas), hydrocarbons, biochar	[12, 42-44]
Combustion	High temperature (1000°C) conversion of feedstocks	Fuel gases for energy production	[45]

Other prospective technologies for SS valorisation include pyro-torrefaction, pyro-gasification, catalytic gasification, chemical looping gasification, vermicomposing, and conversion into plastics and pharmaceuticals. In addition, the large quantities of industrial SS can be directly utilized or co-fired with coal or biomass in existing power plants for energy production [45, 46].

Challenges of sewage sludge valorisation

The challenges of SS valorisation in Poland will be briefly described based on Social-Economic, Environmental and Technological implications. The socio-economic challenges will largely stem from public and government acceptance of product chemicals, fuels and energy produced from SS valorisation. The environmental challenges of SS valorisation may arise from the potential pollutant emissions, greenhouse gases (GHGs) and secondary wastes generated from conversion technologies such as combustion. Lastly, the technical challenges could potentially be due to solids management, low efficiencies of conversion processes, equipment corrosion due to SS components, and reduction of secondary wastes products. In general, the outlined challenges can be potentially addressed by adapting and adopting low carbon strategies augmented by legal frameworks for SS valorisation in the future. Emphasis will need to be focused on the sustainable conversion of industrial SS as this constitutes approximately 90% of the SS stock in Poland.

Conclusions

The main paper examined the current status, prospects and challenges of SS valorisation in Poland. The findings demonstrate that the treatment of wastewater effluent streams from municipal and industrial sources generates significant quantities sewage sludge. Currently, the treated SS is predominantly utilized for agriculture, landfilling and bulk storage. In addition, the analyses revealed that municipal SS is mostly utilized for agriculture, compost production, thermal conversion, bulk storage, whereas industrial SS is used for land reclamation and landfilling. Nonetheless, the bulk of Polish SS is not effectively and efficiently utilized. Therefore, the authors proffered prospective technologies such as co-firing and direct utilization of SS for green electricity production in the future as possible solutions. However, it is pertinent to state that the implementation of novel SS valorisation technologies will require adapting and adopting effective low carbon strategies and legal frameworks in the future.

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AKTUALNY STAN WIEDZY, WYZWANIA I PERSPEKTYWY WYKORZYSTANIA OSADÓW ŚCIEKOWYCH DO PRODUKCJI CZYSTEJ ENERGII W POLSCE

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Abstrakt: Aktualnie zagospodarowanie osadów ściekowych (OŚ) polega m.in. na wykorzystaniu ich jako paliwa do produkcji energii. W przeszłości osady ściekowe w Unii Europejskiej (UE), otrzymane z oczyszczalni ścieków, składowano, spalano w sposób niekontrolowany oraz wykorzystano do użyźniania gleby w rolnictwie. W związku z wprowadzeniem zakazu stosowania ww. sposobów ich utylizacji konieczne było poszukiwanie nowych metod, w szczególności w krajach o wysokiej liczbie ludności, jakim jest na przykład Polska. Jedną z obiecujących metod zagospodarowania osadów ściekowych mogą być takie procesy, jak piroliza, zgazowanie i spalanie, w wyniku których powstaną produkty chrakteryzujące się energetycznymi właściwościami. Jednakże prowadzenie tych procesów wymaga uwzględnienia społecznych, ekonomicznych, środowiskowych i technologicznych czynników. Dodatkowo, regulacje UE w zakresie zagospodarowania osadów ściekowych zakazują termicznego ich przekształcania bez prowadzenia efektywnych procesów wstępnych (tzw. „pre-treatment processes”). W pracy przedstawiono stan bieżący, wyzwania oraz perspektywy wykorzystania osadów ściekowych w procesie produkcji czystej energii.

Słowa kluczowe: waloryzacja osadów ściekowych, czysta energia, zrównoważony rozwój