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Sustainable Sewage Sludge Management Technologies Selection Based on Techno-Economic-Environmental Criteria: Case Study of Croatia

Dinko Đurđević [1,2,*], Saša Žiković [1] and Paolo Blecich [3]

[1] Faculty of Economics and Business, University of Rijeka, 51000 Rijeka, Croatia; sasa.zikovic@efri.hr
[2] Energy Institute Hrvoje Požar, 10001 Zagreb, Croatia
[3] Faculty of Engineering, University of Rijeka, 51000 Rijeka, Croatia; paolo.blecich@riteh.hr
* Correspondence: ddurdevic@eihp.hr; Tel.: +385-1-6326-145

Abstract: The management and disposal of sewage sludge is becoming a growing concern at the global level. In the past, the main goal was to completely eliminate sewage sludge since it was deemed a threat to humans and the environment, but recently different possibilities for energy generation and material recovery are emerging. Existing technologies such as incineration or direct application in agriculture contribute to quantity reduction and nutrient recovery but are unable to fully exploit the potential of sewage sludge within the frameworks of circular economy and bioeconomy. This paper developed a model within the PROMETHEE method, which analyses technologies for the sustainable management of sewage sludge, which could make the most from it. For the empirical part of the study, the Republic of Croatia was used as a country in which sewage sludge is increasing in quantity as a result of recent upgrades and expansions in the wastewater system. Incineration, gasification, anaerobic digestion, and nutrient recovery were analyzed as treatment concepts for the increased amounts of sewage sludge. The model reveals that the best solution is the material recovery of sewage sludge, using the struvite production pathway through analysis of selected criteria.

Keywords: sewage sludge; multicriteria decision; anaerobic digestion; incineration; gasification; material recovery

Citation: Đurđević, D.; Žiković, S.; Blecich, P. Sustainable Sewage Sludge Management Technologies Selection Based on Techno-Economic-Environmental Criteria: Case Study of Croatia. *Energies* **2022**, *15*, 3941. https://doi.org/10.3390/en15113941

Academic Editor: Attilio Converti

Received: 4 April 2022
Accepted: 25 May 2022
Published: 26 May 2022

1. Introduction

Population growth and urbanization alike generate substantial volumes of wastewater. The by-product of wastewater treatment is large amounts of sewage sludge. Sewage sludge is a complex heterogeneous mixture of microorganisms, non-degradable organic matter such as paper, plant residues or feces, inorganic materials, and moisture [1], which require sustainable and pollution-free treatment methods before final disposal.

Annual production amounts of sewage sludge have constantly been growing and will continue to do so in the future [2,3]. Large amounts of sewage sludge disposed of in the environment cause major problems such as increased odors, risk of pathogenic microorganisms, and pollution by traces of heavy metals [4]. Sustainable management of sewage sludge is a major concern in wastewater treatment plants due to the increasing urban population and tightening environmental legislation regarding conventional methods for sewage sludge disposal, such as the direct use in agriculture.

Houillon and Jolliet [5] analyzed the environmental impact of six sewage sludge management scenarios: agricultural application, wet oxidation, pyrolysis, incineration in cement kilns, fluidized bed incineration, and landfilling. Agricultural spreading achieves the lowest non-renewable primary energy consumption but also the highest greenhouse gases (GHG) emissions, along with landfilling. Hospido et al. [6] studied the environmental impact of three sewage sludge treatment scenarios: scenario 1 (anaerobic digestion, mechanical dewatering, and land application), scenario 2 (mechanical dewatering and incineration), and scenario 3 (mechanical dewatering, thermal drying, and pyrolysis). The authors concluded that land application of digested sludge is an acceptable option, as long as the heavy metal content is low. The most effective solution for sewage sludge includes energy and material recovery, but this depends on the specific circumstances.

Although sewage sludge represents only 1–2% of the treated wastewater volume, its disposal is complex and expensive. Sewage sludge treatment and disposal represent between 20% and 60% of the total operating costs in wastewater treatment plants [7,8]. In order to resolve the problem of sewage sludge and to minimize its negative impact on the environment, EU countries started to implement different treatment methods—from wastewater treatment (primary, secondary and tertiary wastewater treatment processes) to sewage sludge treatment processes, as shown in Figure 1. The research community is focused on developing new and advanced technologies for the treatment of sewage sludge, which would be capable of performing energy and nutrient recovery at the same time [9,10].

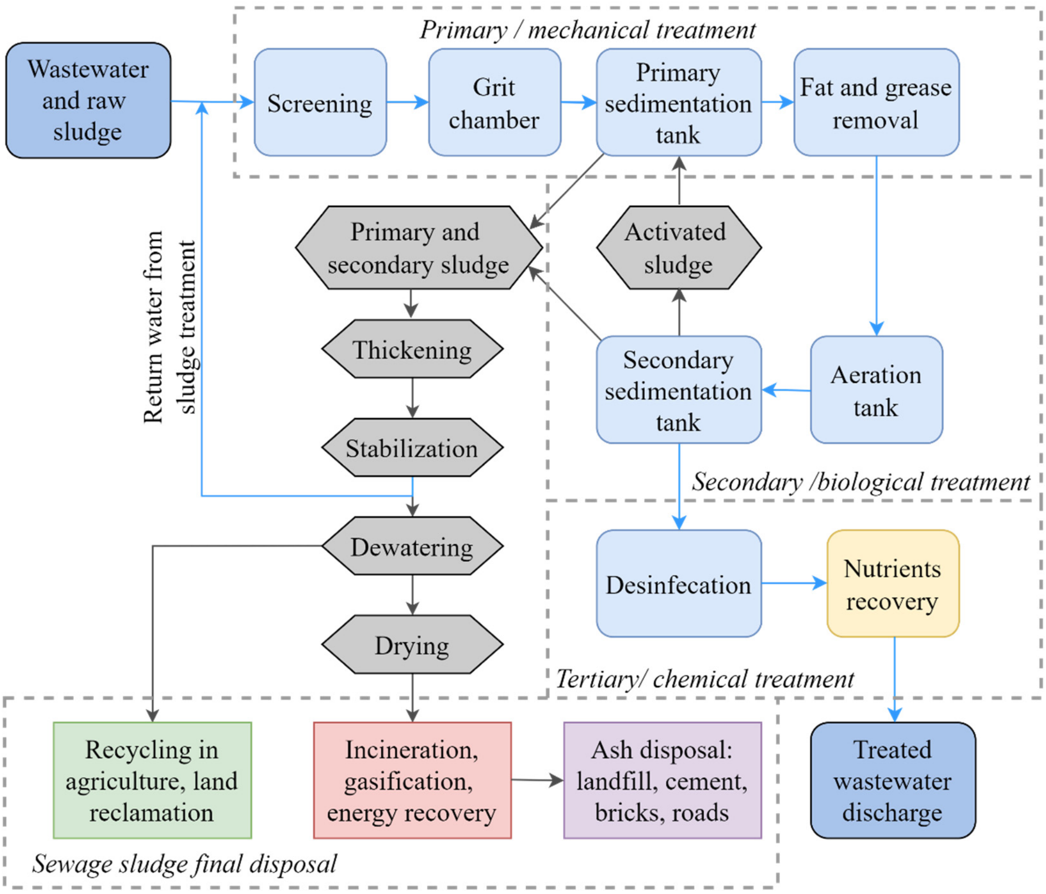

Figure 1. Wastewater and sewage sludge treatment methods in the EU.

The optimal treatment method depends on investment and operating costs, technological challenges, the sludge's physical properties, and the potential utilization of by-products. Sewage sludge disposal pathways must be designed within the waste management hierarchy presented in the Waste Framework Directive [11]. This Directive represents a desirable sequence of actions for waste reduction and management, which is prevention, minimization, reuse, recycling, energy recovery, and disposal as the least desirable option.

Energy content and nutrients (primarily nitrogen and phosphorus) are the two components of sewage sludge that are technically and economically viable for recycling. Energy utilization encompasses a wide range of possibilities, such as anaerobic digestion (AD) with biogas generation, co-digestion, incineration or co-incineration, pyrolysis, gasification, and supercritical (wet) oxidation. Bertanza et al. [12] ranked sewage sludge management strategies and concluded that incineration with energy recovery and digestion with application on agricultural soils were effective solutions for disposal of sewage sludge from wastewater plants with capacities larger than 500,000 PE (population equivalent). Lacroix et al. [13] investigated AD coupled to biogas production and determined that the energy requirements of wastewater treatment plants could be reduced by up to 35%. Raheem et al. [14] performed an extensive analysis of energy recovery from sewage sludge, including incineration, AD, gasification, and pyrolysis. They concluded that sewage sludge could be used as raw material for the production of various new materials within a biorefinery. Hao et al. [15] investigated the disposal of excess sewage sludge using incineration without prior AD. Disposal strategies of sewage sludge must be assessed using the sustainable approach and accounting for the recovery efficiency of the energy content and raw materials present in the sludge [16]. Taki et al. [17] and Bubalo et al. [18] investigated the possibility of using sewage sludge in the production of bricks. They concluded that sewage sludge could be mixed with conventional materials to produce sustainable construction bricks with good physical and mechanical properties. Moreover, sewage sludge can be blended with construction materials; it can be used for biofuel generation (biogas, synthetic gas, bio-oil) or as fuel for energy generation, for the recovery of nutrients (nitrogen and phosphorus), heavy metals, proteins, and enzymes.

Additionally, to examine the impact on the environmental impact of treatment methods for sewage sludge, Life Cycle Analysis (LCA) was extensively studied. Suh and Rousseaux [19] performed an LCA comparison of five scenarios, which included one stabilization process (composting, anaerobic digestion, or lime stabilization), one main process (landfill, incineration, or agricultural application), and sludge transport. The scenario achieving the lowest energy consumption and GHG emissions was found to be the combination of AD and agricultural land application. Johansson et al. [20] carried out LCA on four management strategies for sewage sludge: restoration of mining areas, composting for use on golf courses, hygienization for agricultural use, and supercritical water oxidation with phosphorus recovery. The authors conclude that the lowest environmental impact (biogeochemical emissions) is achieved with supercritical water oxidation, mainly due to the energy recovery from the sludge and the efficient utilization of nutrients.

The above-referenced studies agree that sewage sludge offers various possibilities for the utilization of energy and material content. However, the exact choice of the sewage sludge treatment method depends on many factors and constraints (sludge quantity, properties and composition, heavy metals and pathogens, energy and material reuse, location, policies and regulations, and public opinion). Therefore, it is necessary to perform detailed techno-economic analyses, which could reveal the advantages and outcomes of the specific sewage sludge treatment strategies. This paper's goal was to determine the most efficient sewage sludge treatment options in Croatia.

2. Materials and Methods

The selection of the appropriate technology for sewage sludge treatment is complicated by the many influencing factors and parameters: sludge quantities, properties and composition, energy and material content, available technology, capital investment, operation and maintenance costs, national policies and regulations, public acceptance, and others. Various uncertainties can arise at different stages of the project development, while the potential impact of wrong decisions can be far-reaching in terms of techno-economic performance, public health, and environmental footprint. Therefore, analytical and mathematical methods were developed to ease the decision-making for wastewater and sewage sludge projects. Multiple Criteria Decision Making (MCDM) refers to a decision-making method in the presence of many criteria, even conflicting ones. Generally, the decision-making problem arises when it is necessary to properly assess the relative importance of conflicting criteria and to arrange a system of priorities that would lead to good decisions.

Multicriteria methods have become standard tools in a complex decision system. There are several multicriteria methods that serve as the basis of many models developed by various researchers and for different purposes: from environment and energy management to medicine, agriculture, chemistry, and logistics [21]. In terms of waste management, there are several research topics examined. Makan and Mountadar [22] examined the different waste management schemes in small urban municipalities in Morocco based on the financial, technical, environmental, and social-institutional aspects. Lolli et al. [23] determined economic, environmental, and social aspects as the most important in the process of selecting the most appropriate waste management technology within natural parks. Similarly, Erceg and Margeta [24] examined different waste management options and their applicability in small islands, specifically food waste management. The options, in this case, were examined based on economic, environmental, local/wider social, and technological aspects. In more specific research, Makan and Fadili [25] analyzed composting technologies with the PROMETHEE method, comparing six different systems in terms of environmental, financial/economic, social, and technical criteria.

Based on the aforementioned research, it was established that there is no research connected with the sustainable management of sewage sludge. Therefore, the criteria for the ranking of sewage sludge treatment practices emerged after a careful literature overview and examination of existing literature on waste management topics. Three broad criteria clusters were determined: (1) Technological cluster, (2) Socio-economic cluster, and (3) Environmental cluster. Under the Technological cluster, three criteria groups were further chosen: (1.1) Technology, (1.2) Energy, and (1.3) Other. The Socio-economic cluster was subdivided into the following criteria groups: (2.1) Legal-administrative framework and (2.2) Costs. The Environmental cluster consists of (3.1) Emissions. The 6 groups of criteria were further subdivided into 19 criteria, as shown in Figure 2. The description of each of the 19 criteria is given in Table 1, along with the optimization goal: minimize or maximize.

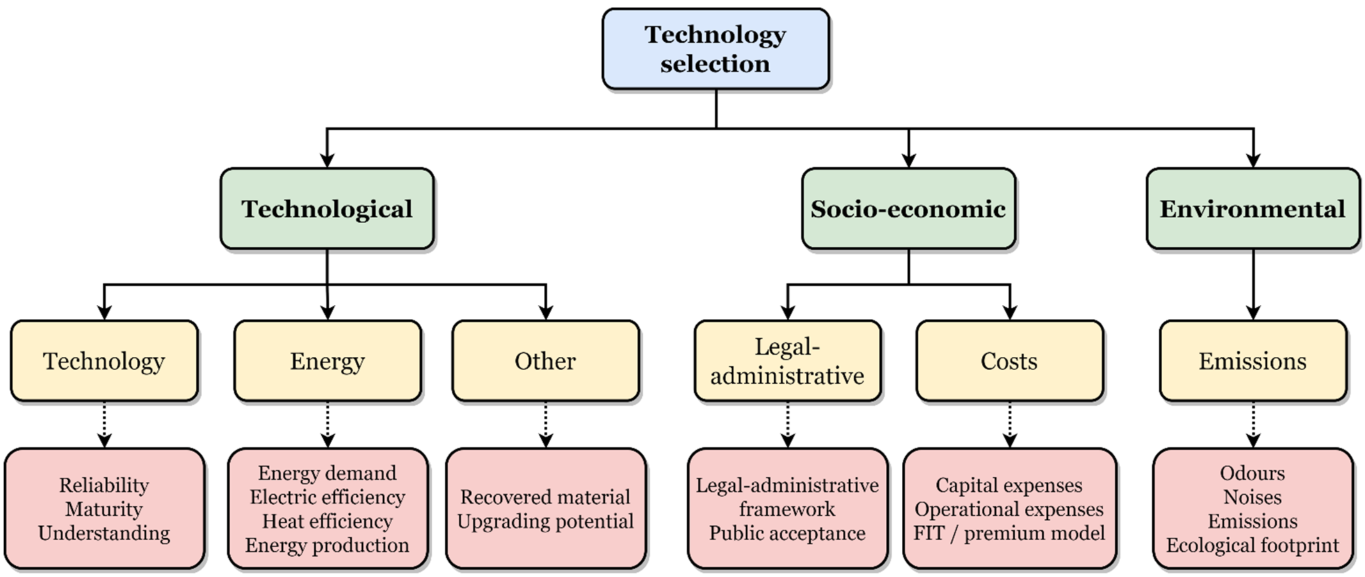

Figure 2. The criteria hierarchy used for assessment and comparison of sludge treatment methods.

Table 1. Description of criteria.

Cluster	Group	Criterium	Ranking	Goal	Description
Technological	**Technology**	Reliability	Qualitative (1–5)	Maximize	To evaluate the level of development for each sludge treatment technology (experimental phase, prototype, demonstration project, industrial-scale, number of installations) and the potential for further improvement.
		Maturity	Qualitative (1–5)	Maximize	To estimate the strengths and weaknesses of each sludge treatment technology and the potential for success and failure. The fewer the shortcomings and the more the advantages, the better the criterion measure.
		Understanding	Qualitative (1–5)	Maximize	Familiarity with using the technology: the extent to which experts are competent to perform tasks and use all of the capabilities offered by each technology.
	Energy	Energy demand	MWh/year	Minimize	Thermal and electricity demand for operation (digesters, reactors, incinerators, aeration, pumping, thickening, dewatering, etc.).
		Electric efficiency	%	Maximize	Electric self-sufficiency: how much electricity can be obtained from an in situ energy source (biogas, sewage sludge)? The ratio of generated electricity to total supplied electricity.
		Heat efficiency	%	Maximize	Thermal self-sufficiency: how much thermal energy can be obtained from an in situ energy source (biogas, sludge)? The ratio of generated thermal energy to total supplied heat.
		Energy production	MWh/year	Maximize	The amount of energy produced by recovering the energy content in the sewage sludge.
	Other	Recovered material	Qualitative (1–5)	Maximize	The potential of a sludge treatment technology to recover the material content from wastewater and sewage sludge.
		Upgrading potential	Qualitative (1–5)	Maximize	Potential for future development and upgrade of a sludge treatment technology (increase efficiency and yield, reduce material and energy consumption).
Socio-Economic	**Legal-Administrative**	Legal-administrative framework	Qualitative (1–5)	Maximize	The set of regulatory acts, bylaws, and directives establishing the scope of work, the responsibilities, and the expectations from the wastewater and sludge treatment technology.
		Jobs	Count	Maximize	Creating new job places.
		Public acceptance	Qualitative (1–5)	Maximize	The public opinion and attitude towards the effects of sludge treatment technology on the environment, landscape, local community, and health.
	Costs	Operational expenses	EUR/year	Minimize	OPEX: day-to-day expenses (energy, material, rent, equipment, payroll, insurance).
		Capital expenses	EUR	Minimize	CAPEX: capital expenditures (acquisition, upgrade, and maintenance of property, buildings, technology).
		Fit/Premium model	Qualitative (1–5)	Maximize	Use of feed-in tariffs for supplying the generated electricity into the grid.
Environmental	**Emissions**	Odors	Qualitative (1–5)	Minimize	Occurrence of unpleasant odors generated during plant operation. The goal is to maximize this criterion, meaning fewer odors emitted into the surrounding area.
		Noise	Qualitative (1–5)	Minimize	The noise pollution from plant operations negatively impacts human activity and animal life. The goal is to maximize this criterion, which means less noise propagating into the surroundings.
		Emissions	tonnes of CO_{2eq}	Minimize	Greenhouse gas emissions from plant operation, using the global warming potential (GWP) common scale for the greenhouse effect of different gases.
		Ecological footprint	Qualitative (1–5)	Maximize	Total environmental impact during the entire service life of the wastewater plant. The ecological footprint is a quantitative representation of the need for natural resources. The goal is to maximize this criterion, which indicates a lesser negative impact on the environment and human health.

Qualitative rankings: 1 = very bad, 2 = bad, 3 = neutral, 4 = good, 5 = very good.

The ranking is presented in qualitative (score 1–5, where 1 is the lowest and 5 is the highest grade) and quantitative terms (specific unit). The qualitative segment is prone to subjectivity, while it is determined and based on the author's experience in the observed field and state-of-art in the observed country, in this case, Croatia. In order to retain as much objectivity as possible, and with the lack of existence of observed technologies in Croatia, interviews with national experts who are familiar with observed technologies and are experts in the fields of climate and environment protection (5 experts) and waste management (6 experts) were conducted. This enabled determination of specified criteria. In the following sections, these are referred to as "Communication with experts", while the entire questionnaires and responses are provided in the Supplementary Materials.

Generally, multicriteria decision-making methods work with quantitative data but exhibit difficulties when it comes to qualitative data. As a remedy, the existing PROMETHEE method facilitates decision-making based on qualitative data, which is often the case with real-world ventures. The present study employs the PROMETHEE method for its capability of making multicriteria decisions based on quantitative and qualitative data with the final goal of determining the most effective technologies and solutions for sewage sludge treatment [26].

The PROMETHEE method offers two types of ranking systems based on the chosen priorities: partial ranking (PROMETHEE I) and complete ranking (PROMETHEE II). Priorities are obtained by comparing possible options in pairs, where the options are ranked from the best to the worst. The partial ranking system consists of positive and negative rankings. Positive ranking (Phi^{+}) measures the level of priority advantage for an option (a) when compared against the remaining options ($n - 1$). This is a general measure of the strengths of option (a). The higher the $Phi^{+}(a)$, the better the option

$$Phi^{+}(a) = \frac{1}{n-1}\sum_{b \neq a} \pi(a,b) \tag{1}$$

Negative ranking (Phi^{-}) measures the level of priority disadvantage for an option (a) when compared against the remaining options ($n - 1$). This is a general measure of the weaknesses of option (a). The smaller the $Phi^{-}(a)$, the better the option

$$Phi^{-}(a) = \frac{1}{n-1}\sum_{b \neq a} \pi(b,a) \tag{2}$$

The partial ranking system of PROMETHEE I is the intersection between the positive ranking and the negative ranking. Here, option (a) receives priority over option (b) if and only if it shows an advantage both in the positive and the negative ranking

$$a\ P^{I} b \ \text{ iff } \ Phi^{+}(a) \geq Phi^{+}(b) \ \text{ and } \ Phi^{-}(a) \leq Phi^{-}(b) \tag{3}$$

where P^{I} denotes the priority in the PROMETHEE I ranking system. The overall ranking (Phi) represents the difference between the positive ranking and the negative ranking

$$Phi(a) = Phi^{+}(a) - Phi^{-}(a) \tag{4}$$

Therefore, the overall ranking $Phi(a)$ combines the strengths and the weaknesses of an option in one single result. The overall ranking $Phi(a)$ can be either positive or negative. The larger the $Phi(a)$, the better the option. The complete ranking system of PROMETHEE II comprises the comparisons between all the observed options. This ranking system calculates and compares the overall priorities of the options, which are obtained from the partial positive and negative rankings. An option (a) is said to have a priority advantage over an option (b) if and only if its overall ranking is higher

$$a\ P^{II} b \ \text{ iff } \ Phi(a) > Phi(b) \tag{5}$$

where P^{II} denotes the priority in the PROMETHEE II ranking system.

In order to easily obtain data and graphical results, the Visual PROMETHEE and GAIA software was used.

3. Sewage Sludge Treatment Technologies

3.1. Sludge Treatment Practices in Europe

EU member states rely on different sewage sludge disposal practices: application on agricultural lands, disposal in landfills and long-term storage, composting, land reclamation, incineration, and others [26–30]. The average sewage sludge production rate is between 20 and 25 kg of dry mass per person per year. Across the EU-28 member states, the total amount of sludge produced was 9.2 million tonnes of dry mass in 2018. However, EU member states are using different sludge management models and disposal practices, depending on various economic, social, technological, and environmental factors. The most widespread disposal practices for sewage sludge are application as fertilizer on agricultural lands (47.5%), incineration (27.2%), composting (11.4%), land reclamation and recultivation (8.3%), and landfilling (5.6%) [31]. Regulations for the use of sewage sludge on agricultural lands are increasingly more stringent and aim to minimize the impact of toxic compounds (heavy metals and organic pathogens) on the environment and human health. Further, the use of sewage sludge as fertilizer is negatively perceived by the public [32,33].

Consequently, in recent years, the share of incineration has been increasing while the shares of agricultural use, landfilling, and land reclamation are decreasing [34]. Incineration of sewage sludge is the preferred disposal practice in Austria, Belgium, Germany, and the Netherlands. In addition to mono- and co-incineration, innovative systems for the thermal treatment of sewage sludge are being developed [35–37], methods such as pyrolysis or gasification [38,39]. The percentage distribution of sewage sludge disposal practices in European countries is shown in Figure 3 (based on available data from Eurostat).

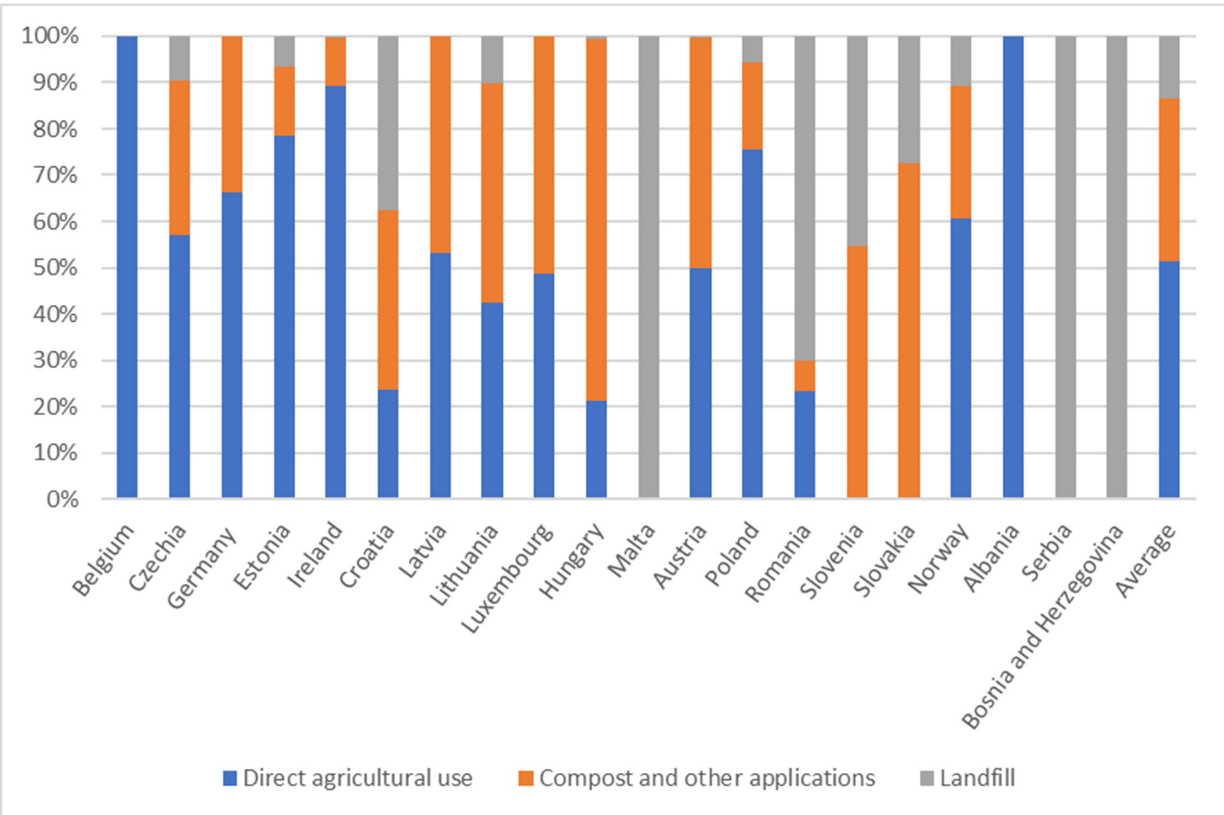

Figure 3. Sewage sludge disposal practices in selected EU member states (Eurostat data for 2019).

3.2. Sludge Treatment Practices in Croatia

The public wastewater system in the Republic of Croatia is significantly underdeveloped with respect to the public water supply system. The public wastewater system covers less populated areas than the water supply system, with smaller agglomerations and rural areas generally relying on local and private wastewater systems. However, recent years have seen upgrades and expansions in the public wastewater system, driven mainly by incentives of EU funding. The wastewater treatment system spread onto all major industrial centers and subsequently included smaller agglomerations and rural areas with as few as 2000 population equivalents. Accordingly, sewage sludge quantities are increasing due to the newly built wastewater facilities. At present, in Croatia, the existing wastewater treatment plants generate a total of 69,654 tonnes of wet sewage sludge per year, as reported in the national waste management information system. The corresponding dry mass of sewage sludge is 26,750 tonnes [40]. The generated quantity of sewage sludge is expected to increase threefold in the next decade as a result of the upgrades and expansions of the wastewater system. By 2031, the annual amount of generated sewage sludge in Croatia will reach 350,000 tonnes of wet matter, which corresponds to about 80,000 tonnes of dry matter [41,42]. Concerning sewage sludge final disposal practices in Croatia, only a smaller fraction of the generated sludge (around 7%) was applied onto agricultural soils or composted in 2020. The remaining sewage sludge is disposed of in landfills. In tourist areas, sludge production shows significant variations throughout the year since more than 70% of the tourists overnight are concentrated in the summer period.

Croatia has yet to establish a nationwide management strategy for sewage sludge that would be economically viable, environmentally friendly, and, at the same time, adherent to the EU legislative and strategic frameworks of sustainable products and circular economy [43–46]. Within those frameworks, priority is given to the use of durable, reusable, upgradable, and reparable products as well as to climate-neutral and resource-efficient technologies and processes. Concerning waste management, priority should be given to the prevention of waste products as well as to the reuse and recycling of the produced waste. For sewage sludge management, this translates into the following order of priorities: (1) increasing the efficiency of wastewater treatment processes, reducing the mass and volume of produced sludge; (2) sludge recycling in agriculture (direct application) and the recovery of nutrients and energy; (3) reuse as a secondary fuel or raw material in various industries; and (4) disposal in landfills, as listed in Table 2.

Table 2. Order of priority for the management of sewage sludge waste within the legislative frameworks of sustainable products and circular economy.

Order of Priority for Waste Management	Sewage Sludge Management Processes	Order of Priority for Sewage Sludge Management
1. Prevention	Applicable	**1. Highly efficient** wastewater treatment processes
2. Reuse	Not applicable	Not applicable
3. Recycling	Material recovery only or combined energy and material recovery	**2.1. Nutrients' recovery:** recycling in agricultural lands, land reclamation and recultivation, sludge incineration and dispersion of ash on agricultural soils, phosphorus, and nitrogen extraction. **2.2. Energy recovery:** anaerobic digestion for biogas production, thermal treatment in mono- and co-incineration plants with generation of thermal energy and electricity, gasification, pyrolysis, incineration in cement kilns, iron and steel production furnaces.
4. Second reuse	Energy recovery only	**3. Energy recovery and reuse as secondary fuel:** mono-incineration in dedicated plants; co-incineration with coal, waste, or biomass; and ash recycling in construction and cement production industries.
5. Disposal	Final disposal	**4. Final disposal:** thermal treatment with limited energy recovery, disposal in landfills.

3.3. Sludge Recycling in Agriculture (Direct Application)

The EU Directive 86/278/EEC [47] specifies the limit values for heavy metal concentrations in the sewage sludge to be applied on agricultural soils as well as the limit values of heavy metals in the soils to be fertilized with sewage sludge and the maximum annual load of heavy metals added to agricultural soils, as reported in Table 3. The Directive also prohibits the use of sewage sludge on soils in which vegetable or fruit crops are growing, while grazing animals must not access grasslands less than three weeks after the sludge application. This Directive was implemented in the national legislations of member states, most of which set lower limits [48]. EU member states are becoming stricter in the implementation of this Directive and setting lower limit values of heavy metal concentrations to protect the environment and human health. Consequently, the direct application of sewage sludge in agriculture has been declining in recent years. Most EU member states set limit values for chromium, although no value is specified in the Directive itself.

Table 3. Limit values of heavy metals in sewage sludge and agricultural soils.

	EU Directive 86/278/EEC [47]—Limit Values of Heavy Metals Concentrations			**Implementation of 86/278/EEC [48]—Limit Values Set by Member States**		
	In Sludge [mg/kg$_{DM}$]	**In Soil [mg/kg$_{DM}$]**	**Annual Load [kg/ha/yr]**	**In Sludge [mg/kg$_{DM}$]**	**In Soil [mg/kg$_{DM}$]**	**Annual Load [kg/ha/yr]**
Cadmium (Cd)	20–40	1–3	0.15	0.8–40	0.4–3.0	0–0.15
Chromium (Cr)	No limit set	No limit set	No limit set	75–1000	30–200	0.04–12
Copper (Cu)	1000–1750	50–140	12	75–1750	36–140	0.2–12
Mercury (Hg)	16–25	1.0–1.5	0.1	0.67–25	0.1–1.5	0–0.1
Nickel (Ni)	300–400	30–75	3	30–400	15–75	0.025–3.0
Lead (Pb)	750–1200	50–300	15	100–1200	40–300	0.025–15
Zinc (Zn)	2500–4000	150–300	30	300–4000	100–300	0.6–30

3.4. Material Recovery from Sewage Sludge

Nitrogen and phosphorus are the most valuable nutrients in the sewage sludge. Other nutrients present in the sewage sludge are potassium, calcium, and magnesium, but their concentrations are lower than in organic fertilizers. A smaller fraction of the total nitrogen content in sewage sludge is available in the form of ammoniacal nitrogen (10%), which can be readily used by plants, but the remaining nitrogen is bonded in organic compounds (90%) and must be mineralized to become plant fertilizer. Similarly, 10% of the total phosphorus content can be easily separated, but the remaining 90% is bonded to iron or aluminum [49]. This means that the nitrogen and phosphorous availability in sewage sludge is generally lower than it is in conventional fertilizers [50,51]. Aside from performing as fertilizer, sewage sludge slows down soil degradation and surface runoff, which can save between 5% and 10% of the agricultural production costs [52].

At the wastewater treatment plant, phosphorus can be recovered using the liquid phase at three locations: (1) wastewater from activated sludge, (2) wastewater from secondary treatment, and (3) wastewater from sludge digestion [53,54]. Phosphorous extraction is achieved using precipitation and crystallization processes to produce struvite, which is a highly valued fertilizer [55,56]. On the other hand, recovery from the solid phase can be performed from (1) primary sludge, (2) excess secondary sludge, (3) raw sludge prior to anaerobic digestion, (4) sludge before dewatering, and (5) from dewatered sludge or after the dewatering. The third possibility is using phosphorus from incinerated sewage sludge ash (ISSA) [57]. ISSA can be spread on agricultural lands as fertilizer if heavy metal concentrations are below limit values. However, if heavy metals concentrations are above limit values, then further chemical treatment is necessary to extract the phosphorous from ISSA. For instance, Germany generates 1.8 million t of dry sludge mass per year, and the amount of recoverable phosphorous is estimated at 50,000 t per year [34], which could meet 40% of the agricultural consumption, if all the produced sludge was treated in mono-incineration plants. The resulting ash could be directly applied to agricultural lands if contaminants levels were below limiting values or, alternatively, would have to be processed by phosphorous extraction systems. Phosphorous recovery is limited to ISSA from mono-incineration plants since the ash contains relatively high fractions of phosphorus and low fractions of contaminants, and recovery rates of up to 90% could be achieved. Phosphorous recovery from ISSA is more technologically demanding but also more rewarding than wet-chemical methods recovering only 10–30% of the phosphorus from untreated wastewaters. It is no wonder that countries are slowly realizing those advantages and choosing the recovery of phosphorus (P) and other nutrients over sludge disposal in landfills or recycling in agriculture (direct use). Sewage sludge could be a key resource of phosphorous in the future, especially in countries with depleted sources of phosphate minerals.

3.5. Anaerobic Digestion

Anaerobic digestion is the most widespread method for the sterilization of sewage sludge. The advantage of anaerobic digestion is the reduction in the mass and volume of sewage sludge and the production of biogas, which can be used as an alternative fuel for internal combustion engines, twin-fuel engines, and cogeneration (CHP) systems [58].

Anaerobic digesters that operate at mesophilic temperatures (35–40 °C) or thermophilic temperatures (50–60 °C) are commonly used systems. Mesophilic digestion is the preferred process due to low thermal energy requirements, reasonable operation and maintenance costs, and good biogas yields. The specific biogas yield is somewhere around 0.3 m^3/kg_{DM}, which is roughly equivalent to 6.0 MJ/kg_{DM} [41,59]. Wastewater treatment plants achieve energy autonomy of 50% or better by converting the biogas into thermal energy for the heating of digesters and electrical energy for the powering the equipment. The material remnant of anaerobic digestion is digestate, which is subsequently dewatered and used as fertilizer on agricultural soils or dried and pelletized to produce low-cost biofuel.

3.6. Sludge Incineration

Sewage sludge thermal treatment includes incineration in mono-incineration plants and co-incineration in coal-fired power plants, municipal waste incineration plants, and cement kilns [53]. Mono-incineration plants can manage sewage sludges with solid fractions as low as 30 wt%, which is generally sufficient for self-sustained combustion [41]. In the case of higher water contents, sewage sludge needs additional drying or, alternatively, it can be co-incinerated with other fuels (coal, biomass, municipal waste) [60]. Incineration reduces the sludge's total mass and volume by up to 85% and thermally destroys the toxic organic components, both of which facilitate further management and disposal. Furthermore, the sludge energy content can be converted into thermal energy or electricity.

Fluidized bed incineration is a well-developed technology for the thermal disposal of different waste materials (non-recyclable industrial and municipal waste, sewage sludge). Fluidized bed incinerators can work with higher moisture contents in the sewage sludge, and the thermal energy for sludge drying is supplied by combustion flue gases and waste heat from the steam condenser. The steam temperature and pressure ranges at the turbine entrance are 300–400 °C and 40–50 bar, respectively. The net electric efficiency is in the range of 20–30%, and the specific electricity generation is 500–800 kWh_{el} per tonne of dry sludge matter, depending on process parameters, sludge composition, and heating value. Flue gases are treated to meet strict emission standards. Nitrogen oxides (NO_x) emissions are reduced using selective non-catalytic reduction (SNCR) by injecting urea into the furnace. Fly ash particles are separated by electrostatic filters, while heavy metals and dioxins are separated in wet scrubbers. Activated coke filters are used to capture mercury and sulfur oxides (SO_x) and reduce unpleasant odors. Among different final disposal practices for sewage sludge, incineration arguably achieves a lower environmental impact in metropolitan areas [61,62]. The by-products of the incineration process are ISSA and flue gases. Depending on the sewage sludge composition, ISSA can contain inorganic oxides (SiO_2, CaO, Fe_2O_3, Al_2O_3, P_2O_5, SO_3, MgO, TiO) and traces of heavy metals (Hg, Cd, As, Sb, Pb). ISSA can be used as secondary material in the construction industry for the manufacture of concrete, cement, and bricks.

3.7. Pyrolysis and Gasification

Pyrolysis is the thermal decomposition of the organic material in sewage sludge in an oxygen-deprived atmosphere. Pyrolysis of sewage sludge is usually performed at temperatures around 500 °C, which provides enough heat to decompose the organic compounds in the sludge. Since no oxygen is present, the sewage sludge decomposes into three products: biochar, bio-oil, and syngas. Biochar is a solid fraction and contains pyrolytic coke and heavy metals. Bio-oil is similar to diesel in composition, but it can contain also smaller amounts of water and tar. Syngas mainly contains hydrogen, methane, and carbon dioxide and can fuel CHP systems to improve the energy self-sufficiency of the wastewater treatment plant or produce green hydrogen with in situ carbon capture [63]. The fraction of the pyrolysis products depends on the sewage sludge composition and process parameters (reactor temperature and pressure, sludge retention time, and heating rates). Depending on retention times and heating rates, slow pyrolysis maximizes the fraction of biochar, while fast pyrolysis maximizes the fraction of syngas. Gasification is similar to pyrolysis, but it is performed at higher temperatures (around 700 °C) by controlling the amount of oxygen and steam in the reactor. The product is syngas with hydrogen, methane, and carbon monoxide as flammable gases. Gasification is usually performed after pyrolysis, and the excess heat from gasification is used for sludge drying and heating of the pyrolysis reactor. The syngas can be utilized in gas turbines or CHP systems to generate heat and electricity [64]. The methane fraction in the syngas can be steam reformed to obtain syngas with higher fractions of green hydrogen [65].

3.8. Hydrothermal Carbonization

Hydrothermal carbonization (HTC) converts sewage sludge into a coal-like product called hydrochar along with aqueous and gaseous by-products. The reaction is performed at a temperature range of 180–280 °C under pressures of 20–60 bar for a duration of 1–5 h [66]. The HTC reaction parameters affect the hydrochar mass yield and heating value as well as the solid to liquid product ratio. The hydrochar achieves heating values between 10 and 15 MJ/kg, and it is used as a low-grade fuel [67]. Sewage sludge drying prior to HTC is not necessary as the ideal feedstock is that with high moisture contents (75–90 wt%). HTC can be integrated with anaerobic digestion to obtain a liquid product rich in organic compounds and recover more than 70% of the sludge energy content via hydrochar and biomethane production [68,69].

4. Sludge Management Scenarios in Croatia

This chapter ranks sewage sludge treatment practices in Croatia using the PROMETHEE multicriteria decision-making method. The present analysis focuses on three treatment practices that are considered fit for present and future circumstances in Croatia: anaerobic digestion, incineration, and gasification. These treatment methods have primarily been selected due to their sustainable aspect. The application of sewage sludge on agricultural lands is gradually being abandoned in Croatia, and nowadays, less than 5% of the total annual sludge production is recycled in agriculture (direct use). The disposal of sewage sludge in special landfills designed for this waste type is the most dominant disposal practice in Croatia, but it will be prohibited in the near future [42]. Gasification is chosen over pyrolysis as this method can work with higher moisture contents in the sludge feedstock (around 80 wt%), which is the case with the sewage sludge from Croatian wastewater treatment plants.

4.1. Input Data for Anaerobic Digestion

Anaerobic digestion utilizes both the energy and the material content of the sewage sludge generated in wastewater treatment plants through the production of biogas and digestate. In Croatia, anaerobic digestion is usually coupled to biogas power plant capacities of around 1 MW_{el}. Table 4 reports the average criterium data obtained from the literature survey, revolving around a biogas capacity of 1 MW_{el}, which equals an input of 76 t of sludge per day. The *Energy production* criterium accounts for produced electricity and disregards produced heat because part of the produced heat is used for digester heating, and the remaining is lost to the environment.

Table 4. Input data for the ranking of anaerobic digestion technology.

Cluster	Group	Criterium	Ranking/Amount	Unit	Literature References
Technological	Technology	Reliability	4.50	-	[70–73]
		Maturity	4.67	-	[70–75]
		Understanding	5.00	-	Communication with experts
	Energy	Energy demand	1135.05	MWh/year	[41,73–77]
		Electric efficiency	36	%	[41,72–77]
		Heat efficiency	51	%	[41,72,74,76]
		Energy production	2842.69	MWh/year	[41,73–77]
	Other	Recovered material	Yes	-	[41,70,72,73,77,78]
		Upgrading potential	Yes	-	[41,70,72,73,75,77,78]
Socio-Economic	Legal-Administrative	Legal-administrative framework	4.00	-	[41,71–73,76]
		Jobs	10.00	-	[41,72,73]
		Public acceptance	4.00	-	[71–73]
	Costs	Operational expenses	739,799.34	EUR/year	[73,75–77,79]
		Capital expenses	1,095,715.57	EUR	[73–79]
		Fit/Premium model	Yes	-	[72,76,78,79]
Environmental	Emissions	Odors	2.50	-	[70–73,80]
		Noise	3.50	-	[70–73,80,81]
		Emissions	43.59	tonnes of CO_{2eq}	[70,73,74,79,82–85]
		Ecological footprint	4.00	-	Communication with experts

4.2. Input Data for Incineration

At present, in Croatia, there are no sewage sludge incineration facilities; however, mono-incineration plants are being planned in the major urban centers. A sludge mono-incineration plant with an electrical capacity of 1 MW_{el} is assumed for further analysis (equal to an input of 76 t of sludge per day) to draw a fair comparison with the other treatment technologies. The number of operating hours is assumed to be 8000 per year. Table 5 reports the average criterium data obtained from the literature survey, referring to a mono-incineration plant with an electrical capacity of 1 MW_{el}.

Table 5. Input data for the ranking of incineration technology.

Cluster	Group	Criterium	Ranking/Amount	Unit	Literature References
Technological	**Technology**	Reliability	5.00	-	[56,86–88]
		Maturity	5.00	-	[56,86–89]
		Understanding	5.00	-	Communication with experts
	Energy	Energy demand	8562.42	MWh/year	[77,86,90–94]
		Electric efficiency	28	%	[77,86,95,96]
		Heat efficiency	48	%	[86,96]
		Energy production	47,670.00	MWh/year	[86,94,97]
	Other	Recovered material	Yes	-	[87–89,98]
		Upgrading potential	Yes	-	[66,87,88]
Socio-Economic	**Legal-Administrative**	Legal-administrative framework	3.00	-	[86,99,100]
		Jobs	24.00	-	[99–102]
		Public acceptance	3.00	-	[66,86,89,93,100]
	Costs	Operational expenses	1,500,000.00	EUR/year	[86,89,92,94,96,97,101]
		Capital expenses	57,000,000.00	EUR	[86,89,94,96,97,100,101,103]
		Fit/Premium model	No	-	Communication with experts
Environmental	**Emissions**	Odors	3.00	-	[92,93,103,104]
		Noise	2.00	-	[103,105]
		Emissions	8248.46	tonnes of CO_{2eq}	[90,92,93,97,103,105,106]
		Ecological footprint	3.00	-	Communication with experts

4.3. Input Data for Gasification

The facility for sewage sludge gasification is assumed to have an electric capacity of 250 $kW_{el,}$ and the number of operating hours is assumed to be 8000 per year (equal to the input of 76 t of sludge per day). The gasification capacity is smaller than the capacity in the sludge incineration option, reflecting the earlier developmental stage of gasification technology [107–109]. Table 6 reports the average criterium data for gasification technology obtained from the literature survey.

4.4. Input Data for Material Recovery

Struvite precipitation and ammonia stripping are the most common technologies for the recovery of phosphorus and nitrogen from anaerobic digestate. Struvite is a compound mineral containing magnesium (Mg), phosphate (PO_4), and ammonium (NH_4). The fertilizing value of struvite has been recognized in recent years when it was proved that struvite could perform as a slow-acting fertilizer, efficiently replacing phosphorous produced from phosphate rocks. Struvite precipitation is not yet developed to a commercial scale. However, it is expected that existing wastewater treatment plants using anaerobic digestion for sludge stabilization will be upgraded with struvite precipitation in the near future [122,123]. Hence, the input data for the ranking of material recovery technology, reported in Table 7, reflect the anaerobic digestion of sewage sludge with the addition of struvite precipitation for phosphorus recovery.

Table 6. Input data for the ranking of gasification technology.

Cluster	Group	Criterium	Ranking/Amount	Unit	Literature References
Technological	**Technology**	Reliability	4.00	-	[66,109,109–111]
		Maturity	4.00	-	[66,109,109–112]
		Understanding	3.50	-	Communication with experts
	Energy	Energy demand	133.33	MWh/year	[109,112–114]
		Electric efficiency	20	%	[108,109,113]
		Heat efficiency	80	%	[107,109,112,113]
		Energy production	122.22	MWh/year	[109,113,114]
	Other	Recovered material	Yes	-	[66,109–111,115]
		Upgrading potential	Yes	-	[66,109,111]
Socio-Economic	**Legal-Administrative**	Legal-administrative framework	3.50	-	[111,116,117]
		Jobs	6.00	-	[113,118]
		Public acceptance	3.50	-	[109,111,112]
	Costs	Operational expenses	118,381.50	EUR/year	[107–109,119]
		Capital expenses	1,210,720.50	EUR	[108,109]
		Fit/Premium model	No	-	Communication with experts
Environmental	**Emissions**	Odors	4.00	-	[108,109]
		Noise	3.50	-	[109]
		Emissions	4800	tonnes of CO_{2eq}	[109,120,121]
		Ecological footprint	4.50	-	Communication with experts

Table 7. Input data for the ranking of material recovery technology.

Cluster	Group	Criterium	Ranking/Amount	Unit	Literature References
Technological	**Technology**	Reliability	3.50	-	[124]
		Maturity	3.00	-	[56,125,126]
		Understanding	3.50	-	Communication with experts
	Energy	Energy demand	1135.05	MWh/year	Communication with experts
		Electric efficiency	36	%	[41,72,74–77]
		Heat efficiency	51	%	[72,74,76,78]
		Energy production	2842.69	MWh/year	[73–75,77,78]
	Other	Recovered material	Yes	-	[126,127]
		Upgrading potential	Yes	-	[53,126,127]
Socio-Economic	**Legal-Administrative**	Legal-administrative framework	3.00	-	Communication with experts
		Jobs	4.00	-	Communication with experts
		Public acceptance	4.00	-	[56,125,126]
	Costs	Operational expenses	40,000.00	EUR/year	[56,125,128]
		Capital expenses	1,600,000.00	EUR	[56,125,128]
		Fit/Premium model	No	-	Communication with experts
Environmental	**Emissions**	Odors	4.50	-	[56,125,126]
		Noise	4.00	-	[56,125,126]
		Emissions	0.00	tonnes of CO_{2eq}	[56,125,126]
		Ecological footprint	5.00	-	Communication with experts

5. Results and Discussion

The above criteria were used as input data for the PROMETHEE multicriteria decision-making method. Figure 4 shows the results obtained using the PROMETHEE I partial ranking. Material recovery technology returns the best result in terms of both positive (Phi^+) and negative rankings, which measure the respective advantages and disadvantages of the observed technology over the other options. Anaerobic digestion technology is ranked in second place, with comparable rankings to that of gasification technology, which is ranked third. Incineration technology is ranked fourth and exhibits the least advantages but most disadvantages over the other sewage sludge disposal methods.

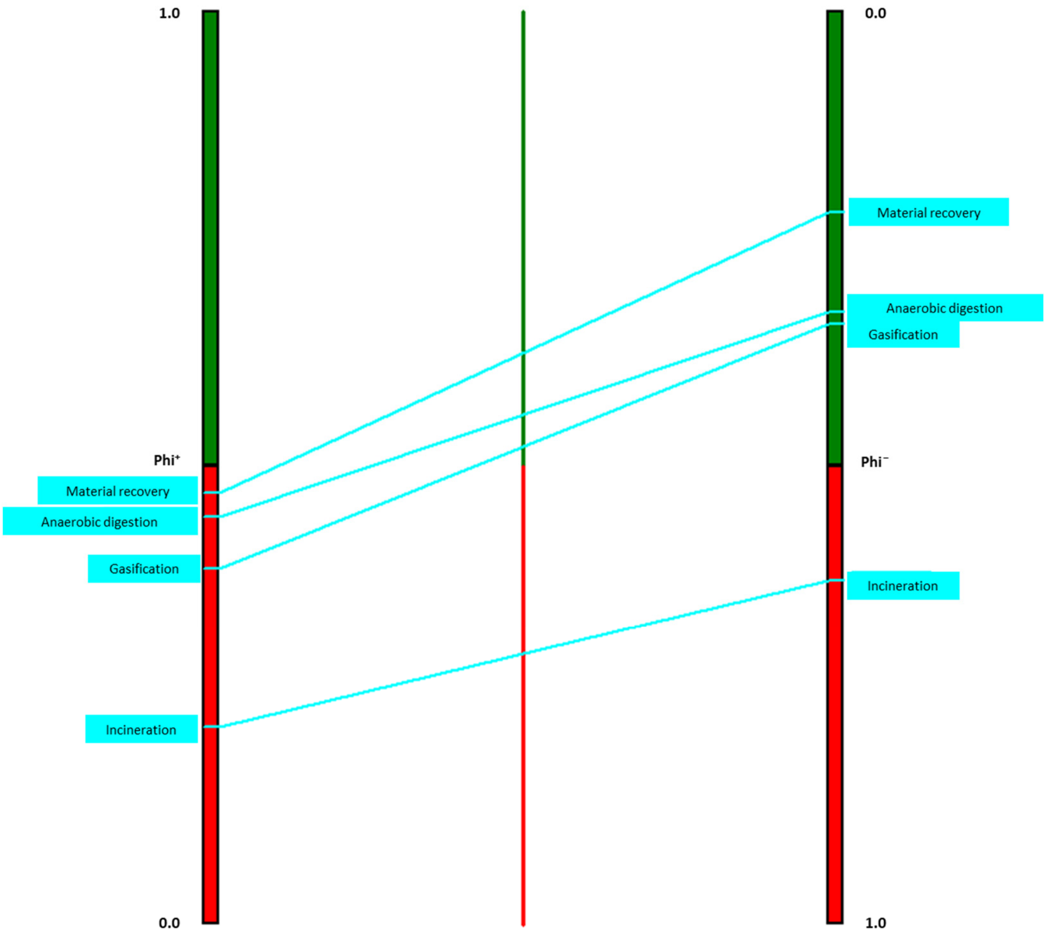

Figure 4. The PROMETHEE I partial ranking of sewage sludge treatment technologies.

All the observed technologies exhibit a negative tendency on the positive ranking side (*Phi*$^+$). This can be explained by the relative lack of knowledge in using and understanding the capabilities of these innovative technologies. Further research and development are necessary to promote these technologies from laboratories and prototypes scale to commercial scale.

Incineration, which is the most familiar among the observed technologies, turns out to be ranked last as a consequence of the negative environmental aspects (emissions, noise, odors, and total footprint). Incineration is oriented toward the destruction of sewage sludge and disposal of the remaining ash, while the other technologies are more focused on the sustainable principles of material recovery and circular economy.

The disadvantages of incineration technology are also observed in the PROMETHEE II complete ranking, where all the other technologies turn out better ranked than incineration, as shown in Figure 5. The complete ranking system reaffirms material recovery as the best sewage sludge treatment technology as it returns most of the sewage sludge material value with the least negative impact on human health and the environment.

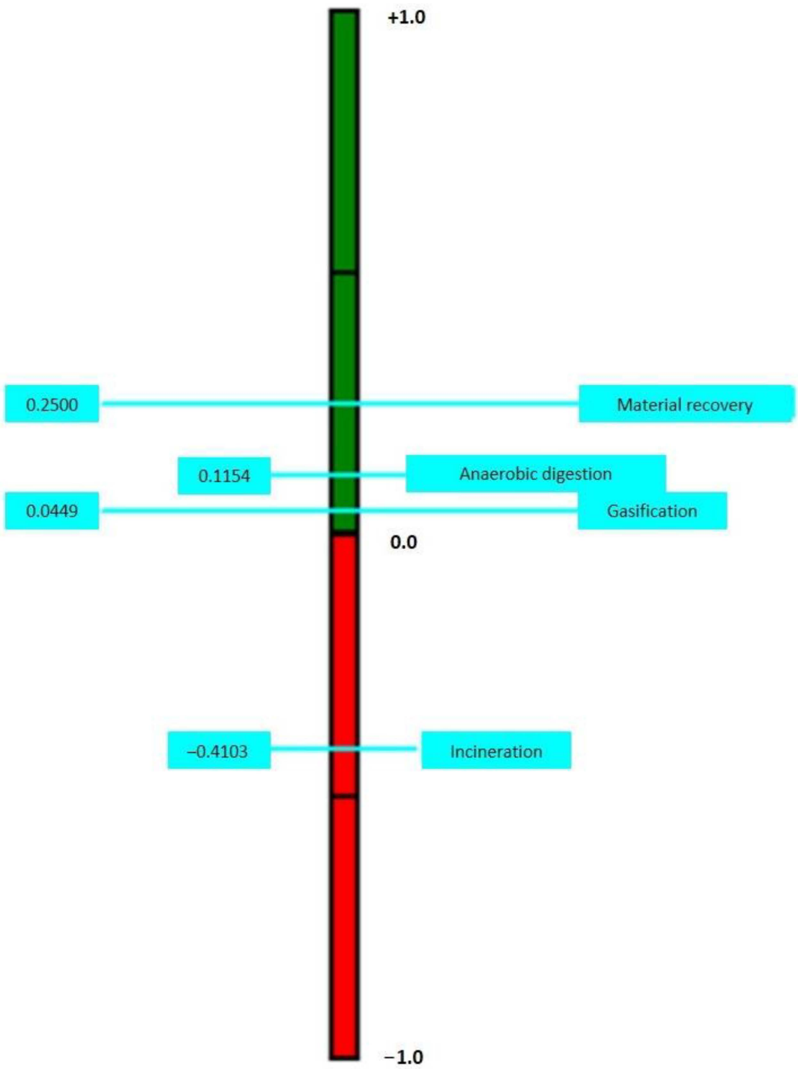

Figure 5. The PROMETHEE II complete ranking of sewage sludge treatment technologies.

The impact of each criteria cluster on the final rankings is depicted using the PROMETHEE rainbow graphical representation in Figure 6. Each criteria cluster and criteria group is attributed a color:

- The Technological criteria cluster is marked in blue;
  - The technology criteria group is marked blue with a red frame;
  - The energy criteria group is marked blue with a green frame;
  - Other criteria group is marked blue with a blue frame.
- The Socio-economic criteria cluster is marked in green;
  - Legal-administrative criteria group is marked green with a red frame;
  - The costs criteria group is marked green with a blue frame.
- The Environmental criteria cluster is marked in yellow.
  - The emissions criteria group is marked yellow with a yellow frame.

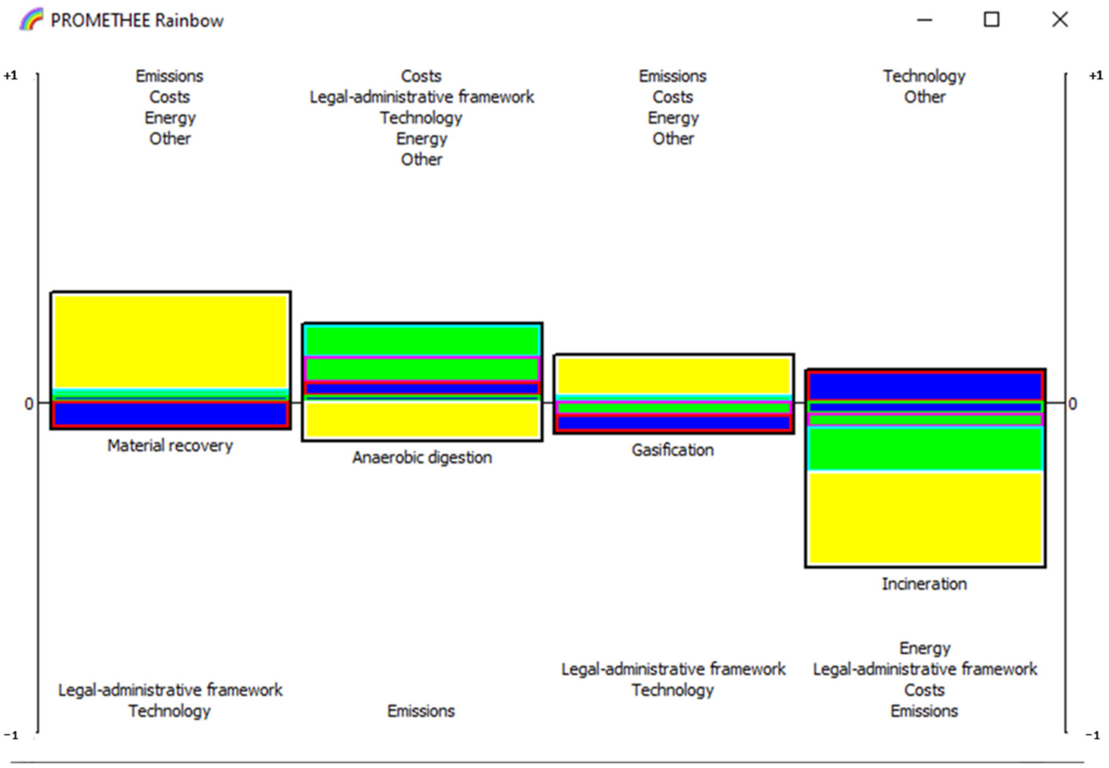

Figure 6. Comparison of strengths and weaknesses of sewage sludge treatment technologies, presented via PROMETHEE Rainbow tool.

The contribution of each criteria cluster in the total ranking of a sewage sludge treatment technology is expressed with the column height. The positive column values suggest technology advantages (strengths), and the negative column values correspond to technology disadvantages (weaknesses). The balance between the technology advantages and disadvantages marks the overall ranking of a technology. For instance, material recovery achieves the largest advantage in the environmental cluster, specifically in the emissions criteria group. The socio-economic cluster returns a weaker advantage, and the technological cluster brings disadvantages to the same technology. For anaerobic digestion, the biggest advantage is in the socio-economic cluster (legal-administrative framework and costs), while the environmental criteria cluster (emissions) presents the biggest disadvantage. Gasification of sewage sludge achieves an advantage in the environmental criteria (odors, emissions, footprint) but also slight disadvantages in the technological and socio-economic clusters. Incineration, as the last-ranked technology, shows the biggest weaknesses in the environmental and socio-economic clusters.

Material recovery and anaerobic digestion are sewage sludge treatment technologies that offer relative advantages in most of the criteria clusters when compared to thermal treatment methods such as gasification and mono-incineration. It should be noted, however, that the results of the PROMETHEE multicriteria decision method are subjective and depend on the input data for the criteria. Different ranking outcomes could be obtained by assuming the criteria rankings differently. This study attempted to perform an unbiased multicriteria comparison based on a detailed literature analysis.

6. Conclusions

The approach to sewage sludge treatment has only recently shifted from unwanted waste material to a valuable source of rare nutrients. An ever-growing number of countries are coming to realize that the sustainable principles of material recovery and circular economy can be effectively implemented in sewage sludge treatment. The emergent strategy is to reduce the amount of waste disposed at landfills as well as to increase the frequency of durable, reusable, upgradable, and reparable products. In the future, sewage sludge management and disposal will be limited only to climate-neutral and resource-efficient technologies. Present-day research is focused on the development of methods and processes capable of extracting most of the nutrient and energy content from sewage sludge while reducing its volume and destroying harmful substances to the greatest possible extent.

Therefore, it is becoming increasingly important to develop methods and define parameters and criteria, allowing for the comparison and ranking of different sewage sludge treatment technologies. In this study, we used a multicriteria decision-making method to rank four different sludge treatment technologies based on the data and specific circumstances in the Republic of Croatia. The results revealed that material recovery and anaerobic digestion of sewage sludge achieve better ranking than thermal treatment methods such as gasification and incineration. Material recovery offers the most advantages in the environmental criteria cluster, with reduced emissions, odors, noise, and ecological footprint when compared to the other sewage sludge treatment technologies. Anaerobic digestion shows the biggest strengths in the socio-economic criteria cluster, with public acceptance, small costs, and mature technology as the most prominent advantages. Gasification and incineration are ranked below material recovery and AD, principally due to a higher environmental impact.

The developed multicriteria decision model can be used for the comparison and ranking of the competing sewage sludge treatment technologies. However, the ranking of sludge treatment technologies is somewhat arbitrary since it depends on the quality of the input data for the ranking criteria. There is no universally preferred sewage sludge technology, but each sewage sludge project should be approached by taking into account a wide range of parameters such as sludge composition and quantities, energy and nutrient content, available technology and familiarity with it, investment size, operational and maintenance costs, national policies and regulations, public opinion, and others.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15113941/s1, Supplementary Materials—Questionnaire and Expert Responses.

Author Contributions: Conceptualization, D.Đ.; methodology, D.Đ. and P.B.; software, D.Đ. and P.B.; validation, D.Đ. and S.Ž.; formal analysis, D.Đ. and P.B.; investigation, D.Đ.; resources, S.Ž.; data curation, D.Đ. and P.B.; writing—original draft preparation, D.Đ.; writing—review and editing, S.Ž. and P.B.; visualization, D.Đ. and P.B.; supervision, S.Ž.; project administration, S.Ž.; funding acquisition, D.Đ. and S.Ž. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Commission, European Structural and Investments Funds 2014–2020, grant number KK.01.1.1.07.0038, by the research project of the Energy Institute Hrvoje Požar, "Development of an integrated solution for strategic long-term climate and energy policy planning and development of joint climate and energy plans".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tyagi, V.K.; Lo, S.-L. Sludge: A waste of renewable source for energy and resources recovery? *Renew. Sustain. Energy Rev.* **2013**, *25*, 708–728. [CrossRef]
2. UN Department of Economic and Social Affairs. *World Population Prospects 2019–Highlights*; UN: New York, NY, USA, 2022; Available online: https://population.un.org/wpp/Publications/Files/WPP2019_Highlights.pdf (accessed on 15 March 2022).
3. Kelessidis, A.; Stasinakis, A.S. Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries. *Waste Manag.* **2012**, *32*, 1186–1195. [CrossRef]
4. Lin, H.; Ma, X. Simulation of co-incineration of sewage sludge with municipal solid waste in a grate furnace incinerator. *Waste Manag.* **2012**, *32*, 561–567. [CrossRef]

5. Houillon, G.; Jolliet, O. Life cycle assessment for the treatment of wastewater urban sludge: Energy and global warming analysis. *J. Clean. Prod.* **2005**, *13*, 287–299. [CrossRef]
6. Hospido, A.; Moreira, T.; Martin, M.; Rigola, M.; Feijoo, G. Environmental evaluation of different treatment processes for sludge from urban wastewater treatments: Anerobic digestion versus thermal processes. *Int. J. Life Cycle Assess.* **2005**, *10*, 336–345. [CrossRef]
7. Andreoli, C.V.; Von Sperling, M.; Fernandes, F.; Ronteltap, M. *Sludge Treatment and Disposal*; Biological Wastewater Treatment Series; IWA Publishing: London, UK, 2007; Volume 6.
8. Guo, W.-Q.; Yang, S.-S.; Xiang, W.-S.; Wang, X.-J.; Ren, N.-Q. Minimization of excess sludge production by in-situ activated sludge treatment processes—A comprehensive review. *Biotechnol. Adv.* **2013**, *31*, 1386–1396. [CrossRef]
9. Yıldız, S.; Oran, E. Sewage sludge disintegration by electrocoagulation. *Int. J. Environ. Health Res.* **2018**, *29*, 531–543. [CrossRef]
10. Praspaliauskas, M.; Pedišius, N. A review of sludge characteristics in Lithuania's wastewater treatment plants and perspectives of its usage in thermal processes. *Renew. Sustain. Energy Rev.* **2017**, *67*, 899–907. [CrossRef]
11. European Parliament. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives, (Text with EEA Relevance), Document 32008L0098. 2008. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN (accessed on 15 March 2022).
12. Bertanza, G.; Pietro, B.; Canato, M. Ranking sewage sludge management strategies by means of Decision Support Systems: A case study. *Resour. Conserv. Recycl.* **2016**, *110*, 1–15. [CrossRef]
13. Lacroix, N.; Rousse, D.; Hausler, R. Anaerobic digestion and gasification coupling for wastewater sludge treatment and recovery. *Water Manag. Res.* **2014**, *32*, 608–613. [CrossRef]
14. Raheem, A.; Sikarwar, V.S.; He, J.; Dastyar, W.; Dionysiou, D.D.; Wang, W.; Zhao, M. Opportunities and challenges in sustainable treatment and resource reuse of sewage sludge: A review. *Chem. Eng. J.* **2018**, *337*, 616–641. [CrossRef]
15. Hao, X.; Chen, Q.; van Loosdrecht, M.C.M.; Li, J.; Jiang, H. Sustainable disposal of excess sludge: Incineration without anaerobic digestion. *Water Res.* **2020**, *170*, 115298. [CrossRef]
16. Karaca, C.; Sözen, S.; Orhon, D.; Okutan, H. High temperature pyrolysis of sewage sludge as a sustainable process for energy recovery. *Waste Manag.* **2018**, *78*, 217–226. [CrossRef]
17. Taki, K.; Gahlot, R.; Kumar, M. Utilization of fly ash amended sewage sludge as brick for sustainable building material with special emphasis on dimensional effect. *J. Clean. Prod.* **2020**, *275*, 123942. [CrossRef]
18. Bubalo, A.; Vouk, D.; Stirmer, N.; Nad, K. Use of Sewage Sludge Ash in the Production of Innovative Bricks—An Example of a Circular Economy. *Sustainability* **2021**, *13*, 9330. [CrossRef]
19. Suh, Y.J.; Rosseaux, P. An LCA of alternative wastewater sludge treatment scenarios. *Resour. Conserv. Recycl.* **2002**, *35*, 191–200. [CrossRef]
20. Johansson, K.; Perzon, M.; Froling, M.; Mossakowska, A.; Svanström, M. Sewage sludge handling with phosphorus utilization-life cycle assessment of four alternatives. *J. Clean. Prod.* **2008**, *16*, 135–151. [CrossRef]
21. Behzadian, M.; Kazemzadeh, R.B.; Albadvi, A.; Aghdasi, M. PROMETHEE: A comprehensive literature review on methodologies and applications. *Eur. J. Oper. Res.* **2010**, *200*, 198–215. [CrossRef]
22. Makan, A.; Mountadar, M. Sustainable management of municipal solid waste in Morocco: Application of PROMETHEE method for choosing the optimal management scheme. *Afr. J. Environ. Waste Manag.* **2013**, *1*, 101–112. Available online: https://www.internationalscholarsjournals.org/journal/ajewm/articles/sustainable-management-of-municipal-solid-waste-in-morocco-application-of-promethee-method-for-choosing-the-optimal-management-scheme (accessed on 1 May 2022).
23. Lolli, F.; Ishizaka, A.; Gamberini, R.; Rimini, B.; Ferrari, A.M.; Marinelli, S.; Savazza, R. Waste treatment: An environmental, economic and social analysis with a new group fuzzy PROMETHEE approach. *Clean Technol. Environ. Policy* **2016**, *18*, 1317–1332. [CrossRef]
24. Erceg, O.; Margeta, J. Selection of food waste management option by PROMETHEE method. *Electron. J. Fac. Civil. Eng. Osijek-E-GFOS* **2019**, *10*, 87–97. [CrossRef]
25. Makan, A.; Fadili, A. Sustainability assessment of large-scale composting technologies using PROMETHEE method. *J. Clean. Prod.* **2020**, *261*, 121244. [CrossRef]
26. Brans, J.P.; Mareschal, B. Promethee Methods, in: Multiple Criteria Decision Analysis: State of the Art Surveys. In *International Series in Operations Research & Management Science 78*; Springer: New York, NY, USA, 2005. [CrossRef]
27. European Commission. *A New Circular Economy Action Plan: For a Cleaner and More Competitive Europe*; European Commission: Brussels, Belgium, 2020; Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0098&from=EN (accessed on 15 March 2022).
28. Werle, S.; Wilk, R.K. A review of methods for the thermal utilization of sewage sludge: The Polish perspective. *Renew. Energy* **2010**, *35*, 1914–1919. [CrossRef]
29. Fytili, D.; Zabaniotou, A. Utilization of sewage sludge in EU application of old and new methods-a review. *Renew. Sustain. Energy Rev.* **2008**, *12*, 116–140. [CrossRef]
30. Perez-Elvira, S.I.; Nieto Diez, P.; Fdz-Polanco, F. Sludge Minimization Technologies. *Rev. Environ. Sci. Bio/Technol.* **2006**, *5*, 375–398. [CrossRef]
31. European Commission. Eurostat, Sewage Sludge Production and Disposal. Available online: https://ec.europa.eu/eurostat/databrowser/view/env_ww_spd/default/table?lang=en (accessed on 15 March 2022).

32. Ekane, N.; Barquet, K.; Rosemarin, A. Resources and Risks: Perceptions on the Application of Sewage Sludge on Agricultural Land in Sweden, a Case Study. *Front. Sustain. Food Syst.* **2021**, *5*, 647780. [CrossRef]
33. Gwara, S.; Wale, E.; Odindo, A.; Buckley, C. Attitudes and Perceptions on the Agricultural Use of Human Excreta and Human Excreta Derived Materials: A Scoping Review. *Agriculture* **2021**, *11*, 153. [CrossRef]
34. Roskosch, A.; Heidecke, P. *Sewage Sludge Disposal in the Federal Republic of Germany*; German Environment Agency, Sections; Waste and Resources: Dessau-Roßlau, Germany, 2018; Available online: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/190116_uba_fb_klaerschlamm_engl_bf.pdf (accessed on 15 March 2022).
35. Fonts, I.; Gea, G.; Azuara, M.; Abrego, J.; Arauzo, J. Sewage sludge pyrolysis for liquid production: A review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2781–2805. [CrossRef]
36. Bianchini, A.; Bonfiglioli, L.; Pellegrini, M.; Saccani, C. Sewage sludge drying process integration with a waste-to-energy power plant. *Waste Manag.* **2015**, *42*, 159–165. [CrossRef]
37. Rada, E.C.; Ragazzi, M.; Villotti, S.; Torretta, V. Sewage sludge drying by energy recovery from OFMSW composting: Preliminary feasibility evaluation. *Waste Manag.* **2014**, *34*, 859–866. [CrossRef]
38. Manara, P.; Zabaniotou, A.A. Towards sewage sludge-based biofuels via thermochemical conversion-a review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2566–2582. [CrossRef]
39. Samolada, M.C.; Zabaniotou, A.A. Comparative assessment of municipal sewage sludge incineration, gasification and pyrolysis for sustainable sludge-to-energy management in Greece. *Waste Manag.* **2014**, *34*, 411–420. [CrossRef]
40. Tomljenović, F. Water Treatment, Energetika Marketing, EGE 5/2021. Available online: http://www.em.com.hr/ege/sadrzaj/2021/5 (accessed on 15 March 2022).
41. Đurđević, D.; Blecich, P.; Jurić, Ž. Energy Recovery from Sewage Sludge: The Case Study of Croatia. *Energies* **2019**, *12*, 1927. [CrossRef]
42. Republic of Croatia, Ministry of Environmental Protection and Energy. Action Plan for the Utilization of Sewage Sludge from Wastewater Treatment Plants on Suitable Surfaces. 2020. Available online: https://www.voda.hr/sites/default/files/dokumenti/akcijski_plan_za_koristenje_mulja_iz_upov-a_na_pogodnim_povrsinama_-_zavrsno_izvjesce.pdf (accessed on 15 March 2022).
43. Republic of Croatia, Croatian Waters, The Potential Environmental Impacts from the Multiannual Water Supply Construction Works in the Period 2014–2023. 2015. Available online: https://www.voda.hr/sites/default/files/strateska_studija_visegodisnji_program_gradnje_komunalnih_vodnih_gradevina.pdf (accessed on 15 March 2022).
44. Republic of Croatia. Waste Management Plan of the Republic of Croatia for the Period 2017–2022. 2017. Available online: https://mingor.gov.hr/UserDocsImages/UPRAVA-ZA-PROCJENU-UTJECAJA-NA-OKOLIS-ODRZIVO-GOSPODARENJE-OTPADOM/Sektor%20za%20odr%C5%BEivo%20gospodarenje%20otpadom/Ostalo/management_plan_of_the_republic_of_croatia_for_the_period_2017-2022.pdf (accessed on 15 March 2022).
45. European Commission. *DG Environment, Disposal and Recycling Routes for Sewage Sludge—Part 2: Regulatory Report*; Office for Official Publications of the European Communities: Luxembourg, 2001; Available online: https://ec.europa.eu/environment/archives/waste/sludge/pdf/sludge_disposal2.pdf (accessed on 15 March 2022).
46. European Commission. *DG Environment, Disposal and Recycling Routes for Sewage Sludge—Part 3: Scientific and Technical Report*; Office for Official Publications of the European Communities: Luxembourg, 2001; Available online: https://ec.europa.eu/environment/archives/waste/sludge/pdf/sludge_disposal3.pdf (accessed on 15 March 2022).
47. Council Directive 86/278/EEC of 12 June 1986 on the Protection of the Environment, and in Particular of the Soil, When Sewage Sludge Is Used in Agriculture. *Off. J. Eur. Communities* **1986**, *181*, 6–12. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31986L0278&from=EN (accessed on 15 March 2022).
48. European Commission. *DG Environment, Final Implementation Report for Directive 86/278/EEC on Sewage Sludge: 2013–2015*; Eunomia Research & Consulting Ltd.: Bristol, UK, 2018; Available online: https://ec.europa.eu/environment/archives/waste/reporting/pdf/Final_Implementation_Report_2013_2015_Sewage_Sludge.pdf (accessed on 15 March 2022).
49. Xu, H.; Zhang, H.; Shao, L.; He, P. Fraction distributions of phosphorus in sewage sludge and sludge ash. *Waste Biomass Valorization* **2012**, *3*, 355–361. [CrossRef]
50. Delin, S. Fertilizer value of phosphorus in different residues. *Soil Use Manag.* **2015**, *32*, 17–26. [CrossRef]
51. Krogstad, T.; Sogn, T.; Asdal, A.; Saebo, A. Influence of chemically and biologically stabilized sewage sludge on plant-available phosphorus in soil. *Ecol. Eng.* **2015**, *25*, 51–60. [CrossRef]
52. Vouk, D.; Nakić, D.; Štirmer, N. Reuse of sewage sludge–problems and possibilities. In Proceedings of the Industrial Waste, Wastewater Treatment and Valorization (IWWATV Conference 2015), Athens, Greece, 21–23 May 2015; Available online: http://uest.ntua.gr/iwwatv/proceedings/pdf/Vouk_et_al.pdf (accessed on 15 March 2022).
53. Daneshgar, S.; Buttafava, A.; Callegari, A.; Capodaglio, A.G. Simulations and Laboratory Tests for Assessing Phosphorus Recovery Efficiency from Sewage Sludge. *Resources* **2018**, *7*, 54. [CrossRef]
54. Desmidt, E.; Ghyselbrecht, K.; Zhang, Y.; Pinoy, L.; der Bruggen, B.V.; Verstraete, W.; Rabaey, K.; Meesschaert, B. Global Phosphorus Scarcity and Full-Scale P-Recovery Techniques: A Review. *Crit. Rev. Environ. Sci. Technol.* **2015**, *45*, 336–384. [CrossRef]
55. Kataki, S.; West, H.; Clarke, M.; Baruah, D.C. Phosphorus recovery as struvite from farm, municipal and industrial waste: Feedstock suitability, methods and pre-treatments. *Waste Manag.* **2016**, *49*, 437–454. [CrossRef]

56. Saerens, B.; Geerts, S.; Weemaes, M. Phosphorus recovery as struvite from digested sludge–experience from the full scale. *J. Environ. Manag.* **2021**, *280*, 111743. [CrossRef]
57. Donatello, S.; Cheeseman, C.R. Recycling and recovery routes for incinerated sewage sludge ash (ISSA): A review. *Waste Manag.* **2013**, *33*, 2328–2340. [CrossRef]
58. Hawkes, A.D. Techno-economic assessment of small and micro combined heat and power (CHP) systems. In *Small and Micro Combined Heat and Power (CHP) Systems*; Woodhead Publishing Limited: Oxford, UK, 2011; pp. 17–41. [CrossRef]
59. Dussan, K.; Monaghan, R.F.D. Integrated thermal conversion and anaerobic digestion for sludge management in wastewater treatment plants. *Waste Biomass Valorization* **2018**, *9*, 65–85. [CrossRef]
60. Pettersson, A.; Amand, L.-E.; Steenari, B.-M. Leaching of ashes from co-combustion of sewage sludge and wood-part 1: Recovery of phosphorus. *Biomass Bioenergy* **2008**, *32*, 224–235. [CrossRef]
61. Piao, W.; Kim, Y.; Kim, H.; Kim, M.; Kim, C. Life cycle assessment and economic efficiency analysis of integrated management of wastewater treatment plants. *J. Clean. Prod.* **2016**, *113*, 325–337. [CrossRef]
62. Cao, Y.; Pawłowski, A. Sewage sludge-to-energy approaches based on anaerobic digestion and pyrolysis: Brief overview and energy efficiency assessment. *Renew. Sustain. Energy Rev.* **2012**, *16*, 1657–1665. [CrossRef]
63. Zhao, M.; Wang, F.; Fan, Y.; Raheem, A.; Zhou, H. Low-temperature alkaline pyrolysis of sewage sludge for enhanced H_2 production with in-situ carbon capture. *Int. J. Hydrogen Energy* **2019**, *44*, 8020–8027. [CrossRef]
64. Lumley, N.P.G.; Ramey, D.F.; Prieto, A.L.; Braun, R.J.; Cath, T.Y.; Porter, J.M. Techno-economic analysis of wastewater sludge gasification: A decentralized urban perspective. *Bioresour. Technol.* **2014**, *161*, 385–394. [CrossRef]
65. Chen, Y.; Yi, L.; Wei, W.; Jin, H.; Guo, L. Hydrogen production by sewage sludge gasification in supercritical water with high heating rate batch reactor. *Energy* **2022**, *238*, 121740. [CrossRef]
66. Wang, L.; Chang, Y.; Li, A. Hydrothermal carbonization for energy-efficient processing of sewage sludge: A review. *Renew. Sustain. Energy Rev.* **2019**, *108*, 423–440. [CrossRef]
67. Wilk, M.; Śliz, M.; Lubieniecki, B. Hydrothermal co-carbonization of sewage sludge and fuel additives: Combustion performance of hydrochar. *Renew. Energy* **2021**, *178*, 1046–1056. [CrossRef]
68. Villamil, J.A.; Mohedano, A.F.; Rodriguez, J.J.; de la Rubia, M.A. Valorization of the liquid fraction from hydrothermal carbonization of sewage sludge by anaerobic digestion. *J. Chem. Technol. Biotechnol.* **2017**, *93*, 450–456. [CrossRef]
69. Gaur, R.Z.; Khoury, O.; Zohar, M.; Poverenov, E.; Darzi, R.; Laor, Y.; Posmanik, R. Hydrothermal carbonization of sewage sludge coupled with anaerobic digestion: Integrated approach for sludge management and energy recycling. *Energy Convers. Manag.* **2020**, *224*, 113353. [CrossRef]
70. Luostarinen, S.; Normak, A.; Edström, M. Overview of Biogas Technology–Knowledge Report, Baltic Forum for Innovative Technologies for Sustainable Manure Management. 2011. Available online: https://www.build-a-biogas-plant.com/PDF/baltic_manure_biogas_final_total.pdf (accessed on 15 March 2022).
71. Scarlat, N.; Dallemand, J.-F.; Fahl, F. Biogas: Developments and perspectives in Europe. *Renew. Energy* **2018**, *129*, 457–472. [CrossRef]
72. Al Seadi, T.A.; Rutz, D.; Prassl, H.; Köttner, M.; Finsterwalder, T.; Volk, S.; Janssen, R. Biogas Handbook, Intelligent Energy Europe. 2008. Available online: https://www.lemvigbiogas.com/BiogasHandbook.pdf (accessed on 15 March 2022).
73. Møller, F.; Martinsen, L. Socio-Economic Evaluation of Selected Biogas Technologies, Scientific Report from DCE-Danish Centre for Environment and Energy, No. 62, Aarhus University, Department of Environmental Science, Aarhus, Denmark. 2013. Available online: https://dce2.au.dk/Pub/SR62.pdf (accessed on 15 March 2022).
74. Kiselev, A.; Magaril, E.; Magaril, R.; Panepinto, D.; Ravina, M.; Zanetti, M.C. Towards circular economy: Evaluation of sewage sludge biogas solutions. *Resources* **2019**, *8*, 91. [CrossRef]
75. Beegle, J.R.; Borole, A.P. Energy production from waste: Evaluation of anaerobic digestion and bioelectrochemical systems based on energy efficiency and economic factors. *Renew. Sustain. Energy Rev.* **2018**, *96*, 343–351. [CrossRef]
76. Carlini, M.; Mosconi, E.M.; Castellucci, S.; Villarini, M.; Colantoni, A. An economical evaluation of anaerobic digestion plants fed with organic agro-industrial waste. *Energies* **2017**, *10*, 1165. [CrossRef]
77. Garcia, A.P. *Techno-Economic Feasibility Study of a Small-Scale Biogas Plant for Treating Market Waste in the City of El Alto, Master of Science Thesis EGI 2014:083MSC*; KTH School of Industrial Engineering and Management: Stockholm, Sweden, 2014; Available online: http://kth.diva-portal.org/smash/get/diva2:741758/FULLTEXT01.pdf (accessed on 15 March 2022).
78. Sgroi, F.; Di Trapani, A.M.; Foderà, M.; Testa, R.; Tudisca, S. Economic performance of biogas plants using giant reed silage biomass feedstock. *Ecol. Eng.* **2015**, *81*, 481–487. [CrossRef]
79. Đurđević, D.; Hulenić, I. Anaerobic digestate treatment selection model for biogas plant costs and emissions reduction. *Processes* **2020**, *8*, 142. [CrossRef]
80. Fuhrmann, M. *Air Quality Assessment-Lower Drayton Farm Anaerobic Digestion Plant*; ETL/437/2020; Earthcare Technical Ltd.: Waterlooville, UK, 2020. Available online: https://consult.environment-agency.gov.uk/psc/st19-5re-bioconstruct-newenergy-limited/supporting_documents/Air%20Quality%20Assessment.pdf (accessed on 15 March 2022).
81. Lapčik, V.; Lapčikova, M. Biogas stations and their environmental impact. *Rud. Geološko-Naft. Zb.* **2011**, *23*, 9–14. Available online: https://hrcak.srce.hr/file/111499 (accessed on 15 March 2022).
82. Iqbal, A.; Zan, F.; Siddiqui, M.A.; Nizamuddin, S.; Chen, G. Integrated treatment of food waste with wastewater and sewage sludge: Energy and carbon footprint analysis with economic implications. *Sci. Total Environ.* **2022**, *825*, 154052. [CrossRef]

83. Bacenetti, J. Economic and Environmental Impact Assessment of Renewable Energy from Biomass. *Sustainability* **2020**, *12*, 5619. [CrossRef]
84. Paolini, V.; Petracchini, F.; Segreto, M.; Tomassetti, L.; Naja, N.; Cecinato, A. Environmental impact of biogas: A short review of current knowledge. *J. Environ. Sci. Health Part A Toxic/Hazard. Subst. Environ. Eng.* **2018**, *53*, 899–906. [CrossRef]
85. Budzianowski, W.M.; Budzianowska, D.A. Economic analysis of biomethane and bioelectricity generation from biogas using different support schemes and plant configurations. *Energy* **2015**, *88*, 658–666. [CrossRef]
86. Schneider, D.R.; Bogdan, Ž. Analysis of a sustainable system for energy recovery from municipal waste in Croatia. *Manag. Environ. Qual.* **2011**, *22*, 105–120. [CrossRef]
87. Joint Research Centre. Waste Incineration, Europska Komisija. December 2018. [Mrežno]. Available online: https://eippcb.jrc.ec.europa.eu/reference/wi.html (accessed on 17 December 2019).
88. European Commission, Joint Research Centre. Waste Incineration-Reference Document on the Best Available Techniques. 2006. Available online: https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-03/superseded_wi_bref_0806_0.pdf (accessed on 15 March 2022).
89. Tsybina, A.; Wuensch, C. Analysis of sewage sludge thermal treatment methods in the context of Circular Economy. *Multidiscip. J. Waste Resour. Residues* **2018**, *2*, 3–15. [CrossRef]
90. Lombardi, L.; Nocita, C.; Bettazzi, E.; Fibbi, D.; Carnevale, E. Environmental comparison of alternative treatments for sewage sludge: An Italian case study. *Waste Manag.* **2017**, *69*, 365–376. [CrossRef]
91. Đurđević, D.; Blecich, P.; Lenić, K. Energy potential of digestate produced by anaerobic digestion in biogas power plants: The case study of Croatia. *Environ. Eng. Sci.* **2018**, *35*, 1286–1293. [CrossRef]
92. Gardoni, D.; Guarino, M. Drying and combustion of an anaerobic digestate: Results and economical evaluation of a demonstrative-scale plant. *Int. J. Eng. Res. Sci.* **2016**, *2*, 148–155.
93. Kratzeisen, M.; Starcevic, N.; Martinov, M.; Maurer, C.; Müller, J. Applicability of biogas digestate as solid fuel. *Fuel* **2010**, *89*, 2544–2548. [CrossRef]
94. Escamilla-García, P.E.; Camarillo-López, R.H.; Carrasco-Hernández, R.; Fernández-Rodríguez, E.; Legal-Hernández, J.M. Technical and economic analysis of energy generation from waste incineration in Mexico. *Energy Strategy Rev.* **2020**, *31*, 100542. [CrossRef]
95. Rutz, D.; Mergner, R.; Janssen, R. *Sustainable Heat Use of Biogas Plants—A Handbook*, 2nd ed.; WIP Renewable Energies: München, Germany, 2012; Available online: https://www.wip-munich.de/biolyfe-handbook/1_2_Handbook-2ed_2015-02-20-cleanversion.pdf (accessed on 15 March 2022).
96. Eboh, F.C.; Andersson, B.-A.; Richards, T. Economic evaluation of improvements in a waste-to-energy combined heat and power plant. *Waste Manag.* **2019**, *100*, 75–83. [CrossRef]
97. Tang, Y.; You, F. Multicriteria environmental and economic analysis of municipal solid waste incineration power plant with carbon capture and separation from the life-cycle perspective. *ACS Sustain. Chem. Eng.* **2018**, *6*, 937–956. [CrossRef]
98. Smol, M.; Kulczycka, J.; Kowalski, Z. Sewage sludge ash (SSA) from large and small incineration plants as a potential source of phosphorus-Polish case study. *J. Environ. Manag.* **2016**, *184*, 617–628. [CrossRef]
99. Rand, T.; Haukohl, J.; Marsen, U. *Municipal Solid Waste Incineration: Requirements for a Successful Project*; World Bank Technical Papers; World Bank: Washington, DC, USA, 2000; Available online: https://econpapers.repec.org/paper/fthwobate/462.htm (accessed on 15 March 2022).
100. Government of the UK, Department for Environment. *Food & Rural Affairs, Incineration of Municipal Solid Waste*; Government of the UK, Department for Environment: London, UK, 2013. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/221036/pb13889-incineration-municipal-waste.pdf (accessed on 15 March 2022).
101. Schneider, D.R.; Lončar, D.; Bogdan, Ž. Cost Analysis of Waste-to-Energy Plant. *Strojarstvo* **2010**, *52*, 369–378. Available online: https://hrcak.srce.hr/file/96613 (accessed on 15 March 2022).
102. Goldstein, J.; Electris, C.; Morris, J. More Jobs, Less Pollution: Growing the Recycling Economy in the US, Tellus Institute with Sound Resource Management. 2007. Available online: https://www.nrdc.org/sites/default/files/glo_11111401a_0.pdf (accessed on 15 March 2022).
103. Victoria State Government. Turning Waste into Energy: Join the Discussion, The State of Victoria Department of Environment, Land, Water and Planning, Victoria. 2017. Available online: https://s3.ap-southeast-2.amazonaws.com/hdp.au.prod.app.vic-engage.files/9415/0897/9363/Turning_waste_into_energy_-_Final.pdf (accessed on 15 March 2022).
104. Mucha, A.P.; Dragisa, S.; Dror, I.; Garuti, M.; van Hullebusch, E.D.; Repinc, S.K.; Muñoz, J.; Rodriguez-Perez, S.; Stres, B.; Ustak, S.; et al. Chapter 7: Re-use of digestate and recovery techniques. In *Trace Elements in Anaerobic Biotechnologies*; Fermoso, F.G., van Hullebusch, E.D., Collins, G., Roussel, J., Mucha, A.P., Esposito, G., Eds.; IWA Publishing: London, UK, 2019; pp. 181–205. [CrossRef]
105. Wiechmann, B.; Dienemann, C.; Kabbe, C.; Brandt, S.; Vogel, I.; Roskosch, A. *Sewage Sludge Management in Germany*; Umweltbundesamt: Dessau-Roßlau, Germany, 2015; Available online: https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/sewage_sludge_management_in_germany.pdf (accessed on 15 March 2022).
106. Hao, X.; Li, J.; van Loosdrecht, M.C.M.; Jiang, H.; Liu, R. Energy recovery from wastewater: Heat over organics. *Water Res.* **2019**, *161*, 74–77. [CrossRef]

107. Barry, D.J. Pyrolysis as an Economical and Ecological Treatment Option for Solid Anaerobic Digestate and Municipal Sewage Sludge. Master's Thesis, The University of Western Ontario, London, ON, Canada, 2018. Available online: https://ir.lib.uwo.ca/etd/5187 (accessed on 15 March 2022).
108. You, S.; Wang, W.; Dai, Y.; Tong, Y.W.; Wang, C.-H. Comparison of the co-gasification of sewage sludge and food wastes and cost-benefit analysis of gasification- and incineration-based waste treatment schemes. *Bioresour. Technol.* **2016**, *218*, 595–605. [CrossRef]
109. Villalba, L.O.; Acevedo, E.R. Technical and economical assessment of power generation technologies firing syngas obtained from biosolid gasification. *Prod. Limpia* **2014**, *9*, 31–43. Available online: http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S1909-04552014000100003&lng=en&nrm=iso (accessed on 15 March 2022).
110. Migliaccio, R.; Brachi, P.; Montagnaro, F.; Papa, S.; Tavano, A.; Montesarchio, P.; Ruoppolo, G.; Urciuolo, M. Sewage sludge gasification in a fluidized bed: Experimental investigation and modeling. *Ind. Eng. Chem. Res.* **2021**, *60*, 5034–5047. [CrossRef]
111. Werle, S.; Sobek, S. Gasification of sewage sludge within a circular economy perspective: A Polish case study. *Environ. Sci. Pollut. Res.* **2019**, *26*, 35422–354632. [CrossRef]
112. Dogru, M.; Midilli, A.; Howarth, C. Gasification of sewage sludge using a throated downdraft gasifier and uncertainty analysis. *Fuel Process. Technol.* **2002**, *75*, 55–82. [CrossRef]
113. McCahey, S.; Huang, Y.; McMullan, J. Sewage Sludge Gasification for CHP Applications. In Proceedings of the International Water Association (IWA) Specialist Conference, BIOSOLIDS 2003 Wastewater Sludge as a Resource, Trondheim, Norway, 23–25 June 2003; Available online: https://www.osti.gov/etdeweb/servlets/purl/20407902 (accessed on 15 March 2022).
114. Di Fraia, S.; Massarotti, N.; Vanoli, L.; Costa, M. Thermo-economic analysis of a novel cogeneration system for sewage sludge treatment. *Energy* **2016**, *115*, 1560–1571. [CrossRef]
115. Zhu, W.; Xu, Z.; Li, L.; He, C. The behavior of phosphorus in sub- and super-critical water gasification of sewage sludge. *Chem. Eng. J.* **2011**, *171*, 190–196. [CrossRef]
116. Vos, J.; Knoef, H.; Hauth, M.; Seifert, U.; Hofbauer, H.; Fuchs, M.; Cusco, L.; Vechot, L.; Pedersen, T.E.; Hummelshoj, H.M.; et al. Gasification Guide: Guideline for Safe and Eco-Friendly Biomass Gasification, Intelligent Energy Europe. 2009. Available online: https://www.osti.gov/etdeweb/servlets/purl/1000226 (accessed on 15 March 2022).
117. Environmental Protection Agency (EPA). Potential Future Regulation Addressing Pyrolysis and Gasification Units, Federal Register/Vol. 86, No. 171/September 8, 2021. Available online: https://www.govinfo.gov/content/pkg/FR-2021-09-08/pdf/2021-19390.pdf (accessed on 15 March 2022).
118. Veress, M.; Bartik, A.; Benedikt, F.; Hammerschmid, M.; Fuchs, J.; Müller, S.; Hofbauer, H. Development and techno-economic evaluation of an optimized concept for industrial bio-SNG production from sewage sludge. In Proceedings of the 28th European Biomass Conference and Exhibition, Virtual, 6–9 July 2020; pp. 901–911. [CrossRef]
119. Alves, O.; Calado, L.; Panizio, R.; Gonçalves, M.; Monteiro, E.; Brito, P. Techno-economic study for a gasification plant processing residues of sewage sludge and solid recovered fuels. *Waste Manag.* **2021**, *131*, 148–162. [CrossRef]
120. Wang, N.-Y.; Shih, C.-H.; Chiueh, P.-T.; Huang, Y.-F. Environmental Effects of Sewage Sludge Carbonization and Other Treatment Alternatives. *Energies* **2013**, *6*, 871–883. [CrossRef]
121. Ramachandran, S.; Yao, Z.; You, S.; Massier, T.; Stimming, U.; Wang, C.-H. Life cycle assessment of a sewage sludge and woody biomass co-gasification system. *Energy* **2017**, *137*, 369–376. [CrossRef]
122. Timonen, K.; Sinkko, T.; Luostarinen, S.; Tampio, E.; Joensuu, K. LCA of anaerobic digestion: Emission allocation for energy and digestate. *J. Clean. Prod.* **2019**, *235*, 1567–1579. [CrossRef]
123. Herbes, C.; Roth, U.; Wulf, S.; Dahlin, J. Economic assessment of different biogas digestate processing technologies: A scenario-based analysis. *J. Clean. Prod.* **2020**, *255*, 120282. [CrossRef]
124. Remy, C.; Jossa, P. Life Cycle Assessment of Selected Processes for P Recovery from Sewage Sludge, Sludge Liquor, or Ash-D9.2, P-REX Deliverable D 9.2 Project. 2015. Available online: https://publications.kompetenz-wasser.de/pdf/Remy-2015-821.pdf (accessed on 15 March 2022).
125. Damalerio, R.G.; Belo, L.P.; Orbecido, A.H.; Pausta, C.M.; Promentilla, M.A.; Razon, L.F.; Eusebio, R.C.; Saroj, D.; Beltran, A.B. Phosphorus recovery from wastewater and sludge. In Proceedings of the 25th Regional Symposium on Chemical Engineering (RSCE 2018), Manila, Philippines, 21–22 November 2018. [CrossRef]
126. Antakyali, D.; Meyer, C.; Preyl, V.; Maier, W.; Steinmetz, H. Large-scale application of nutrient recovery from digested sludge as struvite. *Water Pract. Technol.* **2013**, *8*, 256–262. [CrossRef]
127. Kern, J.; Heinzmann, B.; Markus, B.; Kaufmann, A.C.; Soethe, N.; Engels, C. Recycling and assessment of struvite phosphorus from sewage sludge. *Agric. Eng. Int. CIGR J.* **2008**, *X*, CE 12 01. Available online: https://cigrjournal.org/index.php/Ejounral/article/view/1071/1053 (accessed on 15 March 2022).
128. Sikosana, M.; Randall, D.G.; von Blottnitz, H. A technological and economic exploration of phosphate recovery from centralised sewage treatment in a transitioning economy context. *Water SA* **2017**, *43*, 343–353. [CrossRef]