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Scenario Analysis for Selecting Sewage Sludge-to-Energy/Matter Recovery Processes

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Abstract: The sewage sludges are the byproducts of the wastewater treatment. The new perspective of the wastewater value chain points to a sustainable circular economy approach, where the residual solid material produced by sewage sludge treatments is a resource rather than a waste. A sewage sludge treatment system consists of five main phases; each of them can be performed by different alternative processes. Each process is characterized by its capability to recover energy and/or matter. In this paper, a state of the art of the sludge-to-energy and sludge-to-matter treatments is provided. Then, a scenario analysis is developed to identify suitable sewage sludge treatments plants that best fit the quality and flowrate of sewage sludge to be processed while meeting technological and economic constraints. Based on the scientific literature findings and experts' opinions, the authors identify a set of reference initial scenarios and the corresponding best treatments' selection for configuring sewage sludge treatment plants. The scenario analysis reveals a useful reference technical framework when circular economy goals are pursued. The results achieved in all scenarios ensure the potential recovery of matter and/or energy from sewage sludges processes.

Keywords: sewage sludge treatments plants; sludge-to-energy; sludge-to-matter; scenario analysis; treatment selection; circular economy

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1. Introduction

Wastewater management is one of the most relevant issues in the transition towards circular economy (CE). In the present paper, a specific area of interest relates sewage sludge (SS), the byproduct of wastewater treatment (WWT). Recovery of energy and matter by SS is of great economic and environmental interest. SS contains, in dewatered condition, 50–70% of organic matter, 30–50% of mineral components, 3–4% of nitrogen (N), 0.5–0.25% of phosphorous (P), and significant amounts of the other useful nutrients [1]. Moreover, the phosphorus (P), that can be recovered by SS treatments, is classified as a critical raw material (CRM) [2], estimated to be exhausted in the next 50–100 years [1]; in other words, it is considered a strategic and relevant material from an economic perspective, with a high supply risk [2,3]. On the other hand, SS also contains highly dangerous contaminants, both organic and inorganic, and pathogens (i.e., bacteria, viruses, protozoa, etc.) [1].

SS treatments are highly energy-consuming processes, which are responsible for around 40% of the greenhouse gas (GHG) emissions of the wastewater treatment plants (WWTPs) [4] and of 50% of the annual operating costs of a WWTP [5]. However, SS is a byproduct suitable to produce energy in this way, also contributing to energy recovery. The low calorific value of an SS with 6% moisture content and 65% organic matter is estimated to be 13.5 kJ/kg [6]. This value is comparable with the value of traditional fuels such as lignite and other biomasses. From this point of view, SS can be considered a solid fuel [7]. Energy recovered can be adopted in SS treatments plants and, in some cases, also improve the economic balance of the SS management. For example, the SS combustion provides thermal energy that can be adopted for drying sewage sludges before the sludge combustion. Hence, SS is a resource for different energy/matter recovery scenarios. It is essential that all recovery opportunities are exploited as much as possible, to contribute to overcoming economic and environmental criticalities that arise in this context.

The SS production rate generated from WWT is growing day by day as the water demand, and, thus, the amount of wastewater produced, is on increase [8]. The rapid increase depends on two main factors. The first one is strictly related to the increase in world population; the second one is the indirect consequence of the forced implementation of the European Council Wastewater Treatment Directive 97/271/EC, which requires a higher quality of the effluent treated with the unavoidable increase of the SS produced as a byproduct of wastewater treatments [9].

The SS management is regulated by the prescriptions of the "waste hierarchy", introduced by the Waste Framework Directive 2008/98/EC, which describes the order of actions to be implemented to manage waste in a CE perspective (i.e., prevention, preparing for reuse, recycling, recovery, disposal). To achieve this target, "4Rs" are usually implemented, i.e., reduction, reuse, recycle, and recovery. To take a further step towards achieving a circular approach it is necessary, in addition to implementing the "4Rs", to apply a fifth "R" due to "rethink" of the process [3]. Therefore, a solution consistent with the CE approach and the "nutrients-energy-water" (NEW) paradigm is strictly required [3].

Rethinking the wastewater value chain means promoting a shift from the traditional concept of WWTP to that of wastewater resource recovery facilities [10].

Consistently, the design and the choice of a suitable sewage sludge treatment plant (SSTP) under a sustainable perspective is a fundamental issue in SS management.

To this concern, the main environmental and economic objectives to be pursued by a SSTP are:

1. To convert the undesirable constituents into less dangerous substances (e.g., dead microorganisms, precipitates, or inorganic carbon);
2. To recover energy/matter from sewage sludge;
3. To reduce or eliminate the water in raw SS. Unprocessed sludge contains about 85–95% water; this leads to higher costs of raw SS processing, handling, and transportation [11].

Environmental and economic objectives can be pursued by a proper selection of SS treatments.

Considering the objectives mentioned above, the following research questions are raised:

1. Which key drivers affect the choice of the SSTP configuration to be adopted?
2. Is it possible to provide a preliminary evaluation of the technological options of the SSTP to ensure a more efficient SS management from an economic and environmental perspective?

In line with the research gaps highlighted, the research's purpose consists of identifying a set of reference initial scenarios and the corresponding best treatments' selection for configuring SS treatment plants. The scenario analysis conducted reveals a useful reference technical framework when circular economy goals are pursued.

In this paper, a literature review of sludge-to-energy and sludge-to-matter recovery treatments is carried out in Section 2; here, main features of treatments and their ability to meet the above-mentioned goals are discussed. Energy/matter recovery performance measures useful for SS treatment selection are provided. SS treatments as well as economic and environmental background of SSTS are then analyzed in Section 3. Here, a scenario analysis is performed to support the selection of sustainable SSTP processes. Results obtained are discussed in Section 4. Finally, main findings of the paper and conclusions are provided in Section 5. A list of abbreviations and acronyms adopted in the manuscript is provided in Table A1 (Appendix A).

2. A Literature Review on Sludge-to-Energy/Matter Recovery Processes

A literature review analysis on treatments for sludge-to-energy (StE)/matter (StM) recovery has been carried out.

2.1. Literature Review on Sludge-to-Energy (StE) Processes

Many studies are available in the scientific literature on the energy recovery technologies: the first solution considered is the Anaerobic Digestion (AD), a technological option producing biogas for heat and electric energy production. Li et al. compared the environmental performance of the different techniques adopted in AD (i.e., mesophilic and thermophilic anaerobic digestion, mesophilic and thermophilic high-solids anaerobic digestion, and anaerobic digestion with thermal hydrolysis pretreatment); in line with this this purpose, the life cycle assessment (LCA) methodology was adopted [12]. With the aim of maximizing the biogas production, Gherghel et al. listed the possible pretreatments, which, in combination with AD, could increase biogas production by 21–31% [4]. Oladejo et al. provided a review on the StE processes; the authors highlighted two limitations related to AD. The first one is the long duration of the process (from seven days to five weeks); the second one is the low efficiency of conversion of organic matter [7]. They also considered thermochemical treatments such as combustion, pyrolysis, and gasification as alternatives to energy recovery. The low reaction time of these thermochemical treatments assures high treatment rates. However, thermochemical treatments require an SS with lower moisture content. In addition to the recovery of heat from combustion, the benefit due to further energy recovery treatments from the products of pyrolysis (i.e., pyrolytic oil, biochar, and non-condensable gases) and from the gas produced from gasification were evaluated [7]. Other thermal treatments such as incineration, pyrolysis, and gasification were discussed in [13,14]. An overview of the SS thermal treatments in terms of sustainability was provided in [14]. The results showed that the SS incineration performance is better than pyrolysis and gasification treatments in terms of costs, energy efficiency, nutrient recovery, and flexibility of the feedstock dry matter content. To this concern, the authors showed that the pyrolysis ensures the best performance, considering the byproducts' market value. Moreover, the treatment can be downscaled and adopted to small municipalities (i.e., 10,000 inhabitants). In this context, the maximization of the syngas produced from pyrolysis was investigated in [6]. An overview on main StE technologies adopted in industrial applications (i.e., pyrolysis, gasification, and incineration) was provided by Gao et al. [15]. Werle and Sobek defined the StE solutions as a suitable strategy to comply with circular economy goals. Similarly, the gasification was identified as the most proper thermochemical treatment to improve the environmental performance in SS management [16]. Similarly, the Biochar production from SS and microalgae mixtures as well as the consequent energy recoveries due to co-digestion without SS organic wastes are described in [4,17,18]. The efficiency in energetic terms due to hydrothermal carbonization process (i.e., a process where the SS are processed in an aqueous medium of subcritical water) are dealt with in different studies, most of available works conducted investigated the energy recovery obtained from the treatment application in different part of the SS treatment. It was showed that energy efficiency significantly changes accordingly to the adopted treatments; in most cases, the choice depends on the quantity and typology of the SS to be treated [19–22]. Finally, Singh et al. evaluated the potential for energy recovery by incineration and AD for India [23].

In Table 1, the main scientific contributions to the StE treatments classified according to the energy product obtained are summarized.

Despite the high number of available StE processes, incineration and anaerobic digestion processes are generally adopted in current practice.

Table 1. Summary of the sludge-to-energy (StE) processes.

StE Treatment	Energy Product	References
Anaerobic Digestion	Biogas	Gherghel et al. [4] Li et al. [12] Oladejo et al. [7] Singh et al. [23]
Co-digestion of SS with non-sludge organic wastes	Biogas	Gherghel et al. [4] Thorin et al. [18]
Co-pyrolysis of SS and microalgae	Biochar	Bolognesi et al. [17]
Gasification	Biochar Syngas	Bien and Bien [13] Gao et al. [15] Gherghel et al. [4] Oladejo et al. [7] Tsybina and Wuensch [14] Werle and Sobek [16]
Hydrothermal carbonization (HTC) of sewage sludge coupled with AD	Biogas	Gaur et al. [19]
Hydrothermal carbonization (HTC) with CO_2 gasification	Syngas	Shen et al. [20]
Hydrothermal carbonization of high-ash	Hydrochar	Wang et al. [22]
Hydrothermal carbonization of SS with other biomass	Hydrochar	Zhai et al. [21]
Incineration	Flue gases	Bien and Bien [13] Gao et al. [15] Oladejo et al. [7] Singh et al. [23] Tsybina and Wuensch [14]
Pyrolysis	Biochar Bio-oil Biogas	Bien and Bien [13] Gao et al. [15] Karaca et al. [6] Oladejo et al. [7] Tsybina and Wuensch [14]
Supercritical water processing	Heat self-consumed in the process Electricity	Gherghel et al. [4]
Thermal pre-treatments to enhance energy recovery in AD	Biogas	Gherghel et al. [4]

2.2. Performance Measures of Energy Recovery

The sewage sludge plant produced by wastewater treatment has potential for energy recovery by its stabilization in an anaerobic digestion reactor. Biogas basically consists of methane (65–70% in volume) and carbon dioxide (25–30%) with lower fraction of O_2 (ca 0.35% v/v), CO (<0.1% v/v), N_2 (0.5%), H_2S (ca 1570 mg m^{-3}) [24,25]. The methane production from sludge varies between 80–377 mL (CH_4/g) volatile solid. The value depends on the feedstock, the number of digestion days, the process temperature, and the pretreatment methods used. A wide literature review on sludge-to-energy recovery methods is in [7]. Heating value and production rate of biogas depend on several parameters including the process temperature, the reactor volume, the content of volatile fraction in the sludge, type of biological treatment, and plant capacity [26,27]. A reference lower heating value of biogas is 23,300 kJ/Nm^3 for a concentration of methane of 65%. The anaerobic digestion process is usually operated in the mesophilic temperature range (35–40 °C) while the action of methanogens bacteria well performs in the pH range 6.8–7.2 [28]. Biogas production per unit mass of volatile solid substance can vary in a wide range of values: for a sludge with 75% of volatile solid and a digestion process time of 21–25 days a specific biogas production of 0.6–0.8 (Nm^3/kg) of volatile solid can be obtained [8]. Performance measures indexes measuring the efficiency in sludge-to-biogas conversion highly depends on type of sludge. Biogas production ranges from 0.17 (Nm^3/kg) of raw primary sludge to 0.09 (Nm^3/kg) of digested sludge (raw mixed sludge digestion). In terms of population equivalent (PE), biogas production by primary sludge can vary in 15–22 ($Nm^3/(1000\ PE \times day)$) range [29]. It is worth noting that part of biogas production is used to get the electric power to run the process, which shows an average electric consumption of around 250 (kWh/ton) dry solid. Efficiencies of biogas conversion in electricity ranges from 25%, in case of small plant capacity (up to 100 kW) to 45% (more than 500 kW). As far the mono-incineration of sludge is concerned [30], the process efficiency in energy conversion highly depends on dry matter (DM) concentration, which, in turn, depends on the type of sludge. For raw primary sludge, the electric production is around 1.3 (MJ/kg dry); such a value reduces to 0.8 (MJ/kg dry) for digested sludge [31]. An intermediate value of around 1 (MJ/kg dry) of energy conversion can be obtained for raw mixed sludge. Out of the several parameters affecting the economic convenience of biogas production for energy transformation in thermal and/or electric power (e.g., by a cogeneration system), the most significant one is the plant capacity [32]. The plant capacity of 20,000 PE is the minimum value for the economic convenience of the biogas production by anaerobic digestion.

2.3. Literature Review on Sludge-to-Matter (StM) Processes

Gherghel et al. provided a wide review of the StM solutions. The first solution considered is represented by the crystallization treatment for the recovery of phosphorus in form of struvite (i.e., the product of the precipitation of ammoniacal nitrogen and phosphorus). The authors highlighted the possible reuse of struvite as base material in the production of fertilizers, fire-resistant panels, and as binder material in cements. Another relevant recovery considered in this study is focused on the heavy metals one. To this concern, solutions, such as ultrasonication, pyrolysis, and gasification were evaluated. Ultrasonic and pyrolysis treatments of SS, followed by an activation process (i.e., physical and/or chemical), were identified as a solution to produce SS-based adsorbents (SBAs). The organic carbon-containing complexes and inorganic composites from SS, thermal treated, were considered sources of products like artificial lightweight aggregates (ALWA), slacks, bricks, and glass. Moreover, was considered the addition of raw SS for the production of cement and mortar products as well as the addition of the ash derived from the SS combustion to mineral construction materials, cements or concretes, avoiding the ashes landfilling and the consequent negative environmental impact, and, thus, promoting a sustainable model [4]. The proposed solutions offer great potential from a CE perspective; the treatments described provide an overview of the different materials highlighting the recovery potentiality, ensuring to keep products and materials in use, and regenerating natural systems. Havukainen et al. developed a study using the AshDec technology, and evaluated the P-recovery for the SS and manure ash in Finland [33]. Kleemann et al. investigated the possibility of recover phosphorus from incineration SS ash (ISSA) and from pyrolysis SS char (PSSC). They conducted acid leaching experiments and stated that the proportion of P extracted from PSSC was higher due to the higher content of whitlockite, a form of calcium phosphate. Consistent with research conducted, the authors suggested further investigations to find a way to recover P from PSSC [34]. According to Cieslik et al., it is possible to introduce a “no waste generation” concept for the SS management. In this regard, a detailed analysis of technologies for the P-recovery from SS ashes (i.e., acid extraction, thermochemical treatment, cementing) and from leachates (i.e., precipitation of phosphorus in form of struvite, hydroxyapatite) was conducted [35]. An overview of the emerging technologies for the P-recovery, considering the features, costs, and further key performance indicators (e.g., social acceptance, operating costs, cost of implementation, etc.), was carried out to evaluate the applicability of new technologies [36]. In this context, the study of Gorazda et al. represents a link between the topics of StE and P-recovery. The authors evaluate the potential of the solid residue of gasification as a P-source, the study showed that the gasification waste of a common phosphate raw material ensure the same P-recovery of SS ash [37]. Guedes et al. evaluated the possibility of the P-recovery from electrokinetically based technologies (i.e., processes based on the application of a low current between electrodes) [38], while Horttananinen et al. evaluated the potential for N-recovery from thermal drying of SS [39].

In Table 2, the main contribution of the StM treatments available in scientific literature are summarized, classified according to matter recovered/product obtained from the treatment and the matter recovery treatment.

Table 2. Summary of the sludge-to-matter (StM) processes.

StM Treatment	Matter Recovered/ Product Obtained	References
AD	Nutrients	Barampouti et al. [40]
AirPrex ®	P	Gherghel et al. [4]
AshDec ®	P	Gherghel et al. [4] Havukainen et al. [33]
Calcium phosphate precipitation	P	Shaddel et al. [36]
Composting	Nutrients	Lu et al. [41] Rehana et al. [42]
Co-pyrolysis of SS and microalgae	Biochar	Bolognesi et al. [17]
Electro dialysis from incineration SS ash (ISSA)	P	Cieslik et al. [35]
Electrokinetic based processes	P	Guedes et al. [38]
Extraction using mineral or organic acids from ISSA	P	Cieslik et al. [35]
Gasification	P Heavy metals	Gherghel et al. [4] Gorazda et al. [37] Tsybina and Wuensch [14] Werle and Sobek [16]
Hydrothermal treatments	Protein	Gherghel et al. [4]
Incineration	P	Gorazda et al. [43] Kleemann et al. [34] Tsybina and Wuensch [14]
Microwave treatment	Heavy metals SBAs	Gherghel et al. [4]
PHOSPAQ ®	P	Gherghel et al. [4]
Phosphiric acid production	P	Shaddel et al. [36]
Precipitation of phosphoric minerals from SS and leachates	P	Cieslik et al. [35]
Pyrolysis	SBAs Nutrients Heavy metals	Gherghel et al. [4] Kleemann et al. [34] Tsybina and Wuensch [14]
Seaborne ®	P	Gherghel et al. [4]
Struvite precipitation	P	Shaddel et al. [36]
Thermal drying	N	Horttananinen et al. [39]

Table 2. *Cont.*

StM Treatment	Matter Recovered/ Product Obtained	References
Thermal solidification-artificial lightweight aggregates (ALWA)	Building materials	Gherghel et al. [4]
Ultrasonication	Heavy metals Protein Enzymes	Gherghel et al. [4]
Vitrification-GlassPack	Glass	Gherghel et al. [4]

In Table 2, the 'matters' includes the nutrient (i.e., P, N, protein, enzymes) or heavy metals. On the contraray, the 'products' are considered Biochar, SBAs, building materials, and glass.

Despite the high number of available StM treatments, anaerobic digestion and composting processes are generally more adopted in current practice.

2.4. Performance Measures of Matter Recovery

The incineration treatment generates mainly two byproducts, i.e., the flue gas and the SS incineration ash (ISSA), the composition of ISSA produced from SS incineration is summarized in Table A2 (Appendix A). As mentioned, the first is used to produce heat and electricity, while, through the second, it is possible to recover matter. The nutrients present in the SS are indeed retained in the ISSA. According to Kasina et al., an average of 6% by weight of ISSA is present in the dewatered and incinerated SS [44]. The mass content of P in the ISSAs is approximately 7.2–8.6%, up to 8-fold higher than that of the SS [14,34,43].

Two main byproducts, biogas and digestate, are recovered from AD treatment. The digestate constitutes a significant fraction of the raw material that is introduced to the treatment, about 80–90%. The physicochemical characteristics of the digestate are highly variable and depend on the composition of the raw material, as well as on the operating conditions of the treatment. For the SS, in general, the digestate contains 1.9% of dry matter. On average, an AD digestate contains 2.8 g of N, 0.43 g of P, 0.1 g of K, 0.04 g of Ca, 0.03 g of Mg, 0.1 mg of Zn, 0.15 mg of Cu, 0.12 mg of Cd, and 0.16 mg of Ni on a dry basis, per one kg of digestate, the rest consists of traces of various organic/inorganic matters. Once the digestate has been produced, it is possible to obtain the recovery of nutrients through subsequent treatments allowing to spread on agricultural land [40,45].

The composting treatment is considered the preliminary phase to the spreading of the SS on agricultural land to be used as fertilizer or soil amendment. It is an aerobic stabilization allowing killing the pathogens, producing humus, and reducing the moisture content of the SS. The main criticality of the composting treatment related to SS is the high water content of the SS. The water prevents a uniform aerobic condition throughout the mass, avoiding a correct stabilization. Therefore, different bulking agents are adopted with the aim to improve the treated material's structure, promote uniform oxygenation, and improve the moisture content [41]. The compost's characteristics depend on the type of bulking agent used; thus, all the studies conducted are addressed to identify the proper mixtures to mix the SS and improve the compost usability. In 2020, a study investigated on the composition of a compost obtained by mixing SS, two bulking agents (sawdust and coir pith), a heavy metal adsorbent (zeolite), and two liming materials (lime and flyash) in different percentages. The added elements allowed to improve the bioavailability of heavy metals and their solubility, making the compost suitable for spreading on agricultural land. As part of the study, eight different samples were analyzed and, with particular reference to the presence of nutrients, a maximum percentage of N of 1.72%, of P of 1.24%, of K of 0.29%, of Ca of 19.06%, of Mg of 12.72%, and 0.492% of S was recorded [42].

3. Selecting Technological Options in a Sewage Sludge Treatment Plant

3.1. The Sewage Sludge Treatment System (SSTS)

A Sewage Sludge Treatment System (SSTS) consists of five main phases (Figure 1). By the first phase, thickening treatment, the water content of SS is reduced. The minimization of SS volume to be processed allows reducing handling and tanks' storage capacity. The benefits in terms of flexibility (i.e., variable volumes, variable quality of the influent, etc.) and investment costs related to material handling equipment to be adopted are remarkable.

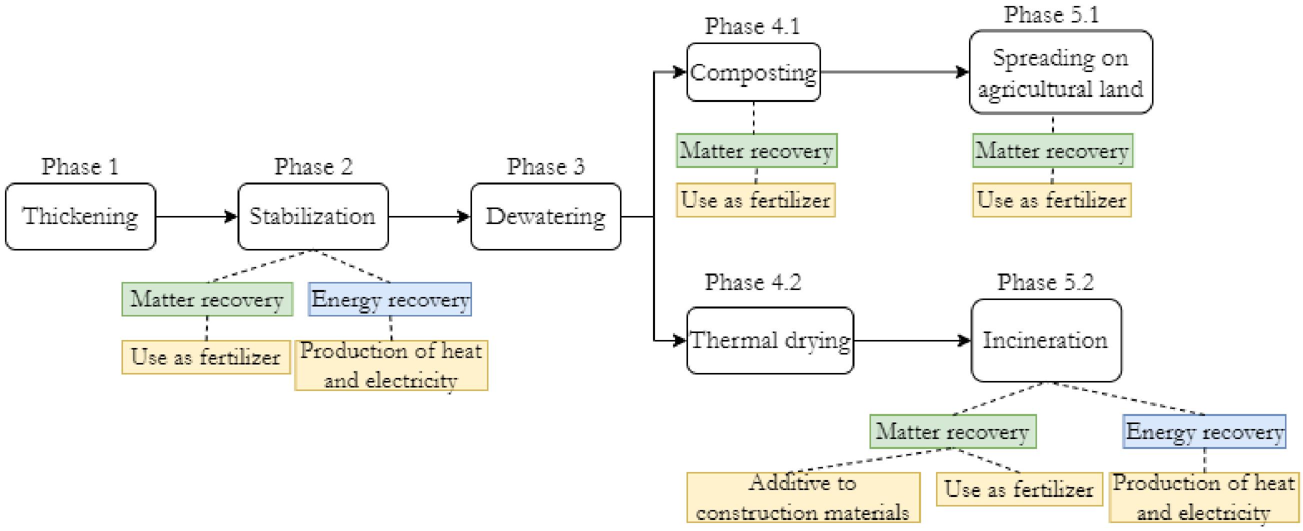

Figure 1. Framework of the sewage sludge treatment system (SSTS) considered by the present study with the indication of energy and matter recoveries, which are achieved within each phase.

The second phase consists of a stabilization treatment; this step contributes to reducing pathogens content, eliminating bad odors, and mitigating the potential for further biodegradation of the SS. An efficient stabilization treatment facilitates the operations finalized to recover and reuse SS and to ensure a safe manipulation of the SS by the operators. The third phase consists of dewatering treatment allowing handling the dewatered SS as a solid material. The composting (i.e., phase 4.1) or thermal drying (i.e., phase 4.2) are optional treatments whose adoption is strictly related to the final matter/energy recovery options.

3.2. Economic and Environmental Background of SSTS

In scientific literature, many economic and environmental issues affecting the SSTS have been addressed. Regarding the environmental impact of SS treatments, it has already been pointed out that SS, being rich in contaminants and pathogens, could represent a threat to human health and the environment. Similarly, recent studies proved that the high energy consumption and the chemical emission produced during the SS treatment are responsible for 40% of the total GHG emissions of the entire wastewater treatment [4]. Generally, in developed countries, it is estimated that the energy consumption required from WWTPs is responsible for 3% of total energy consumption. Similarly, the CO_2, N_2O, and CH_4 emissions from WWTPs account for 4%, 3%, and 5% of total emissions, respectively. The relevance of the environmental impact due to SS treatment is related to substance emitted and electricity consumption; in particular, the N_2O and the energy consumption are individuated as the primary sources of GHG emissions [46].

A widely-used methodology to assess the environmental impact of SS treatments is the life cycle assessment (LCA). Buonocore et al. compared different scenarios referred to different wastewater and sludge disposal practices. The first scenario was based on the landfilling of SS. The second one included a partially circular pattern, i.e., the recovery of energy from AD and the SS landfilling. In the third scenario, a gasification process was added to AD to enhance heat and electricity production. The fourth scenario differs from the third for the adoption of the wastewater for fertirrigation. The last scenario assumed that a supply of green electricity mix was adopted from WWTP. The LCA analysis results showed that the most impacted categories for all the scenarios were Freshwater Eutrophication Potential, Human Toxicity Potential, Global Warming Potential, and Fossil Depletion Potential [47]. To this concern, a new impact category in LCA (i.e., quantitative microbial risk assessment) has been included to evaluate the effects of pathogens on human health [48]. Gourdet et al. carried out an LCA to assess the environmental impacts of some technological parameters related to SS treatments; the work results showed that the SS line's environmental performances could be enhanced, increasing the efficiency of the AD treatment and reducing the $FeCl_3$ consumption of the process. In other words, according to the authors, higher efficiency in the production of biogas could lead to a significant reduction of the environmental impact [49]. The LCA methodology was adopted to compare the environmental impact of different final recovery options as land spreading, composting, incineration, landfilling, and wet oxidation. Results showed that the SS land spreading is the alternative with the lower impact on abiotic depletion, fossil fuel depletion, and global warming categories, but with the highest impact on toxicity for humans and ecosystems. The authors proved that the SS's composting before land spreading allows reducing the negative impacts of SS land spreading on all categories previously mentioned to the exclusion of global warming and resources depletion categories [50].

Regarding the economic implications of SS treatments, it has been already highlighted that SS management represents a significant item-cost of the total costs of a WWTP. A costs estimation of different SS treatments has been provided by Kacprzak et al., according to the authors at the disposal of raw sludge on land corresponds to a cost of 160 €/t of DM produced; the disposal of dry sludge on land has a cost of 210 €/t of DM. Similarly, for the use of the SS in forestry, composting, incineration, reclamation of areas, and landfilling has an estimated cost of 240 €/t of DM, 310 €/t of DM, 315 €/t of DM, 255 €/t of DM, and 255 €/t of DM, respectively [5]. Tsybina and Wuensch evaluated the total cost due to the treatments of incineration, pyrolysis, and gasification. A value of 35 M€ in capital costs, 5.5 M€ per year in running cost, and 157 €/Mg of dry-solid produced in specific costs, has been estimated [14].

The economic convenience of carrying out specific treatments is analyzed for each scenario in Section 4.

3.3. Technological Options

Each of the phases introduced in the general framework of a SSTS (Figure 1) can be carried out by different possible technological options. In this paper, the authors consider sustainable technological options, which are most adopted in practical cases. For the thickening phase (first phase of a SSTS), the alternative technology options considered are: thickening in sedimentation ($Thick_1$), gravity thickening ($Thick_2$), dissolved air flotation ($Thick_3$), and a hybrid solution (i.e., $Thick_2$ for primary sludge and gravity belt thickening for secondary sludge, indicated as $Thick_4$). Similarly, for the stabilization treatment (Sta), the second phase in a SSTS, four options have been identified: lime stabilization, (Sta_1); aerobic digestion, (Sta_2); anaerobic digestion, (Sta_3); and a hybrid solution (Sta_4), i.e., Sta_3 for primary sludge and Sta_2 secondary sludge. For the sludge dewatering phase (third phase), three options are identified: drying beds dewatering (Dew_1); filter press dewatering (Dew_2); and belt press dewatering (Dew_3).

The fourth phase consists of SS composting (phase 4.1) whose matter generates two recovery options (phase 5.1): spreading of the not-dewatered SS (Fin_1) or of dewatered SS (Fin_2) on the agricultural land. The thermal drying (phases 4.2) is a preliminary treatment of SS for energy and matter (ash) recovery by incineration (phase 5.2, Fin_3).

Alternative treatments considered for each phase of SSTS are summarized in Figure 2.

Figure 2. Summary of the alternative technological options considered by the scenario analysis for each SSTS phase.

3.4. Scenario Analysis for Selecting Technological Options for a SSTP

In this section, a scenario analysis is proposed to select technological options and configure a sewage sludge treatment plant (SSTP). Each scenario is identified by a set of scenario variables.

Input Variables to the Scenario Analysis for the Selection of Treatments of a SSTP

Input variables that are considered as most significant for identifying the initial scenario to be considered in the selection process are:

1. Plant capacity (PC): it represents the number of equivalent inhabitants to be served by the plant. Five classes of PE are identified.
2. Secondary WWT (SWWT) performed in WWTP: it represents the type of secondary treatment adopted in the WWTP (upstream process for SSTPs), which affects the quality and quantity of SS to be treated. The first wastewater treatment considered ($SWWT_1$) is the chemical treatment; the second possible treatment ($SWWT_2$) is the activated sludges treatment.
3. Lime utilization (LIME): it represents the adoption of lime as the main reagent within the secondary chemical treatment. The first option considered is the use of other reagents instead of lime within the secondary chemical treatment ($LIME_1$), while the second option is represented by lime within the same phase ($LIME_2$).

4. WWT plant (WWTP): this variable represents the configuration of the sludge line. Two configurations are considered: the first one is on a "single line" (option $WWTP_1$) where the primary and the secondary SS are processed together on the same plant. The second one is identified as "separated lines" (option $WWTP_2$); in this case, two different lines are adopted to treat the primary and secondary SS;
5. Organic load from the WWTP (OL): the variable represents the content of the soluble and particulate organic matter in water treated from the WWTP. It is given by the ratio between the amount of the load of BOD_5 (F, kg BOD_5) over the total mass of the mixed liquor volatile suspended solids (MLVSS, kg), per unit time (T, day)

$$OL = \frac{F}{MT}\left[\frac{\text{kg BOD}_5}{\text{kg MLVSS} \times \text{d}}\right] \quad (1)$$

Two ranges of OL values are considered to express the relevance of the organic load in the wastewater stream: OL $\leq$ 0.1 (OL_1); OL > 0.1 (OL_2);

The input variables adopted to support the selection of proper SSTP treatments are summarized in Table 3.

Table 3. List of the input parameters of the scenario analysis.

Input Variables [Unit of Measurement]	Range of Variability
PC [PE]	#1: [0, 5000] PE #2: [5000, 10,000] PE #3: [10,000, 20,000] PE #4: [20,000, 100,000] PE #5: [100,000, +∞] PE
SWWT [#]	$SWWT_1$: chemical treatment $SWWT_2$: activated sludges
LIME [#]	$LIME_1$: not Lime $LIME_2$: Lime
WWTP [#]	$WWTP_1$: single line $WWTP_2$: separated lines
OL $\left[\frac{\text{kg BOD}_5}{\text{kg MLVSS} \times \text{d}}\right]$	OL_1: $OL \leq 0.1 \frac{\text{kg BOD}_5}{\text{kg MLVSS} \times \text{d}}$ OL_2: $OL > 0.1 \frac{\text{kg BOD}_5}{\text{kg MLVSS} \times \text{d}}$

By combining the possible values assumed by the input variables, eighty possible scenarios are identified. However, meeting technological constraints reduces the actual number of possible scenarios. The adoption of lime as the main reagent in the secondary treatment (option $LIME_2$) could be considered, provided that in the chemical secondary treatment option $SWWT_1$ is adopted. The SWWT value affects the values of OL and WWTP so such input variables will be considered, provided that the secondary treatment of WWTP is based on activated sludge (option $SWWT_2$). Indeed, the OL is a measure of the activated sludge plants; therefore, the plants that operate with a secondary chemical treatment ($SWWT_1$) do not produce a secondary sludge. In these cases, a separate treatment is not allowed.

In case of PC = #1 and PC = #2 (PE $\in [0,\ 10,000]$) only a single line (option $WTTP_1$) is considered as the best choice from an economic perspective. Furthermore, the method of final recovery is considered as being dependent on plant capacity, only. Finally, the composition of SS produced is assumed to be compliant with limits set by the Council Directive 86/278/EEC.

After considering the technological or economic constraints coming from field experience, literature findings, and normative regulations, the initial set of 80 configurations reduces to 26 sustainable SS treatment.

The strategy suggested can be improved through quantitative assessments, considering the specific characteristics of the SS produced.

All proposed SSTP configurations are illustrated and discussed in the next section.

4. Results and Discussions

For each initial scenario identified by a set of input variables, the corresponding most appropriate sewage sludge plant configuration is identified on the basis of opinion of experts and findings from scientific literature. The set of 26 initial scenarios and corresponding plant configurations are summarized in Table 4, where each line identifies the possible values assumed by the input variables (i.e., PC, SWWT, LIME, OL, and WWTP) and the corresponding SSTP configurations, divided into six columns, suggested by the study conducted (i.e., Thick, Sta, Dew, Comp, ThDry, Fin). It is possible to observe that different technological options, according to Figure 2, are available for each of six treatments (e.g., $Thick_1$, $Thick_2$, $Thick_3$, $Thick_4$, Sta_1, etc.). Authors provide the notes shown in "StE" and "StM" columns if the SSTP configuration suggested includes treatments with the recovery of energy (StE—yes) and/or matter (StM—yes). Notation adopted for identifying input variables is in Table 3 while the selected processes are identified by notation defined in Figure 2. Finally, in the "StE" and "StM" columns information on possible recovery of energy and/or matter by adopting the suggested SS treatments are provided.

Table 4. Scenario analysis: summary of initial 26 scenarios vs. corresponding SSTP configurations.

ID Scenario	Initial Scenario					Sewage Sludge Treatment Plant Configuration							
	PC [PE]	SWWT [#]	LIME [#]	OL $[\frac{kg\ BOD_5}{kg\ MLVSS \times d}]$	WWTP	Thick	Sta	Dew	Comp	ThDry	Fin	StE	StM
1	#1	$SWWT_2$	-	OL_1	-	$Thick_1$	no	no	no	no	Fin_1	no	yes
2	#1	$SWWT_2$	-	OL_2	-	$Thick_1$	Sta_2	no	no	no	Fin_1	no	yes
3	#1	$SWWT_1$	$LIME_2$	-	-	$Thick_1$	Sta_1	no	no	no	Fin_1	no	yes
4	#1	$SWWT_1$	$LIME_1$	-	-	$Thick_1$	Sta_2	no	no	no	Fin_1	no	yes
5	#2	$SWWT_1$	$LIME_2$	-	-	$Thick_2$	Sta_1	Dew_1	no	no	Fin_2	no	yes
6	#2	$SWWT_1$	$LIME_1$	-	-	$Thick_2$	Sta_2	Dew_1	yes	no	Fin_2	no	yes
7	#2	$SWWT_2$	-	OL_1	-	$Thick_2$	no	Dew_1	yes	no	Fin_2	no	yes
8	#2	$SWWT_2$	-	OL_2	-	$Thick_2$	Sta_2	Dew_1	yes	no	Fin_2	no	yes
9	#3	$SWWT_1$	$LIME_2$	-	-	$Thick_3$	Sta_1	Dew_2	no	no	Fin_2	no	yes
10	#3	$SWWT_1$	$LIME_1$	-	-	$Thick_3$	Sta_2	Dew_2	yes	no	Fin_2	no	yes
11	#3	$SWWT_2$	-	OL_1	$WWTP_1$	$Thick_2$	no	Dew_3	yes	no	Fin_2	no	yes
12	#3	$SWWT_2$	-	OL_2	$WWTP_1$	$Thick_2$	Sta_2	Dew_3	yes	no	Fin_2	no	yes
13	#3	$SWWT_2$	-	OL_1	$WWTP_2$	$Thick_4$	no	Dew_3	yes	no	Fin_2	no	yes
14	#3	$SWWT_2$	-	OL_2	$WWTP_2$	$Thick_4$	Sta_2	Dew_3	yes	no	Fin_2	no	yes
15	#4	$SWWT_1$	$LIME_2$	-	-	$Thick_3$	Sta_1	Dew_2	no	no	Fin_2	yes	yes
16	#4	$SWWT_1$	$LIME_1$	-	-	$Thick_3$	Sta_3	Dew_2	yes	no	Fin_2	yes	yes
17	#4	$SWWT_2$	-	OL_1	$WWTP_1$	$Thick_2$	no	Dew_3	yes	no	Fin_2	yes	yes
18	#4	$SWWT_2$	-	OL_2	$WWTP_1$	$Thick_2$	Sta_3	Dew_3	yes	no	Fin_2	yes	yes
19	#4	$SWWT_2$	-	OL_1	$WWTP_2$	$Thick_4$	no	Dew_3	yes	no	Fin_2	yes	yes
20	#4	$SWWT_2$	-	OL_2	$WWTP_2$	$Thick_4$	Sta_4	Dew_3	yes	no	Fin_2	yes	yes
21	#5	$SWWT_1$	$LIME_2$	-	-	$Thick_3$	Sta_1	Dew_2	no	yes	Fin_3	yes	yes
22	#5	$SWWT_1$	$LIME_1$	-	-	$Thick_3$	Sta_3	Dew_2	no	yes	Fin_3	yes	yes
23	#5	$SWWT_2$	-	OL_1	$WWTP_1$	$Thick_2$	no	Dew_2	no	yes	Fin_3	yes	yes

Table 4. *Cont.*

ID Scenario	Initial Scenario				Sewage Sludge Treatment Plant Configuration								
	PC [PE]	SWWT [#]	LIME [#]	OL $[\frac{kg\ BOD_5}{kg\ MLVSS\ \times d}]$	WWTP	Thick	Sta	Dew	Comp	ThDry	Fin	StE	StM
24	#5	$SWWT_2$	-	OL_2	$WWTP_1$	$Thick_2$	Sta_3	Dew_2	no	yes	Fin_3	yes	yes
25	#5	$SWWT_2$	-	OL_1	$WWTP_2$	$Thick_4$	no	Dew_2	no	yes	Fin_3	yes	yes
26	#5	$SWWT_2$	-	OL_2	$WWTP_2$	$Thick_4$	Sta_4	Dew_2	no	yes	Fin_3	yes	yes

"-" indicates that the corresponding variable is not relevant to the assessment of the scenario.

4.1. Plant Capacity #1 (Max 5000 PE)

For plant capacity values in the first range of capacity variability high investment costs are not considered sustainable and the plant configuration suggested generally includes the processes of thickening in sedimentation, stabilization, and spreading of not dewatered SS on agricultural land. Dedicated thickening systems are not evaluated as economically sustainable [32] while a stabilization treatment is required to ensure the safe handling and disposal of SS with a significant reduction of the running costs and the environmental impacts.

The dewatering of SS requires not negligible investment and operating costs and, at the same time, allows reduction of transport costs. A trade-off economic analysis is required case by case to evaluate the opportunity of including the dewatering treatment. The experts' opinion identifies the cost-effective threshold of dewatering treatment at plant capacity of 5000 PE: beyond such capacity value it reveals as convenient spreading dewatered SS on agricultural land since transport costs overcome costs of dewatering treatments.

On the basis of the above general considerations, four scenarios belonging to this class of plant capacity have been identified.

According to scenario 1, upstream treatment of wastewater includes:

- a secondary treatment by activated sludges, i.e., SWWT = $SWWT_2$.
- OL ≤ 0.1 (kg BOD_5/(kg MLVSS $\times$ d), i.e., OL = OL_1.

In this scenario, a dedicated stabilization phase is not recommended (Sta = no) in configuring the SSTP, since the SS can be considered stabilized by the biological oxidation phase of the waterline, being the OL's value adequately low i.e., OL = OL_1 [32].

Scenario 2 differs from scenario 1 for the input variable OL: OL > 0.1 (kg BOD_5)/(kg MLVSS $\times$ d), i.e., OL = OL_2. Therefore, the aerobic digestion process (Sta_2) is required for the SSTP configuration. Indeed, in low plant capacity, the anaerobic digestion process (Sta_3) is not recommended since it is considered too costly for low plant capacity [32,51].

According to scenario 3, differently from scenario 1, it is assumed a chemical secondary treatment of wastewater (i.e., SWWT = $SWWT_1$), performed by LIME (i.e., LIME = $LIME_2$). Consequently, the SSTP will include a lime stabilization (Sta_1) [32]. On the contrary, considering scenario 4, the aerobic digestion process (Sta_2) is suggested since the sludge is treated without lime (LIME = $LIME_1$) in the secondary treatment of the SWWT and needs to be biologically stabilized [32].

None of the first four scenarios depends on the WWTP sludge line configuration (single or separated). In the single line, the primary and the secondary sludge are mixed and treated within the same facility (WWTP = $WWTP_1$). On the contrary, in case of separated WWTP sludge lines the primary and the secondary sludge are treated separately (WWTP = $WWTP_2$), improving the efficiency of the SSTP. Separate treatments are more effective while requiring higher operating costs and investment. In plants with the single line configuration (WWTP = $WWTP_1$), the SS is not separated; therefore, primary and secondary sludges will be treated jointly.

The SSTP will not include separate treatments of the SS even in the case of separate flows of primary and secondary SS (WWTP = $WWTP_2$) since the configuration of the separated lines for SS is not economically sustainable for low plant capacity.

4.2. Plant Capacity #2 (5000 < PE ≤ 10,000)

For plant capacity values in the second range of capacity variability, the SSTP configuration generally includes a gravity thickening treatment ($Thick_2$), followed by a stabilization treatment, dewatering through drying beds (Dew_1), composting (only if the SS has been stabilized biologically), and spreading of dewatered SS in agricultural land (Fin_2). In these cases, the growing volumes of SS produced justify an investment in dedicated thickening systems [32]. As far as the dewatering treatment is concerned, the adoption of mechanical systems is not suggested, since they are too costly for this class of WWTPs capacity [32]. In class of plant capacity, the dewatering treatment is sustainable from economic point of view and SS are spread on agricultural land in a dewatered state (Fin_2).

Four scenarios included in this class of plant capacity have been identified.

According to scenario 5, the upstream treatment of wastewater includes:

- a chemical secondary treatment (SWWT = $SWWT_1$).
- the use of lime in the secondary treatment (LIME = $LIME_2$).

In this scenario, a stabilization treatment through lime stabilization (Sta_1) is suggested since the SS in this case cannot be stabilized biologically due to the use of lime and, consequently, a composting treatment (Comp = no) is not recommended, since this kind of treatment is not considered compatible with a chemical stabilization.

Scenario 6 differs from scenario 5 only for the input variable LIME as:

- LIME = $LIME_1$, i.e., lime was not used as the main reagent during the secondary treatment.

In this case, a stabilization through aerobic digestion (Sta_2) is suggested, and then, being the SS biologically stabilized, a composting treatment is recommended (Comp = yes).

According to scenario 7, upstream treatment of wastewater includes:

- an activated sludges secondary treatment, i.e., SWWT = $SWWT_2$.
- OL $\leq$ 0.1 (kg BOD_5)/(kg MLVSS $\times$ d), i.e., OL = OL_1.

Being the OL's value adequately low, a dedicated stabilization phase is not recommended (Sta = no) [32], while a composting treatment (Comp = yes) is suggested before spreading the SS on agricultural land.

Scenario 8 differs from scenario 7 only for the input variable OL as:

- OL > 0.1 (kg BOD_5)/(kg MLVSS $\times$ d), i.e., OL = OL2.

In this case, a stabilization treatment through aerobic digestion (Sta_2) and a composting treatment (Comp = yes) is suggested. The prescription of an aerobic digestion (Sta_2) instead of anaerobic one (Sta_3) follows the same consideration highlighted for class #1, in which aerobic digestion is considered more economically sustainable [51].

Similarly to scenarios from 1 to 4, the SSTP will not include separate treatments of the SS even in the case of separate flows of primary and secondary SS (WWTP = $WWTP_2$) since the configuration of the separated lines for SS is not economically sustainable for low plant capacity.

4.3. Plant Capacity #3 (10,000 < PE ≤ 20,000)

The SSTP configuration suggested for the WWTPs with plant capacity ranging in the third class of plant capacity is very similar to the one suggested for a second class plant capacity (i.e., thickening, stabilization, dewatering, composting, and spreading of dewatered SS on agricultural land). The main difference relates to higher sustainable investments due to higher plant capacity. Consistently, higher investments in dissolved air flotation ($Thick_3$) and mechanical dewatering systems can be made to achieve better technological performance.

Six scenarios belong to this class of plant capacity have been identified.

According to scenario 9, upstream treatment of wastewater includes:

- a chemical secondary treatment (SWWT = $SWWT_1$).
- the use of lime within the secondary treatment (LIME = $LIME_2$).

In this scenario, a thickening through dissolved air flotation ($Thick_3$) and filter press dewatering (Dew_2) are recommended. They are expensive systems but offer better technological performance on chemical SS [32]. According to scenario 5, a stabilization treatment trough lime stabilization (Sta_1) is suggested, and, consequently, a composting treatment (Comp = no) is not recommended.

Scenario 10 differs from scenario 9 only for the input variable LIME as:

- LIME = $LIME_1$, i.e., lime was not used as the main reagent during the secondary treatment.

In this case, a stabilization trough aerobic digestion (Sta_2) is suggested, and then, being the SS biologically stabilized, a composting treatment is recommended (Comp = yes).

According to scenario 11, upstream treatment of wastewater includes:

- an activated sludges secondary treatment, i.e., SWWT = $SWWT_2$.
- OL $\leq$ 0.1 (kg BOD_5)/(kg MLVSS $\times$ d), i.e., OL = OL_1.
- a single sludge line configuration (WWTP = $WWTP_1$).

Due to a single line configuration of the WWTP (WWTP = $WWTP_1$), a gravity thickening ($Thick_1$) followed by the belt press dewatering (Dew_3) are considered as more flexible treatments to face with SS flowrate variability; however, such a choice causes a lower average performance of the SS thickening of the primary and secondary mixture.

Being that the OL's value is adequately low, a dedicated stabilization phase is not recommended (Sta = no) [32] while a composting treatment (Comp = yes) is suggested before spreading the SS on agricultural land.

Scenario 12 differs from scenario 11 only for the value of the input variable OL, as OL = OL_2. In this case, stabilization through aerobic digestion (Sta_2) is suggested.

According to scenario 13, upstream treatment of wastewater includes:

- an activated sludges secondary treatment, i.e., SWWT = $SWWT_2$.
- OL $\leq$ 0.1 (kg BOD_5)/(kg MLVSS $\times$ d), i.e., OL = OL_1.
- a separated sludge line configuration (WWTP = $WWTP_2$).

For this scenario, a gravity thickening is the appropriate treatment for the primary SS and a gravity belt thickening for the secondary SS ($Thick_4$) to exploit the great sedimentability of primary SS and to offer greater SS storage capacity in case of the SS flowrate variability [32].

Although the separated primary and secondary SS treatments can be considered the most appropriate option for the stabilization phase, such an option is not economically sustainable. In such a scenario, the low value of OL suggests the adoption of a composting treatment (Comp = yes) before SS spreading on the agricultural land without a dedicated stabilization phase (Sta = no). Finally, a belt press dewatering (Dew_3) is suggested as it is considered the most effective treatment which is also economically sustainable in this class of plant capacity (>10,000 PE) [32].

Scenario 14 differs from scenario 13 only for the value of the input variable OL, as OL = OL_2. In this case, stabilization through aerobic digestion (Sta_2) reveals the most effective treatment, also sustainable from an economic point of view in this class of plant capacity.

4.4. Plant Capacity #4 (20,000 < PE < 100,000)

The SSTP configuration suggested for the fourth class's WWTPs plant capacity is very similar to the SSTP of the third plant capacity class. Considering the six different scenarios (i.e., scenarios from 15 to 20), the configurations of the SSTP suggested for scenarios 15, 17, and 19 are identical to the ones suggested for scenarios 9, 11, and 13, respectively. The main difference relates to the stabilization treatment, which consists of an anaerobic digestion (Sta_3) for scenarios 16 and 18 having high organic load, i.e., OL > 0.1 (kg BOD_5)/(kg MLVSS $\times$ d), and no lime use in the secondary treatment was previously carried out in the WWTP (LIME = $LIME_1$).

Finally, scenario 20 differs from scenario 14 only in the separate adoption of the anaerobic digestion for the primary SS and the aerobic digestion (Sta_4) for the secondary SS to maximize biogas production [52].

4.5. Plant Capacity #5 (PE $\geq$ 100,000)

Finally, for the WWTPs with high plant capacity ($\geq$100,000 PE), it is suggested to carry out a series of treatments that have as final objective the SS's incineration (Fin_3), i.e., thickening, stabilization, filter press dewatering (Dew_2), thermal drying (ThDry = yes). This choice is consistent with the highest cost of the incineration treatment, applicable only in the case of very large plants [32]. In this case, six scenarios have been considered (i.e., scenarios from 21 to 26), where solutions similar to the ones belonging to the previous class of plant capacity are suggested: here the difference relates only to the high dewatering level required for incineration: here a filter press dewatering (Dew_2) and a thermal drying (ThDry = yes) are recommended [32].

5. Conclusions

The increasing flowrate of wastewater plants (WWTP) and of the corresponding sewage sludges (SS) give rise the scientific and industrial interest in building up an easy tool for identifying sustainable sewage sludge treatment plant (SSTP) configurations. SS is at the same time a source for energy/matter recovery and a source of contaminants and pathogenic substances. Sustainability of solutions should be searched under a circular economy perspective and be compliant with environmental, economic, and technological constraints. The design of SSTP is generally considered complex due to conflicting objectives and interests.

The paper, after reviewing scientific literature on technical and economic performance of sludge-to-energy and sludge-to-matter recovery technologies, proposes a reference model to support decision-making by a scenario analysis in selecting sustainable processes of a SSTP. On the basis of SSTP capacity and treatments adopted in the upstream WWTPs facilities producing sludge to be treated, 26 initial scenarios are considered; they cover almost all potential practical situations a technical decision maker can be faced with. Scenarios differ in quantity and quality of sludge to be treated. Each scenario is identified by a set of input variables. Literature findings and experts' opinions allowed us to relate input variables of a WWTP to a sustainable SSTP configuration compliant with economic and environmental constraints.

The suggested SSTP configurations identified in the present study are consistent with the sustainable circular economy goals concerning technological constraints of different alternative treatments considered for each phase of SSTS.

It is worth observing that matter recovery occurs in all scenarios while energy recovery is a target pursued in capacity plant higher than 20,000 PE. Indeed, in a smaller capacity plant, the high investment cost of energy recovery facilities results is hard to justify. In most cases, the performances are not consistent with the low volume of SS to be treated. The scenario analysis approach proposed can be considered a guide to standardize decision-making in SSTP configuration. The model reveals a useful tool for decision-makers who are not really experts of the SS treatments plant, while requiring a technical awareness of technological solutions that can be considered eligible for further deep analysis.

On the one hand, the intended results underline the effectiveness of the study conducted to support the decision-making process concerning the management of the SS from a CE perspective. On the other hand, further studies are required on these issues; the study conducted provides a preliminary evaluation of the environmental impact due to each alternative treatment considered; the SSTP configurations suggested are based on experts' opinions and findings from the scientific literature. From this point of view, an in-depth analysis of each scenario's economic and environmental aspects could allow quantifying the impact related to a different scenario. For this scope, many existing methodologies allow investigating the economic and environmental aspects (e.g., SWOT, LCA, LCC, ERA, etc.), providing a 'weight' associated with the proposed scenario. Consistent with this issue, further deep technical/economic analyses are required to better support decision-making in detailed economic/environmental evaluations.

To this concern, the future directions to follow for further studies in this field are to carry out an in-depth economic and environmental analysis of the SSTP, as well as it could be useful to carry out simulations of the configurations suggested on a pilot plant and compare the results obtained with those of other authors or of the theoretical analysis itself.

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Appendix A

A list of abbreviations and acronyms adopted in the present manuscript is provided below (Table A1).

Table A1. List of abbreviations and acronyms.

Abbreviation	Meaning
#1	Plant capacity ∈ [0, 5000] PE
#2	Plant capacity ∈ [5000, 10,000] PE
#3	Plant capacity ∈ [10,000, 20,000] PE
#4	Plant capacity ∈ [20,000, 100,000] PE
#5	Plant capacity ∈ [100,000, +∞] PE
AD	Anaerobic digestion
Al	Aluminum
ALWA	Artificial lightweight aggregates
As	Arsenic
Ca	Calcium
Cd	Cadmium
CE	Circular economy
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
Comp	Composting
Cr	Chromium
CRM	Critical raw material
Cu	Copper
Dew_1	Drying beds dewatering
Dew_2	Filter press dewatering
Dew_3	Belt press dewatering
Dew_i	Dewatering

Table A1. *Cont.*

Abbreviation	Meaning
DM	Dry matter
ERA	Environmental risk assessment
Fe	Iron
$FeCl_3$	Ferric chloride
Fin_1	Spreading of not dewatered sludge on agricultural land
Fin_2	Spreading of dewatered sludge on agricultural land
Fin_3	Incineration
Fin_i	Final recovery
GHG	Greenhouse gas
H_2S	Hydrogen sulfide
HTC	Hydrothermal carbonization
ISSA	Incineration sewage sludge ash
K	Potassium
LCA	Life cycle assessment
LCC	Life cycle costing
LIME	Lime utilization
$LIME_1$	Not lime utilization during chemical secondary treatment
$LIME_2$	Lime utilization during chemical secondary treatment
Mg	Magnesium
Mn	Manganese
N	Nitrogen
N_2	Dinitrogen
N_2O	Nitrous oxide
NEW	Nutrients-energy-water
Ni	Nickel
O_2	Dioxygen
OL	Organic load
OL_1	Organic load $\leq 0.1\ \frac{\text{kg BOD}_5}{\text{kg MLVSS} \times \text{d}}$
OL_2	Organic load $> 0.1\ \frac{\text{kg BOD}_5}{\text{kg MLVSS} \times \text{d}}$
P	Phosphorus
Pb	Plumbum
PC	Plant capacity
PE	Population equivalent
PSSC	Pyrolysis sewage sludge char
S	Sulfur
SBAs	Sewage sludge-based adsorbents
SS	Sewage sludge
SSTP	Sewage Sludge treatment plant
SSTS	Sewage sludge treatment system
Sta_1	Lime stabilization

Table A1. *Cont.*

Abbreviation	Meaning
Sta_2	Aerobic digestion
Sta_3	Anaerobic digestion
Sta_4	Anaerobic digestion for primary sludge, aerobic digestion for secondary sludge
Sta_i	Stabilization
StE	Sludge-to-energy
StM	Sludge-to-matter
SWOT	Strengths, weaknesses, opportunities, and threats
SWWT	Secondary wastewater treatment
$SWWT_1$	Chemical secondary treatment
$SWWT_2$	Activated sludges secondary treatment
ThDry	Thermal drying
$Thick_1$	Thickening in sedimentation
$Thick_2$	Gravity thickening
$Thick_3$	Dissolved air flotation
$Thick_4$	Gravity thickening for primary sludge, Gravity belt thickening for secondary sludge
$Thick_i$	Thickening
WWT	Wastewater treatment
WWTP	Wastewater treatment plant
$WWTP_1$	Single sludge line configuration
$WWTP_2$	Separated sludge line configuration
Z	Zinc

In Table A2 the composition of ISSA produced from SS incineration adapted by [34].

Table A2. Incineration sewage sludge ash (ISSA) composition.

Element	ISSA Composition [mg/kg]
P	≅53
N	≅400.5
K	≅8252.5
Ca	≅101.3
Mg	≅13.7
Mn	≅675.5
Fe	≅44
Ni	≅117.5
Cu	≅1593.5
As	≅30
Cd	≅4
Cr	≅115
Pb	≅672.5
Al	≅33.6

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