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Sustainability assessment of alternative waste-to-energy technologies for the management of sewage sludge

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ABSTRACT

The management of sewage sludge still represents a challenge in the EU sustainability plan for biowaste. Although there are consolidated alternatives for the valorization of sewage sludge (incineration, pyrolysis and gasification), technical issues related to heavy metals and other pollutants are not sufficiently understood considering the whole waste-to-energy process. In addition, societal-economic and environmental aspects are usually not included in the evaluation of these conversion technologies. In this study, we propose an integrated assessment from a sustainability perspective to evaluate the valorization of sewage sludge by thermal conversion, comparing different alternatives based on existing Waste-to-energy (WtE) technologies. The results provide an insightful vision on the challenges to manage the sewage sludge disposal and to transform the obtained waste into new raw materials with added value. In addition, the evaluation of the WtE alternatives shows that they face important challenges preventing their application, being the gasification the best performing technology according to the sustainability assessment. Finally, a decentralized scheme based on sewage sludge gasification is further evaluated using real data from wastewater treatment plants in Andalusia.

1. Introduction

The sewage sludge (SS) is the final output of the wastewater treatment plants (WWTP, domestic or industrial effluents) which should to be managed or safely disposed (Melo et al., 2018). More than 7.5 million tons (dry basis, db) of sewage sludge were produced in 27 EU Member States in 2019 (Eurostat 2022). Currently, most SS from WWTP in Europe is landfilled, incinerated, or reused in agriculture as soil amendment (Kacprzak et al., 2017). However, the European Union's target aims to reduce final waste disposal by 50 % compared with 2000 by 2050 (Fytili and Zabaniotou, 2018). Therefore, to accomplish these goals, the management and reuse of this waste must be optimized. Moreover, the European Commission has launched a public consultation about developing a sustainability plan for biowaste, where the increase in the end-use efficiency of them is a central issue. They propose converting SS to heat and electricity or, as alternative, producing solid, liquid, and gaseous advanced fuels (European Commission, 2019). Together with the increasing of the global demand for renewable energy, novel Waste-to-Energy (WtE) technologies play an increasingly important role in waste management. Thus, the thermal valorization of waste appears as an obvious strategy to produce renewable energy by pyrolysis, gasification or combustion (Dong et al., 2019; Syed-Hassan et al., 2017), while promoting circular economy (energy and resource producer). However, each WtE technology presents different advantages, but also some issues which must be solved before its implementation. The selection of the best alternative in each case should consider three key factors: energy delivery, sustainability and location. However, most studies are focused in the thermal and/or energy or economic performance, but only a few cover environmental aspects, such as the production of by-products (liquid and solid residues) with a high load of contaminants (mainly heavy metals) (Ronda et al., 2019); the location aspects, such as the possible scenarios for a centralized treatment of SS; or the sustainability aspects, such as the valorization of by-products.

In this study, fast and slow pyrolysis, as well as gasification and combustion are analyzed as WtE alternatives for SS management with

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Abbreviations: SS, Sewage sludge; dafb, Dry ash free basis; db, Dry basis; DSS, Dry sewage sludge; FPB, Fast pyrolysis biochar; GBA, Gasification bottom ash; IBA, Incineration bottom ash; RW, Residual water; SPB, Slow pyrolysis biochar; WtE, Waste-to-energy; WWT, Wastewater treatment; % v/v, Volume percentage; % w/w, Weight percentage.

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energy recovery. The pyrolysis is the thermal destruction of organic material at moderate to high temperature (300–700 °C) in the absence of oxygen. It can be performed at slow heating rate (slow pyrolysis) or at higher heating rate (fast pyrolysis). The first one is conducted to reduce the volume of waste, maximizing the biochar production, while the second one aims at yielding liquid bio-oil (Kan et al., 2016). Although pyrolysis is already commercial, most plants are based on the slow pyrolysis process, being the fast pyrolysis still in development. The gasification is used in cases where a fuel in a fluid state (syngas) is preferred for further uses (Migliaccio et al., 2021). Thus, in gasification, higher temperatures are used (800–900 °C) in an oxygen deficient environment (ER < 1). In a gasifier, multiple reactions take place, such as drying and volatilization, tar cracking and other gas–gas and gas–solid reactions, producing a combustible gas (syngas). Finally, the combustion or incineration of sewage sludge can be also considered as a thermochemical process to produce heat which can be used for several applications (Makarichi et al., 2018). Currently, the applications of incineration are mainly focused on the elimination of harmful substances or aiming significant volume reduction for final disposal (landifilling). Incineration is a widely applied method in north Europe, USA or Japan (Zhu et al., 2015); however, the relatively low demand of heat in the Mediterranean area makes this alternative less attractive. In the combustion, higher temperatures are used (>850 °C) in presence of oxygen, resulting in the transformation of carbonaceous materials into mainly CO_2 and H_2O, and substantial heat generation.

Tarpani and Azapagic (2018) demonstrated that the economic viability of sludge handling alternatives was highly dependent on the recovery potential and the income from their (by-)products. The valorization of the (by-products) could improve the economic viability of the thermal process and simultaneously solve the high cost of disposal of (non-)hazardous residues. Although there are different alternatives for material valorization, as construction buildings materials (Galvín et al., 2021), low-cost adsorbents (Dias et al., 2017) or material recovery (Arroyo et al., 2014); the sustainability of these alternatives is not sufficiently convincing, as there are environmental and social issues associated. For example, it is common that by-products from the thermal treatment of SS have a high concentration of trace elements and toxic substances (Ronda et al., 2019), which limits their application. Since the properties and the composition of these solid by-products are very different according to the applied thermal process, a detail description of each alternative must consider not only energy efficiency criteria but also the sustainability of the management of the solid by-products. Scarce information is available in the scientific literature, as it is evidenced by the main reviews in the field, in which, although including technical, economic or sustainability aspects, they rarely address them simultaneously (Fytili and Zabaniotou, 2018; Makarichi et al., 2018; Murphy et al., 2013).

Finally, it is also important to consider the analysis of parameters allowing the selection of the plant location, such as availability and composition of SS, transport distances between generation of SS and the facilities, etc. Murphy et al., (2013) studied the environmental impact of the Miscanthus production and processing in Ireland incorporating factors such as the transport to a biomass distributor (hub). Thus, a location-allocation methodology should be used to select the best promising technology and the best sites for the facilities, as this issue may determine to large extent the viability of the selected alternative in waste management.

The aim of this work is to assess the valorization of sewage sludge by their thermal conversion with existing WtE technologies, comparing the different alternatives and identifying the most sustainable option for its management. It could be applied in any European region as part of the EU action plan for the Circular Economy. Finally, to explicitly consider the location issue, a study case is included with real DSS characterization data from the Spanish National Registry and real geographic locations of WWT plants, applied to Andalusia.

2. Materials and methods

2.1. Characterization of selected sewage sludge sample

Due to the highly variable composition of SS, the potential benefits arising from the SS thermal conversion are hard to be generalized and must be evaluated on a case-by-case basis. In this work, the used SS was taken from an urban wastewater treatment plan in Spain, where the SS was processed in a rotary dryer, leaving the plant as dried SS (DSS) in form of granulated particles. The sample was characterized by elemental composition (C—H—N—S) (ASTM D5373 and the UNI 7584) and Cl by ion chromatograph. The moisture content was determined by the difference in weight between the wet sample and after drying in an oven at 60 °C until constant weight and the ash content by standard TAPPI T 211 (Blázquez et al., 2013). The main elements, including heavy metals were measured by Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) after dissolution by a HNO_3:$HClO_4$:HF (3:1:1 v/v/v) solution. A summary of the characterization of DSS is showed in Table 1.

2.2. Simulation of selected WtE technologies for the study

In this study, four alternatives of sewage sludge disposal with energy recovery are analyzed: (1) flash pyrolysis, (2) slow pyrolysis, (3) gasification and (4) combustion. Although qualitative comparisons of these alternatives exist in literature (Dong et al., 2019; Raheem et al., 2018; Syed-Hassan et al., 2017), they are mainly reviews with generic data from different works. In this work a qualitative and quantitative comparison is made for a specific sewage sludge applying the specified energy recovery alternatives.

The proposed alternatives for waste (dried-SS) valorization to final products, as well as the market products which can be obtained for each alternative are presented in Fig. 1. Since the target products and objectives of each alternative are different, resulting yields, characteristics of the obtained products are also different.

Table 1
Characterization of the used dried sewage sludge (DSS) from a real WWT Plant.

Elemental analysis (% w/w,dafb)		C	43.30
		N	9.15
		H	6.86
		S	2.60
		Cl	0.03
		O	38.09
Ashes content (% w/w, db)			23.32
Moisture (%w/w)			16.50
PCI (MJ/kg_{dafb})			14.60
Metal content	(g metal/kg DSS)	Al	13.103
		Ca	23.423
		Fe	9.839
		K	0.759
		Mg	3.364
		Mn	0.271
		Na	2.694
		P	3.954
		Cu	0.260
		Ti	1.335
		Si	19.868
	(mg metal/kg DSS)	Ni	20.703
		As	5.485
		Be	<0.300
		Cd	1.650
		Co	10.361
		Cr	42.051
		Hg	3.993
		Pb	67.118
		Sb	1.828
		Se	<1.00
		Sn	96.769
		Tl	<1.300
		V	21.940
		Zn	744.401

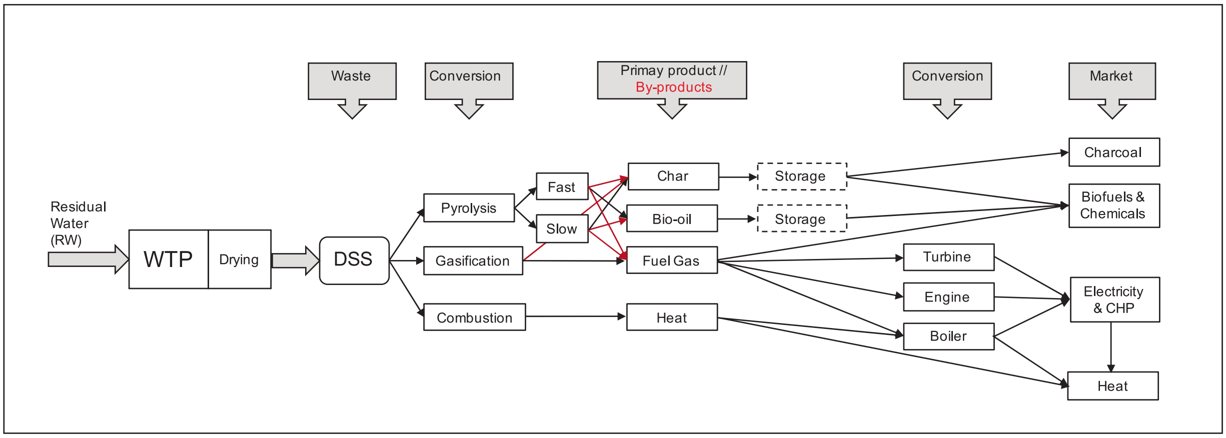


Fig. 1. Proposed alternatives of waste (dried- SS)valorization to final products and by-products (in red).

A summary of the comparison between studied WtE technologies, the main obtained products, yields, characteristics, limitations, and operational conditions are presented in Table I of the supplementary material. Moreover, the state of development is also different for each alternative. While the incineration is a common practice for SS management in some Western countries, other technologies as gasification or pyrolysis for SS treatment need further research to ensure techno-economic and environmental viability. Other important point is the capacity of plant, since the gasification and combustion are viable for high capacities (>100 MW_{th} input), while pyrolysis is used in relatively smaller plants (up to 25 MW_{th} input) (Meier et al., 2013).

In this study, for each WtE alternative, a plant configuration is proposed (Fig. 2). Then, using data of Table 1, each suggested WtE plant was simulated (for 1 ton of DSS as basis) to estimate the outlet streams using literature correlations and the corresponding mass and energy balances. Finally, the obtained results were analyzed and compared.

2.2.1. *Slow pyrolysis*

The modelling of slow pyrolysis was based on the use of a rotary kiln since it is the only type of reactor that has successfully achieved industrial implementation (Babler et al., 2017). The proposed configuration (Fig. 2a) was based on several pilot-plants proposals and studies from literature (Agarwal et al., 2015; Babler et al., 2017; Bridgwater, 2012; Ledakowicz et al., 2019; Neves et al., 2011). Moreover, the operational conditions were selected with aiming to maximize the production of biochar. Outlet streams were simulated using experimental correlations (Barry et al., 2019; Neves et al., 2011), and the corresponding mass and energy balances from data of Table 1.

2.2.2. *Fast pyrolysis*

The configuration of the modelling of fast pyrolysis (Fig. 2b) was based on pilot and commercial plants (Jones et al., 2013; Btg-btl, 2018; Valimaki, 2013), using a fluidized bed reactor. Moreover, the operational conditions were selected aiming to maximize the production of bio-oil. The product yields and the compositions of each stream were estimated using experimental correlations (Arazo et al., 2017; Barry et al., 2019), and the corresponding mass and energy balances from data of Table 1.

2.2.3. *Gasification*

The proposed configuration for gasification is showed in Fig. 2c, where the configuration and operational conditions were selected to maximize the produced syngas, including a novel cleaning step of gases (Kaasalainen et al., 2017). From the data in Table 1 and selected operating conditions, product yields are calculated using correlations (Gómez-Barea et al., 2010). Moreover, some assumptions based on the literature were considered for the determination of the gas composition (de Andrés et al., 2011; Gómez-Barea et al., 2010; Prabhansu et al., 2015; Sun et al., 2021; Syed-Hassan et al., 2017; Woolcock and Brown, 2013). Finally, for the simulation of WtE plant, the abatement of main pollutants are estimated according to literature data (Sun et al., 2011; Vehlow, 2015).

2.2.4. *Incineration (combustion)*

The combustion is a thermochemical process that occurs at high temperature in presence of air in excess, resulting in the transformation of material into CO_2 and H_2O, producing heat (Syed-Hassan et al., 2017), which can be used in boilers for steam generation. The incineration has reached a high level of maturity (Makarichi et al., 2018; Werther and Ogada, 1999), with almost 500 incineration plants in operation in Europe in 2019 (Sun et al., 2021). However, it presents social issues for its implementation (e.g., Mediterranean area). The proposed scheme for the incineration plant (Fig. 2c) was based in a moving grate incinerator, which predominant worldwide. The combustion plant was simulated (mass and energy balances) for the selected DSS (Table 1) and taking into account the following assumptions: (1) 99.9 % of C from DSS is burned in the combustion chamber, and 0.1 % unburned C leaves the system in L5; (2) 96 % of ashes leaves the system with the bottom ash (L5); (3) 99.8 % of reacted C, forms CO_2, being the rest CO; (4) 85 % of reacted N, forms NH_3, being the rest NO_x; (5) NOx is composed by NO (90 %, molar) and NO_2 (10 %, molar); (6) the air stream (L3) has an excess of 60 %; (7) 85 % of Cl from DSS forms HCl, being the rest metallic chlorine compounds; (8) the used $Ca(OH)_2$ to remove HCl has an excess of 30 % and the yield of the reaction is 90 %; (9) the used $Ca(OH)_2$ to remove SO_2 has an excess of 60 % and the yield of the reaction is 98 %; and (10) the used NH_3 to remove NO_x has an excess of 50 % and the yield of the reaction is 80 %.

2.3. *Estimation of heavy metal content in the obtained solids*

The metal content in biochar and ashes from the studied processes was also estimated using our previous results for elements partitioning during thermal conversion of SS (Ronda et al., 2019), and by the corresponding mass balances (Table 1).

2.4. *Criteria for the sustainability assessment*

The classification for the sustainability assessment was based on three categories: technical performance, societal-economic and environmental impacts. First, for each category, different levels are defined. The technology category was classified in 8 levels: (1) the conversion technology is not ready for commercial applications, (2) there are important limitations for the energy integration of the process, (3) the process has limited scalability, (4) there are severe operational issues

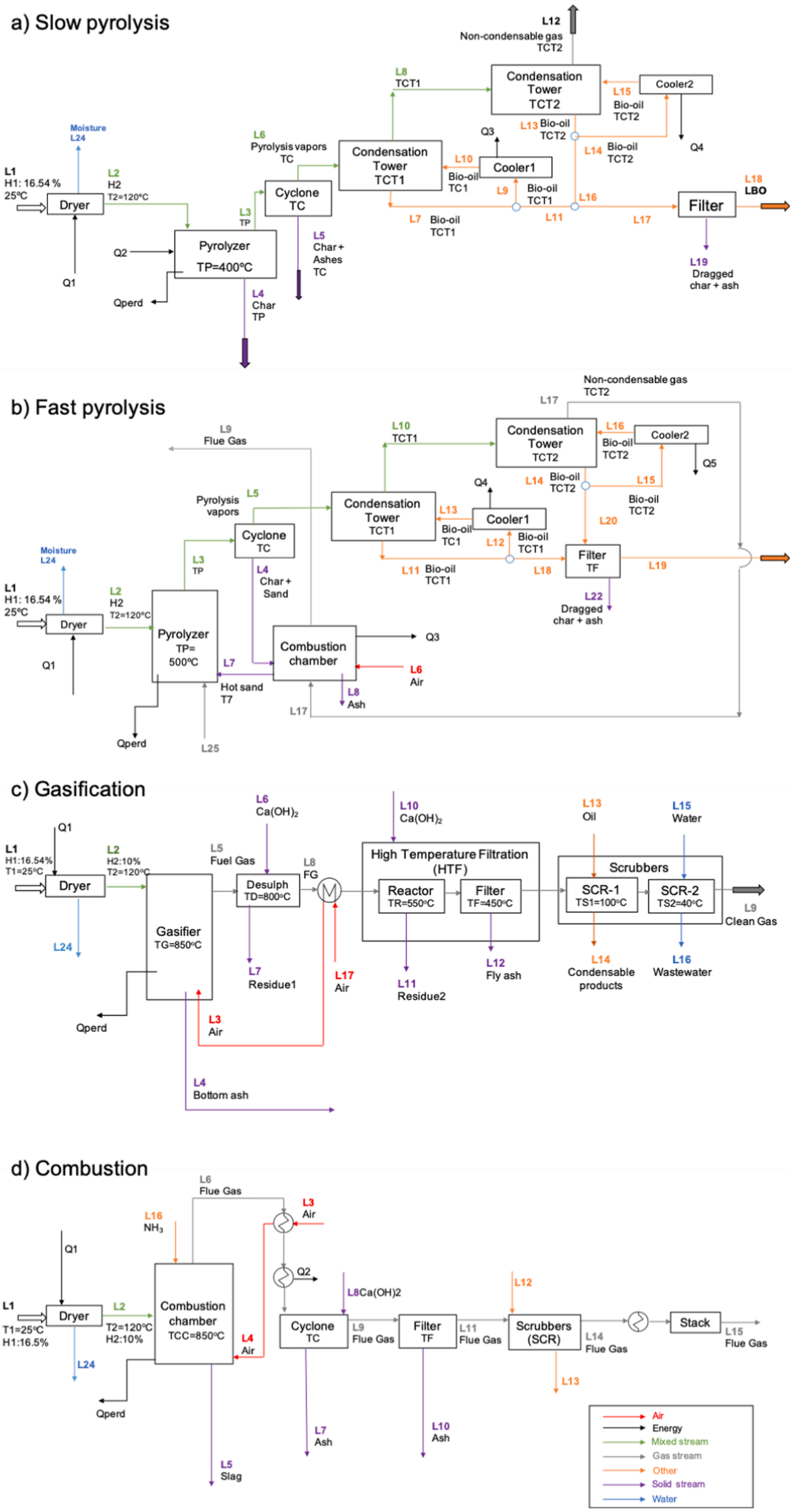


Fig. 2. Simplified scheme for four modelled WtE plants: (a) slow pyrolysis, (b) fast pyrolysis, (c) gasification and (d) combustion.

caused by the complexity of the process, (5) the by-products cannot be recovered with high efficiency, (6) there are important uncertainties in the fate of heavy metals in the output streams, (7) the process is reliable with moderate uncertainty on the fate of heavy metals in the by-products and (8) the reliability of the process is very high, and no major issue has been identified so far. The societal-economic category was classified in 6 levels: (1) the proposed alternative does not meet basic principles for sustainability and circular economy, (2) a reduction of disposal costs from the valorization of the main product is credible (by-products excluded), (3) a reduction of disposal costs is credible when the valorization of by-products is included, (4) there is a strong societal opposition to the proposed management, (5) there is some support from producers and/or relevant public authorities and (6) there is a strong support from relevant public authorities for the implementation of this alternative. Finally, the environmental category was classified in 4 levels: (1) there is a higher environmental impact in all categories compared to current management, (2) the considered alternative management has similar environmental impact or might reduce some environmental impacts (uncertain), (3) the considered alternative compares favorably with current management and (4) the considered alternative has the best environmental impact compared to current management and other alternatives considered in the study. Later, for each of the process studied, the corresponding levels were selected according to the position of the technology for each category. Finally, the coordinate position for each process was obtained.

The criteria for the assessment of the sustainability were inspired by the *Specifications for the Application of the United Nations Framework Classification for Resources to Anthropogenic Resources* (Heiberg et al., 2018), following the same approach as in a previous work of the authors (analyzing the use of existing alkaline residues as sorbents for acid gas removal in bioenergy plants) (Haro et al., 2018a).

2.5. Criteria for the location assessment

A location-allocation study was performed using the gasification as the selected alternative. The location assessment should be the last step, after selecting the best technology in each situation, and before its final implementation in a determined area (Haro et al., 2018b). For this study, it is necessary to know the current and foreseeable management, identifying and characterizing all current WWTPs in the area. As an example, the region of Andalucia has been selected, thanks to the availability of high-quality data. All WWTP in Andalusia have been identified and characterized using data from the Spanish National Registry of Sewage Sludge, including plant size, type of treatment, digestate production, use and composition (dry content, organic matter, C/N ratio, heavy metals, etc.). The resulting data was processed using GIS and minimizing the distance between the generation of DSS and the valorization plant. Only plants processing more than 9000-person equivalent were considered for the study since lower capacities do not involve anaerobic digestion. The location-allocation study included up to ten potential hubs for the centralized treatment of the digestate, considering proximity, type of treatment and current use of the digestate. The model was used to identify the number and location of the potential hubs considering: (1) the shortest route from resource site to the facilities and (2) the minimization of the transport distances and selection of the best sites for the facilities (Singlitico et al., 2019). Finally, for each scenario overall system balances must be determined to select the best alternative.

3. Results and discussions

3.1. Evaluation of selected WtE technologies

For each selected thermal conversion process, a configuration for the WtE plant was proposed based on the selected DSS (Table 1). Fig. 2 shows a simplified scheme for the four configurations: (a) slow pyrolysis, (b) fast pyrolysis, (c) gasification, and (d) combustion. Moreover, to allow a fair comparison of results, all results are expressed per ton of dried waste (L1).

3.1.1. Slow pyrolysis

In the proposed slow pyrolysis plant, the material was dried at 120 °C and its moisture content reduced from 16.5 to 10 % in the dryer unit using 338.41 MJ (Q1). This step was common in all WtE configurations. Then, it was fed to the pyrolizer at 400 °C, where it was converted into three fractions (solid biochar, bio-oil, and gas): 46.35 %, 36.41 and 17.24 % for biochar, bio-oil and gas fractions, respectively. These values are in agreement with other authors (Agarwal et al., 2015; Barry et al., 2019; Callegari and Giuseppe-Capodaglio, 2018; Sanginés et al., 2015). Q2 (893.67 MJ) was the heat supplied to the pyrolizer and it may be supplied by an external source, burning the non-condensable gas or, even, burning part of the biochar. From the reactor it was obtained the solid stream (L4 = 288.6 kg), formed mainly by biochar and a gaseous stream and 638.7 kg of condensable and non-condensable gases (L3). Qper (7.79 MJ) was the energy losses in the pyrolizer. After the reactor, a hot gas filtration was placed to obtain and particle-free vapors (L6 = 624 kg) and to separate the dragged solids (L5 = 14.74 kg), as it was assumed that 5 % of solid were dragged with L3. Moreover, an efficiency of 97 % for the cyclone was considered. Finally, a two-stages condensing tower was used to separate the non-condensable gas fraction (L12 = 142.9 kg) and the obtained bio-oil, which was completely cleaned before its outlet (L18 = 470.6 kg). The removed energy in each stage of the condensing towers was 192.42 and 89.18 MJ, respectively.

Main results for products yields and the composition of each stream are summarized in Table 2 and the distribution of main elements in obtained products for slow pyrolysis are showed in Fig. I of supplementary materials, together the distribution of main elements in obtained products for fast pyrolysis.

It was observed a high yield of biochar, in agreement with previous studies (Agarwal et al., 2015; Barry et al., 2019; Callegari and Giuseppe-Capodaglio, 2018; Gerasimov et al., 2019; Wei et al., 2019), which was the main product of the proposed SP Plant. Data from estimated elemental composition, as well as the high ash content in biochar were also similar to obtained experimentally by other authors. However, it was observed a notably higher N content in biochar, which can be explained by the fact that some *N*-compounds formed during the slow pyrolysis were retained in the biochar at relatively lower temperatures, but they were volatilized when the temperature increases. The obtained biochar had a high calorific value (18.38 MJ/kg) and, therefore, it is suitable as a fuel. Moreover, it could be used as an effective carbon sequestration material thanks to its $H/C < 0.6$ and $O/C < 0.4$ ratios (Tag et al., 2016). In addition, the biochar can be used as soil amendment in agricultural uses, significantly improving the yield of some crops. It has also demonstrated potential benefits in remediation and restoration of contaminated soils, or in wastewater treatments and gas adsorption (thanks to its specific properties, such as large specific surface area) (Callegari and Giuseppe-Capodaglio, 2018). The obtained gas fraction from slow pyrolysis was composed mainly CO_2, CO, H_2 and CH_4 (similarly that for fast pyrolysis, although different concentration); however, the slow pyrolysis favored the formation of CO_2 versus CO, being the main compound in the gas fraction. Due to the high fraction of CO_2, the heating value of the gas, significantly decreased, obtaining a value of 4.06 MJ/kg. Therefore, the gas fraction in the SP is not an interesting by-product. Pyrolysis oil from SS was the other interesting product, which has several potential applications (Morgano et al., 2018). Although the composition of two separated phases had not been obtained, it is known that it is formed by a water phase and an organic phase. The selected operational conditions for slow pyrolysis allowed obtaining a highly calorific bio-oil, with a heating value of 15.91 MJ/kg, mainly due to the content of high calorific species such as pyridine and pyrrole (Morgano et al., 2018). Although the bio-oil can be used as alternative fuel, it presents some issues: the high oxygen content, producing the inherent instability and promoting polymerization reactions that can lead to increased viscosity and decreased fuel qualities (Morgano et al., 2018), the presence of *N*-compounds (probably from the high protein content of sewage sludge), which can be easily converted to NO_x and N_2O during combustion (Syed-Hassan et al., 2017), or the sulfur content, which can be a barrier for its commercialization due to the SOx pollution caused in engine combustion (Li et al., 2022). Therefore, although the obtained bio-oil could be considered a interesting by-product, these issues make

Table 2
Main results (yields, elemental composition and low heat value of obtained products) from WtE modelling for slow and fast pyrolysis.

	Slow pyrolysis				Fast pyrolysis				
	Char	Bio-oil	Gas			Char	Bio-oil	Gas	
Yield (%w/w)	46.35	36.41	17.24		Yield (%w/w)	32.65	40.62	26.73	
Elemental composition					**Elemental composition**				
(%w/w)			**(% v/v, N_2 free)**		**(%w/w)**			**(% v/v, N_2 free)**	
C	43.00	29.10	CO	26.37	C	17.96	42.50	CO	38.30
N	4.60	14.27	CO_2	60.73	N	2.93	11.74	CO_2	13.66
H	3.20	8.93	CH_4	4.57	H	1.15	8.11	CH_4	18.24
O	0.00	45.22	H_2	7.73	O	5.08	35.19	H_2	27.96
S	1.02	2.48	Others	0.60	S	1.46	2.46	Others	1.84
Ashes	48.18	0.00			Ashes	71.42	0.00		
LHV (MJ/kg)	18.38	15.91	4.06		LHV (MJ/kg)	7.25	20.46	16.79	

the application of this bio-oil as a fuel more problematic and requiring additional treatments before its implementation (Shen and Zhang, 2003; Syed-Hassan et al., 2017).

Regarding the energy distribution of sewage sludge products (Fig. I of the Supplementary material) obtained from slow pyrolysis, it was observed that the bio-oil retains around 50 % of the energy from the DSS, although the bio-char is the largest material fraction. It was also estimated that the energy content in the gas (700 MJ/t DSS), was insufficient to cover the energy demand the pyrolysis process (894 MJ/t DSS). Thus, an external heat source was necessary.

3.1.2. Fast pyrolysis

In the proposed configuration for fast pyrolysis WtE plant (Fig. 2b), four main sections were included: Drying (at 120 °C); pyrolysis (at 500 °C); separation of solids from pyrolysis vapors; and cleaning of products (gas and bio-oil). The resulting product yields and streams compositions are showed in Table 2. The distribution of main elements in obtained products are showed in Fig. Ib of supplementary material.

In this configuration, the main objective was to obtain a high energy content bio-oil, which can be used as fuel. For this purpose, the selected temperature was set at 500 °C. In the pyrolizer, the DSS was heated with hot sand (at 700–750 °C, coming from a combustion chamber using the non-condensable gases and the char fraction, using N_2 (L25) as fluidization agent at a rate of 1.5). The sand flow (L7 = 9805 kg) was calculated according to energy needs of the process, and it was in the range to 10–15 times the DSS mass flow (L2). Moreover, a pyrolysis reaction enthalpy value of 225 kJ/kg DSS was considered, while the energy losses (Qper) were assumed 5 % of the inlet energy, (Papadikis et al., 2008). The obtained product yields were 32.65 %, 26.73 % and 40.62 % for char, gas, and bio-oil fraction, respectively, what is in agreement with previous authors (Arazo et al., 2017; Barry et al., 2019; Bridgwater, 2012; Fernández-Akarregi et al., 2013; Neves et al., 2011). Solids were recovered using a cyclone with an efficiency of 95–98 % (although this value can be refined knowing the particle size distribution). In the combustion chamber, the char and non-condensable gases were burned to heat the sand, obtaining the ashes (L8 = 188.8 kg) and the flue gas streams (L9 = 3953 kg), which could be used to dry the material upstreams. Moreover, the energy balance was closed with a Q3 stream (1386 MJ/t DSS), indicating that the energy obtained in the combustion chamber was higher than needed for heating up the sand. Finally, two quenching towers in series were used to separate the non-condensable gas fraction (L17 = 1614 kg) and the obtained bio-oil (L19 = 431.7 kg), similar to those used by Jones et al., (2013). The removed energy in condensation towers were 213.70 and 155.30 MJ, respectively (higher than in the slow pyrolysis configuration). The bio-oil was completely cleaned using a filter to separate the dragged particles (L22). In the modelled process, both bio-oil streams (L18 and L20) were obtained together, due to the lack of suitable information for their characterization; however, according to the necessity, these streams could be obtained separately (Park et al., 2010).

It is observed that the total bio-oil yield for fast pyrolysis is similar to slow pyrolysis, while the biochar yield decreases with a corresponding increase in the gas yield as the process moves from slow to fast pyrolysis, according to results obtained by other authors (Barry et al., 2019). The elemental composition obtained from each product agreed with experimental results from literature characterization, despite the high heterogeneity of the sewage sludge and the different reactor configuration utilized. Thus, Alvarez et al. (2016) obtained a bio-oil at 500 °C in a conical spouted bed reactor with a 45 % of carbon, 8.8 % of hydrogen, 6.6.% of nitrogen, 0.7 % of sulfur, 39.0 % of oxygen and LHV of 18.8 MJ/kg. Pedroza et al. (2014) obtained similar values (42.1 % C, 10.1 % H 7.2 % N, 40 % O and 0.6 % S) for the bio-oil produced at 550 °C in a rotating cylindrical reactor. The obtained LHV (20.46 MJ/kg) was in the range of literature values (Bridgwater, 2012; Syed-Hassan et al., 2017) and higher to obtained by the slow pyrolysis due to higher C content and lower O-compounds. It is noted that the composition of the pyrolytic oil is needed to know the quality of the obtained oil, however, it could not be estimated due to lack of information in the literature on the fractionation (distillation) of the bio-oil. Despite this, some studies indicated that the fast pyrolysis of sewage sludge allows the production of the bio-oil with higher quantity of light fractions, which indicates a better quality of the obtained product (Fonts et al., 2012; Park et al., 2010), improving the possible applications of the bio-oil, which was the main product of the proposed FP Plant. The composition of the gas fraction (v/v) is 38.3 % CO, 13.66 % CO_2, 27.96 % H_2, 18.24 % CH_4 and 1.84 % others, also comparably with results obtained by other authors. Results indicate (Fig Ib of the supplementary material) that the most energy content (higher than 50 %) remained in bio-oil fraction (the main objective of the fast pyrolysis). Moreover, the energy of char and gas (considered as by-products of the process) can be used in the own process to minimize the cost of energy and to achieve an energy self-sufficient process thanks to the excess energy stream (Q3) of 1386 MJ/t DSS.

3.1.3. Gasification

The proposed configuration is showed in Fig. 2.c, where after drying and moderate heating (from 25 °C to 120 °C), the DSS is introduced in the fluidized bed gasifier which operates at 850 °C. The cleaning includes the removal of main pollutants (H_2S, HCl, CO_2 and particles) (Vehlow, 2015). The desulfurization was performed at high temperature (800 °C) using an alkali residue ($Ca(OH)_2$) to capture the H_2S and the waste solid resulting from desulfurization (CaS) was stabilized to sulphate ($CaSO_4$) and separated in a solid residue fraction (L7). The yield of the desulfurization process was proved to be higher than 90 % in the selected operational conditions. Downstream, for the High Temperature Filtration (HTF) step, a reactor for chlorine and CO_2 capture using the same alkaline residue ($Ca(OH)_2$) was located after cooling to about 550 °C and separating other solid residue fraction (*L*11), followed by a filter at 450 °C which allows the condensation of most of heavy metals in a fly ash stream (L12). For the dichlorination, a yield of 87 % was assumed (Sun et al., 2011). Finally, at low temperature, several scrubbers (SCR-1 and SCR-2) were placed to separate condensable products, separating a waste oil fraction and to obtain the clean gas (L9). The main novelty of the proposed gasification process is the cleaning step of obtained gases.

The gasification plant was simulated at a temperature of 850 °C and an ER = 0.3 from the selected DSS (Table 1) and it gave the following product yields 28.11 %, 56.00 and 15.89 % for biochar, gas, and condensable fractions, respectively. It was assumed that all S in the DSS was converted into H_2S; 15 % of Cl formed metals chlorides and remained in the ashes, while the other 85 % converted into HCl; and that the 35 % of N reacted with metals staying in the ashes and the remainder formed *N*-compounds in gas phase (later, some of them will be condensate with the tar). Therefore, the stream L5 contained the gases (condensable and non-condensable), the formed pollutants (HCl, NH_3 and H_2S) along with the dragged particles. However, as the L5 stream needs removing the tar fraction and an adequate cleaning system to obey the regulations, the previously described cleaning systems were incorporated, to obtain the final gas stream (L9). With these considerations, the products yields, and the elemental composition calculated are showed in Table 3.

For the modelled gasification plant, it was observed that the obtained yields agreed with those obtained by other authors for similar conditions. It is observed a high conversion of carbonaceous residue into a combustible gas, with a solid residue (char) mainly formed by ashes, where metals are retained in this char matrix. Moreover, the biochar shows a low LHV, so, it has fewer commercial applications (on the contrary that in a pyrolysis-WtE configuration). The tar production in the gasification process is another barrier, as it requires additional cleaning treatment to avoid blocking the downstream equipment and problems in the application of the producer gas in heat and power generation or chemical production. In the proposed configuration, the condensable products are removed after the gas cleaning systems at high temperature (in L9 stream). The final content of tar in the gas depends on the maximum permissible limit for its intended application (Syed-Hassan et al., 2017) and in this work, a value lower than 0.1 % v/v_{db} has been considered. The obtained gas yield is higher than 50 %, with a composition in the range of previous studies (de Andrés et al., 2011; Gómez-Barea et al., 2010; Prabhansu et al., 2015; Sun et al., 2021; Syed-Hassan et al., 2017; Woolcock and Brown, 2013). However, the gas efficiency is related to moisture and ash content of the raw material (Syed-Hassan et al., 2017) and therefore, they can vary for other used sewage sludge. Obtained results shows considerable results for production of hydrogen-rich syngas, with a total produced gas of 393 Nm^3_{db}/t DSS, with a LHV of 4.86 MJ/ Nm^3_{db}.

Finally, it can be concluded that although the gasification process required an extensive gas cleaning for syngas applications, the syngas is a higher value product that can be further process in energy and chemical applications, while the others outlet streams don't have significant valued applications.

3.1.4. Incineration (combustion)

In the proposed configuration for incineration WtE plant (Fig. 2d), it can be observed that the combustion is performed around 850 °C (TCC) using hot air (L4 = 8668 kg), which is heated at 400 °C using the flue gas after the combustion chamber (a total of 2558 MJ/t DSS is needed to heat the air). The total energy produced during the combustion of SS (11730 MJ/t DSS) allowed an excess energy stream (Q2 = 7522 MJ/tDSS), which could be used to dry the DSS (L1), due it needs 338.41 MJ/t DSS or used in a gas boiler. The energy losses in combustion chamber is 401.52 MJt DSS, higher than other processes due to the reactor configuration. In the combustion chamber is also injected an ammonia solution stream (L16 = 14.76 kg) to remove most of the nitrogen oxides (NO_x) in the flue gas. The NO_x is the sum of formed NO and NO_2 during the combustion by different mechanisms (Werther and Ogada, 1999). For selected conditions of simulated combustion plant (temperature, excess air ratio, etc.), a ratio of 9:1 is considered in the formation of this compound, which are removed using a NH_3 solution in combustion chamber (Syed-Hassan et al., 2017, Werther and Ogada, 1999). After energy recovery, the flue gas is passed through a cyclone together with a calcium hydroxide solution stream (L8 = 80.58 kg) to remove the SO_2 and HCl from gases, leaving the system a solid stream (L7: ashes + waste from cleaning gases) and L9 (flue gases). Before the dust removal using an electrostatic filter, the activated carbon is sprayed into the flue gas pipeline to adsorb heavy metals and dioxins. Then, flue gas passes to a scrubber system to be cleaned, leaving the system a wastewater stream, which has to treated in compliance of the Directive 2000/76/CE before its discharge. Finally, 9188 kg of cleaned flue gas (L15), which is in line with the emission standards is discharged into the atmosphere through the induced draft fan.

The bottom ash is mainly the ash originally present in the DSS and the unburned C. Although, some heavy metals are volatilized, being collected in the cyclone and the filter downstreams, most of them remained in the bottom ash, and thus, this stream is considered as hazardous waste (and it has to be treated as such). Considering the bottom ashes, some metals could be recovered (Dong et al., 2019), and remaining ashes are landfilled, so leaching studies are necessary to assess the associated environmental impacts.

In the case of incineration of waste, the most important issues are: (1) the energy balance and (2) the compliance of Directive 2000/76/CE about waste incineration. Table 4 summarizes the relevant indicators for energy and regulatory issues.

Although the incineration is the most mature technology, it has associated air pollution problems, which should be mitigated with a modern and complex air pollution control equipment. Thus, according to waste minimization (volume reduction), the incineration is the best process, offering nearly complete destruction of organic materials. However, the energy recovery from DSS is in form of heat, which is not commonly used in Mediterranean area (being the other outlet streams without significant valuable applications); has the highest GHG emission; and the obtained ashes are considered as hazardous materials. Therefore, from energy, environmental and economical point of views, this process is less attractive. These issues are considered in the sustainability assessment section.

Table 3
Main results from gasification WtE modelling.

	Char	Condensables	Gas	
Yield (%w/w)	28.11 %	15.89 %	56.00 %	
Elemental composition (%w/w)			Gas composition (% v/v)	
C	5.91	24.19	CO	23.68
N	8.74	11.74	CO_2	33.95
H	0.19	8.14	CH_4	7.37
O	3.02	55.93	H_2	29.47
S	0.00	0.00	C_2H_x	5.53
Ashes	82.14	0.00		
LHV (MJ/kg)	2.45		LHV (MJ/Nm^3_{db})	4.86

Table 4
Main results from incineration WtE modelling.

Parameter	Obtained value	Limit
% C in ashes (% w/w)	2.74	3 %
% O_2 in exit gases (%w/w)	5.87	6 %
$[NO_x]_{L15}$, mg/Nm^3	439.9	500
$[SO_2]_{L15}$, mg/Nm^3	85.09	200
$[HCl]_{L15}$, mg/Nm^3	3.49	10
Particles, mg/Nm^3	10.73	30
Cd + Tl, mg/Nm^3	0.00078	0.05
Hg, mg/Nm^3	0.0019	0.05
Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V	0.055	0.5

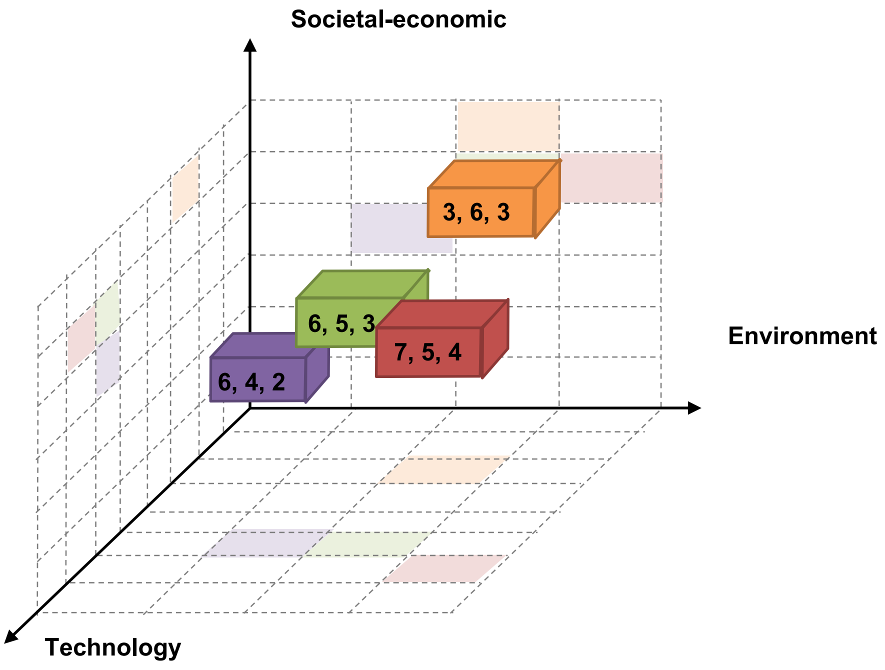
3.2. Estimation of heavy metal content in obtained solids

The content of metals in obtained biochars and ashes from the studied configurations were estimated and are showed in Table II of the supplementary material. It is observed, in general, that most of heavy metals in sewage sludge are immobile under pyrolysis conditions, as it is widely reported in the recent literature. Thus, Callegari and Guiuseppe-Capodaglio (2018), studied the properties of biochars obtained from sewage sludge pyrolysis and they determined that the leachability of solid reduced after a pyrolysis process, increasing at the same time the heavy metal stability. Ledakowicz et al., (2019) studied the thermochemical treatment of sewage sludge by integration of drying and pyrolysis/autogasification and they concluded that the final product biochar hardly leached out heavy metals content. Barry et al., (2019) evaluated the pyrolysis as an economical and ecological treatment option for municipal sewage sludge and they proved that the leachability of pyrolysis biochar derived from sewage sludge was significantly reduced after the process. Moreover, the leaching of heavy metals was lower for slow pyrolysis char than obtained by fast pyrolysis.

However, the combustion of biochar can generate the corresponding ashes where metals are concentrated. Therefore, these ashes would be treated as hazardous materials according to the Directive 2008/98/CE of waste and contaminated soil. On the other hand, they could be used as recyclable material for road construction application, studying previously their leaching properties (Galvín et al., 2021).

In biochars from pyrolysis processes, the nutrients content (as Na, K or P) is high, indicating that they can be used as fertilizer or for soil bioremediation. However, the chemistry of these compounds needs to be studied before their application due to the high concentration of hazardous metals (Callegari and Giuseppe-Capodaglio, 2018; Ledakowicz et al., 2019). Thus, for the P-chemistry, some authors suggest that the quality of a biochar to be used as fertilizer is related to the content of brushite, which is preserved in pyrolysis process to a much larger extent than gasification and incineration ones (Thomsen et al., 2017; Xu et al., 2012). Moreover, the stability of heavy metals increased in the obtained biochar from pyrolysis processes, and the leachability of them is reduced

1. The proposed alternative does not meet basic principles for sustainability and circular economy
2. A reduction of disposal costs from the valorization of the main product is credible (by-products excluded)
3. A reduction of disposal costs is credible when the valorization of by-products is included
4. There is a strong societal opposition to the proposed management
5. There is some support from producers and/or relevant public authorities (e.g., funding opportunities)
6. There is a strong support from relevant public authorities for the implementation of this alternative



1. There is a higher environmental impact in all categories compared to current management
2. The considered alternative management has similar environmental impact or might reduce some environmental impacts (uncertain)
3. The considered alternative compares favorably with current management
4. The considered alternative has the best environmental impact compared to current management and other alternatives considered in the study

1. The conversion technology is not ready for commercial applications
2. There are important limitations for the energy integration of the process
3. The process has limited scalability
4. There are severe operational issues caused by the complexity of the process
5. The by-products cannot be recovered with high efficiency
6. There are important uncertainties in the fate of heavy metals in the output streams (main product and by-products)
7. The process is reliable with moderate uncertainty on the fate of heavy metals in the by-products
8. The reliability of the process is very high, and no major issue has been identified so far

Fig. 3. Criteria for the three categories (technical performance, societal-economic and environmental impact) in the sustainability assessment and classification of the considered alternatives for the sustainable management of SS (red: slow pyrolysis, orange: fast pyrolysis, green: gasification, purple: combustion).

compared to raw sewage sludge. Some literature studies indicated that the heavy metals leaching is higher in biochar obtained from fast pyrolysis, while the leaching of nutrient species is lower (most likely due to the higher ash content and reduced carbon matrix) compared to slow pyrolysis biochar (Barry et al., 2019). Thus, slow pyrolysis biochar would be more attractive for feedstock with high content of metals (as sewage sludge), where a reduced leachability is desirable. In any case, before the application of sewage sludge char as fertilizer, it is necessary a more detailed studied on the heavy metals.

Currently, ashes from sewage sludge combustion are mostly landfilled and they must be treated as hazardous waste (Syed-Hassan et al., 2017). It is mainly because of concerns related to the possibility of heavy metals leaching from the ash. However, some authors have proposed different application for them: as the P fertilizer production (Ledakowicz et al., 2019; Xu et al., 2012) or the use of ash in concrete related applications (Arroyo et al., 2014). In any case, the leachability of heavy metals has to be studied before any application.

3.3. Sustainability assessment

Based on the previous results, Fig. 3 shows the sustainability performance of each of the considered alternatives for SS management based on three categories: technical performance, societal-economic and environmental impacts. The detail for the classification is provided in Table III of the Supplementary Material. The classification for the slow pyrolysis was 7,5,4. The level 7 in technology is because of the process is reliable and it is performed in commercial applications. However, due to the high and variable content of heavy metals in the original sewage sludge, some uncertainties exit on the fate of them in the by-products, mainly at temperatures higher than 400 °C. According to the social-economic criterion (5), the slow pyrolysis is having some funding opportunities in recent years, promoting circular economy. Finally, the slow pyrolysis presents a level 4 in the environmental criterion, because it can be considered the best environmental alternative in the study. At the operational conditions of the process, the obtained by products reduce the environmental impacts respect to original SS obtaining new added-value products.

The fast pyrolysis showed a classification of 3,6,3. Therefore, it is a very attractive process but with limited scalability (i.e., level 3 in technology). Thus, the existing fast pyrolysis units are smaller than gasification or incineration units and it is not expected that they can reach the same capacity. Therefore, a modular approach instead of larger units is applicable for large scale pyrolysis plants. Moreover, it presents strong funding opportunities for the implementation of this alternative (level 6 in social-economic), as it is a promising alternative to produce commercially viable fuels. Finally, the fast pyrolysis presents a level 3 in the environment criteria, because it can be considered a more favorable alternative than current management (landfilled, incinerated, or directly reused in agriculture as soil amendment) but it needs the management of some obtained byproducts.

The classification for the gasification was 6,5,3. The level 6 in technology is because of there are important uncertainties in the fate of heavy metals in the output streams, mainly focused on the cleaning gas step. According to the social-economic criterion, the gasification presents a level of 5, because it receives some funding opportunities in recent years, with the purpose to obtain new renewable energy sources. Finally, akin to fast pyrolysis, the gasification presents a level 3 in the environment criterion, because it is more environmental favorable than current management (mainly, incineration or landfill).

For the combustion, the classification was 6,4,2. The combustion is a common practice to management of SS in some countries, however, the fate of heavy metals in the output streams must be studied according to the composition of original SS (level 6 in technology). Moreover, it presents a strong social opposition to the processed management (level 4 in societal-economic criteria). Finally, it shows a level 2 in the environment criteria because it reduces some environmental impacts, but this process needs the management of obtained byproducts as hazardous residue.

Even though the results are specific for the selected case study in Spain, similar results could be obtained from other European regions if the proposed methodology is applied.

3.4. Location assessment for the valorization of SS using gasification in Andalusia

The gasification process is selected for the location assessment because of it is the non-conventional technology with the best results in the sustainability study. Moreover, as scalability is the most limiting factor for the deployment of this technology, a decentralized scheme has been proposed. The used location-allocation model identified 10 potential hubs in Andalusia for a gasification plant, next to the largest WWT Plants. In Fig. II of supplementary material, a map of Andalusia is showed, locating all existing WWT plants (blue points) and sludge hub candidates (yellow diamonds). From obtained data, 3 scenarios were defined for the centralized treatment of DSS (considering a decentralized drying, 17 % moisture as received). For each scenario, the location-allocation model determined the number of hubs and the best location for them, and they were also localized in the Fig. II of the supplementary material with red symbols. For 1-Hub, all SS is dried at the WWT Plant and transported to 1 centralized plant for valorization. In this scenario, the selected location was the plant “Copero” (red triangle). For 2-Hubs, all SS is dried at the WWT Plant and transported to 2 centralized plants for valorization. In this scenario, the selected locations were the plant “Copero” (red triangle) and “Guadalhorce” (red diamond). Finally, for 3-Hubs, all SS is dried at the WWT Plant and transported to 3 centralized plants for valorization. In this scenario, the selected locations were the plant “Copero” (red triangle), “Guadalhorce” (red diamond) and “El Bobar” (red square).

Table 5 shows the results with total DSS treated in the facility, its average LHV and the electricity export after the overall system balance, in each selected scenario.

4. Conclusions

This study provides an analysis of consolidated alternatives for the valorization of sewage sludge. The proposed sustainability assessment includes the most relevant societal-economic, environmental, and technological aspects in line with the EU sustainability plan for biowaste. The four proposed WtE configurations provided energy products with higher added value (char, bio-oil, syngas or heat). Moreover, some by-products could be used as a fertilizer, in soil bioremediation or concrete production; solving technical issues related to heavy metals. Real data from wastewater treatment plants in Andalusia has been used to get an accurate vision of the challenges to be faced in the widely application of gasification/pyrolysis compared to incineration (combustion). The results indicate that scalability is a relevant barrier in their deployment, whereas heavy metals are equally relevant for all waste-to-energy alternatives. Considering the further analysis of the gasification, a decentralized scheme has been proposed and the resulting potential for power generation.

Table 5

Estimated values for the treatment of DSS according to each selected scenario.

Scenario	Hub	Treated DSS (kt/year)	LHV (MJ/kg)	Electricity export (MW)
1-Hub	Copero	89.4	14.7	5.6
2-Hubs	Copero	47.5	14.7	3.0
	Guadalhorce	42.0	14.6	2.6
3-Hubs	El Bobar	20.8	14.5	1.3
	Copero	47.1	14.8	3.0
	Guadalhorce	21.5	14.7	1.4

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2023.01.025.

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