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Environmental Assessment of Solid Recovered Fuel Production from Screening Waste Using a Life Cycle Assessment Approach

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Abstract: The circular economy, as a new model of waste management through energy self-sufficiency and valorisation, can be applied to wastewater treatment plants (WWTPs). Screening waste from WWTP pretreatment is the only waste that is not energetically recovered and thus constrains the achievement of zero waste. Previous studies demonstrated the technical feasibility of producing solid recovered fuel (SRF) from this waste. Environmental benefits, including waste reduction, resource conservation, or reduced greenhouse gas emissions are analysed in this work. Environmental impact is quantified using the life cycle assessment (LCA) methodology through the SimaPro 9.2. software and the CML-IA baseline v3.08 impact methodology, that propose 11 impact categories. Five scenarios were established to compare current landfill disposal with the production of densified and non-densified SRF using solar and thermal drying. Within the system boundaries studied, from waste generation to SRF production, results show that landfill is the most environmentally damaging option while producing non-densified SRF using solar drying is the most environmentally viable scenario.

Keywords: environmental analysis; circular economy; waste to energy; wastewater treatment plants

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1. Introduction

Wastewater management has long been recognised as a critical component in achieving sustainable and circular economies, particularly emphasising energy self-sufficiency and waste reduction [1]. Treatment at wastewater treatment plants (WWTPs) generates waste streams of various compositions and characteristics, such as sands, oils and, most of all, sludge [2]. All these wastes are currently recycled or valorised for energy recovery [3]. However, screening waste from pretreatment generally offers no sustainable alternatives to current landfill disposal, which generates large environmental negative impacts [4], such as soil and water pollution, generating harmful gases [5]. In addition, according to regulations [6], landfill disposal will be limited to 10% by 2035. As a result, there is a pressing need to identify and implement innovative approaches to waste screening, in agreement with the waste minimization concept promoting zero-waste strategies in WWTPs [7], and can be considered as a crucial strategy for the circular economy [8]. An ideal goal for any production sector is to modify its product chain, improving the efficiency, enabling reuse of all by-products in the value chain and reducing waste production, trying to fulfil the zero-waste criterion [9].

Screening waste includes solid mixtures of organic matter, sanitary textiles, paper and plastics [10], and at WWTPs it typically ranges from 1% to 2% of the total waste generated [11]. Due to the relatively low volume of screening waste compared to other WWTP waste, it has received limited scientific attention [12]. Previous research has focused primarily on the study of anaerobic digestion treatments as an alternative to landfill disposal, with methane production tending to range from 0.19 [13] to 1.04 L CH_4/g vs. [4], whereas other potential areas of research have tended to be overlooked [7]. Nevertheless, one study has identified similarities between the composition of screening waste and mechanical biological treatment (MBT) waste, suggesting the possibility of exploring common treatments for both types of waste, such as biofuel production [14]. Furthermore, an analysis of screening waste from the Biofactoría Sur of Granada (Spain) concluded that the waste possessed properties suitable for transformation into solid recovered fuel (SRF) [15]. In addition, ISO 21640:2021 recognises 'solid waste from urban wastewater treatment' as a viable source for SRF production [16]. SRF is an alternative to fossil fuels and has been recognised as a viable option for use in various industrial sectors, such as power plants and cement plants [17–19].

SRF production lacks a standardised preparation technology [20]. Generally, the process involves shredding, removing unsuitable fractions (e.g., metals or inerts) and drying and conditioning the product [21]. In the case of screening at the Biofactoría Sur of Granada, non-densified and densified SRF was produced at a laboratory scale. The production process includes the drying, cleaning and shredding stages for non-densified SRF. The pelletising stage is incorporated for densified SRF, taking as variables the size of the matrix and the moisture content of the input stream. By characterising the produced SRF, it can be determined that its properties comply with the stipulated requirements of ISO 21640:2021 [16] for lower calorific value (LCV), chlorine content and mercury [15]. Consequently, one previous study has demonstrated the technical feasibility of the production of SRF from screening waste [22]. The next necessary step towards potentially implementing the process would be to analyse the environmental impact derived from the exposed processes using a greater number of variables [23].

Life cycle assessment (LCA) standardised by ISO 14044 [24] is one of the most useful and established methodologies in the analysis of potential environmental impacts [25]. LCA is a powerful computerised tool that, in the case of waste, analyses impact from generation to disposal [26,27]. This methodology identifies and quantifies all inputs (including both energy and resources) and outputs (main emissions to water, air, and land) [28].

Several studies have applied LCA to assess the environmental impacts of SRF production from different types of waste, such as municipal solid waste, construction and demolition waste and industrial waste [18,29]. The first publication dates to 2001 and compares the production of refuse-derived fuel (RDF) in different waste treatment plants, considering wet, dry and pellet RDF as production options [30]. A few studies have evaluated the environmental impact of producing SRF from municipal solid waste (MSW) and its subsequent energy recovery, compared to the disposal of MSW in landfills [31–34]. Some studies concluded that implementing an SRF production system significantly saves greenhouse gas emissions [33]. In addition, the production and use of densified SRF can have potential environmental benefits relative to the use of fossil fuels [34].

This context highlights the need for an alternative to landfill disposal of the screening waste. As discussed above, producing densified and non-densified SRF would be a technically feasible alternative. As a second step towards its implementation in an industrial setting and taking into account other studies on SRF and MSW, this SRF production process needs to be evaluated environmentally in comparison with landfill disposal. For this purpose, in this paper the LCA methodology has been used to compare current landfill disposal with SRF production scenarios, making this helpful research a complement to environmental impact studies and a framework for waste management companies.

2. Materials and Methods

In this research, environmental impact was evaluated using the LCA methodology, which has been widely applied to evaluate many waste treatments [35]. LCA comprises the following phases: (i) definition of the goal and scope, statement of the objective of the analysis, setting of the functional unit and identification of the system boundaries; (ii) inventory and scenario analysis; (iii) impact assessment with assignment of the impact potential of the unit flows to the category indicators and impact factors; and (iv) interpretation of the results [5,36,37].

This study used SimaPro 9.2 software with Ecoinvent ® v.3.8 and Agri-footprint as its databases, to allow the modelling and analysis of various life cycles systematically and transparently as well as to measure the environmental impact of processes across selected life cycle stages and to identify the hotspots in all aspects of the chain [38].

2.1. Goal and Scope Definition

This work was carried out based on the results obtained in previous studies developed in Granada, specifically on the wastewater management processes of the Biofactoría Sur, which is the facility selected for the analysis. This facility treats more than 18 mm^3 annually and generated 442.18 tons of screening waste in 2021. The treatment process consists of the following phases: pretreatment (where screening waste is generated), primary treatment or decanting, biological treatment, secondary decanting and treated wastewater outlet (Figure 1) [39].

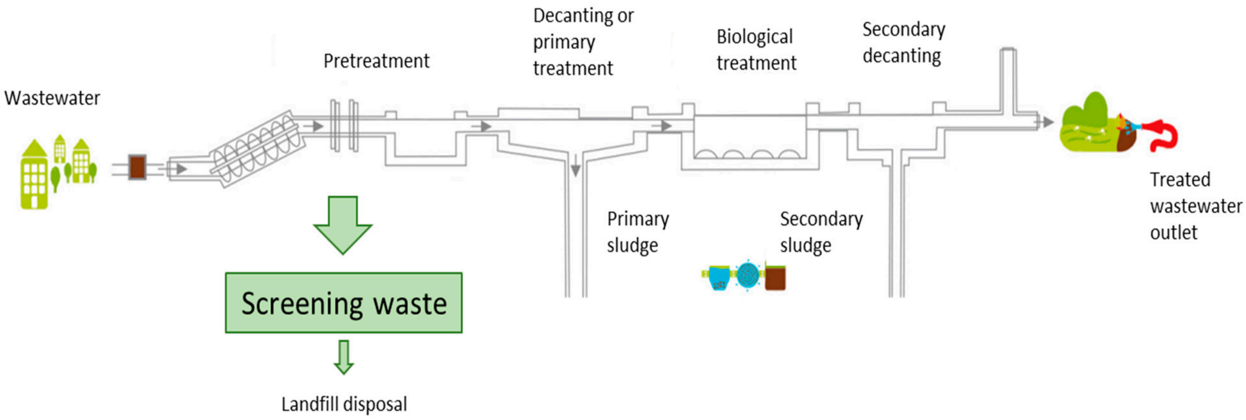

Figure 1. Wastewater treatment process (Own representation of the company's scheme).

The objective of such a study includes the rationale and audience for the assessment, while the scope establishes a functional unit (FU) and boundary of the system under analysis [36]. The main objective of this comparative LCA study is to assess the environmental impacts of SRF production from raw screening waste in Spain as a substitute for current landfill disposal.

The LCA methodology is applied to a supply chain that starts from the wastewater management in WWTP to obtain SRF. The function of the examined system (from waste to energy) is the generation of fuel that can be used as an energy source for the generation of electrical and/or thermal energy in specific plants or at industrial sites.

The primary function of the process is to transform the waste into a fuel. An FU is an objective criterion for comparing defined scenarios and relating inputs and outputs [24]. In such studies, an FU should be defined in terms of input to the system [40]; for this research, this was 1 kg of raw screening waste. This type of residue was defined according to the characterisation developed for the raw screening waste of the Biofactoría Sur with the main results: 77.3% moisture, 9.4% (of total solids) of ash content, 91.0% (of total solids) of volatile solids, 60.5% organic matter and elemental analysis with values of 48.05% of Carbon, 7.71% of Hydrogen and 2.89% of Nitrogen [15]. While the remaining total solids were composed of the fractions presented in Table 1 [15].

Table 1. Fractions present in the raw screening waste [15].

Waste Fractions	Description	Volume from Total Solids (%)	Process Unit in SimaPro	Amount [kg] *
Sanitary textiles	Tampons, sanitary towels, wipes, etc.	52.10	Sanitary textiles	0.1183
Paper and cardboard	Newspapers, brown corrugated cardboard, package paper rolls, office paper	11.80	Waste paperboard, sorted (GLO) market for cut-off, S	0.0268
Organic	Leaves, flowers, plant parts, food scraps, etc.	5.50	Wood chips, wet, measured as dry mass (Europe without Switzerland) market for cut-off, S	0.0125
Plastics	Plastic film, bottles, rigid plastic, packaging, condoms, wrapping and bags	5.00	Polystyrene, general purpose (GLO) market for cut-off, S	0.0113
Other	Fractions that are very costly to separate, including inert debris, hair, organic matter and fine particulates (<20 mm)	25.90	Compost (GLO) market for cut-off, S + sand (RoW), market for sand cut-off, S	0.0588

* Note: Value refers to the FU of 1 kg of raw screening waste.

2.2. Proposed Scenarios

The inventory modelling stage plays a pivotal role in LCA analyses by establishing a connection between all unit processes within the study up to the final product [41]. This phase strives to procure all the required quantities to develop the product/waste flows and elementary flows, which are subsequently categorised into inputs and outputs within the chosen system boundaries [42]. The inputs comprise the materials, energy and resources that enter the unit process, while the outputs comprise the products, waste and emissions generated due to the process [43]. Specifically, a gate-to-grave analysis was conducted here, starting from the raw screening up to the various final waste scenarios. The transformation of raw material into the fractions present in the waste (Table 1) involves several degradation processes that are difficult to quantify, which is why it has not been included in the system boundaries. Biogas recovery or the thermochemical process after SRF production were not considered part of the present research.

The study establishes a systematic framework for evaluating five distinct waste management scenarios, providing a thorough comparative analysis of landfill disposal against innovative processes for producing solid recovered fuel (SRF). The defined scenarios have been established based on the SRF production process, and these are identical to those proposed in a previous article on the economic study [44] (Figure 2):

- *Scenario 1 (S1): Disposal in landfill.*

The elimination of waste in the landfill of Alhendín (Granada) will be considered, so this scenario will be composed of transport from the WWTP and its subsequent elimination.

- *Scenario 2 (S2): Production of non-densified SRF with solar drying.*

Greenhouse drying will be considered and a shredded fuel with homogeneous particle size will be obtained.

- *Scenario 3 (S3): Production of non-densified SRF with thermal drying.*

For this scenario, drying will be conventional by means of thermal heating, obtaining the same fuel after shredding as in the previous scenario.

- *Scenario 4 (S4): Production of densified SRF with solar drying.*

As a continuation of scenario 2 and as a post-treatment to improve SRF characteristics, in this case the fuel obtained will be in the form of pellets.

- *Scenario 5 (S5): Production of densified SRF with thermal drying*.

S5 will be complemented with the densification stage to obtain pellets as SRF.

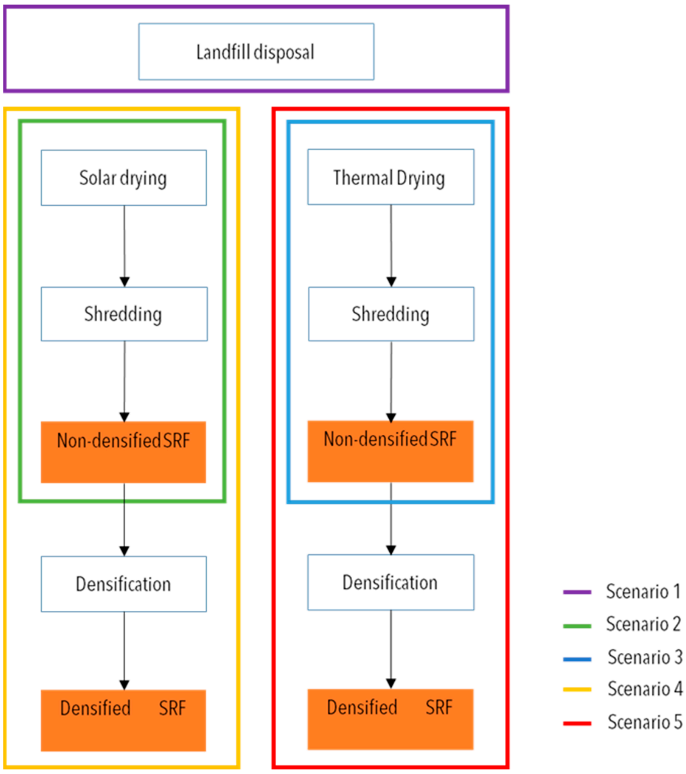

Figure 2. Scheme of scenarios proposed.

To set out the boundaries of the system and to define what was and was not included in the environmental assessment, the figures below are presented. The diagrams define the materials and processes as well as the inputs and outputs corresponding to landfill disposal (Figure 3a) and alternative SRF production scenarios (Figure 3b). By investigating both densified and non-densified SRF production using solar and thermal drying methods, this research introduces a perspective on the effectiveness and sustainability of SRF as an alternative fuel source. This comprehensive approach allows for a clearer understanding of the environmental implications associated with each method.

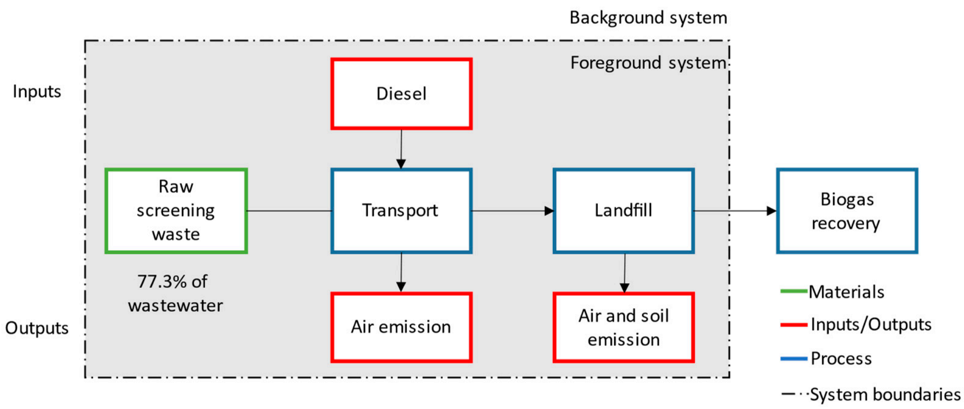

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Figure 3. *Cont.*

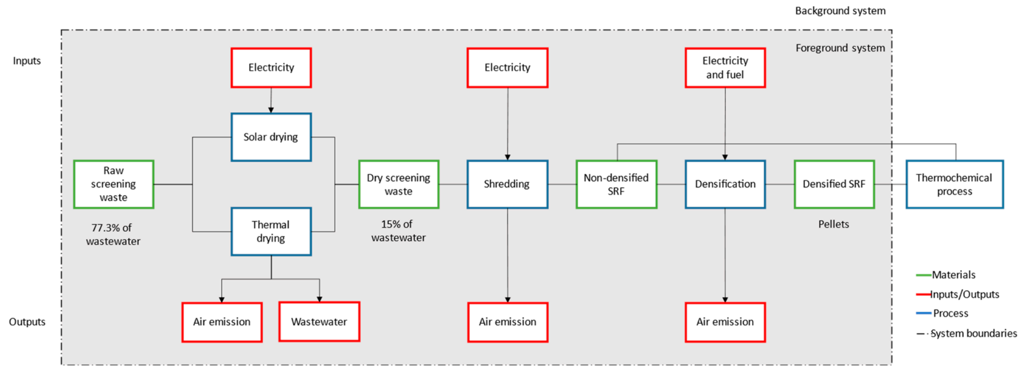

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Figure 3. (**a**) Flowchart of landfill disposal of raw screening waste. Scenario S1. (**b**) Flowchart of solid recovered fuel (SRF) production from raw screening waste. Scenarios S2, S3, S4 and S5.

2.3. Inventory Analysis

All processes were defined for the FU obtained after the compaction process, which was outside the system boundaries. The data collected for the life cycle inventory were mainly primary data obtained from Emasagra, the company that operates the WWTP being considered. This was supplemented with secondary data from the Ecoinvent v.3.8 and Agri-footprint databases, then completed with literature data (Table 2). The inventory of processes involved in the scenarios and defined in SimaPro is described below.

- Transport: only road transport to landfill was considered, whose environmental impact is fundamental to the LCA methodology. The distance from the waste collection point (Biofactoría Sur of Granada) to the destination landfill is 19.7 km. For the scenarios with SRF production, all the screening waste treatment would be carried out at the Biofactoría per se, so transport did not need to be considered in such cases.
- Landfilling: it was not possible to obtain primary data on the emissions produced from the current disposal of screening waste in the specific landfill for Biofactoría Sur. Based on this, the authors have used secondary data for these emissions, obtained for similar landfills in Spain, generally for the disposal of organic municipal solid waste.
- Drying: the objective of this process is to achieve approximately 15% moisture content in the screening waste, a percentage that some authors regard as 'dry residue', which would also meet the moisture requirements for use as fuel in some thermochemical processes [22]. This stage was defined for two drying processes to compare their potential environmental impact. Firstly, solar drying or bio-drying was carried out in a greenhouse containing a scarification roller and a system for moving air in and out [45]. Secondly, which is more established in drying processes, trommel drying was implemented, which is more efficient for waste with a large amount of water [38].
- Shredding: triturating the already dry screening waste is a complicated task due to the high percentage of sanitary textiles and their resistance to grinding. The process aims to reduce and homogenise the particle size of the residue. Once this stage is completed, the residue becomes SRF without densification.
- Densification: the output stream of the previous process, non-densified SRF, is the input stream of this process. This stage involves the conditioning of the SRF as pellets through compaction.

Table 2. Life cycle inventory referred to FU of 1 kg of raw screening waste.

Inputs	Database Process Unit	Unit	Value	Notes
		Transport		
Materials	Raw screening waste	kg	1	Moisture of 77.3%
Processes	Transport, truck < 10 t, EURO3, 20% LF, empty return/GLO energy	tkm	0.039	
		Landfill		
Materials	Raw screening waste	kg	1	Moisture of 77.3%
Processes	Screening from WWTP (waste scenario). Treatment of municipal solid waste, landfill, cut-off, S	p	1	
		Solar drying		
Materials	Raw screening waste	kg	1	Moisture of 77.3%
Processes	Greenhouse for solar drying	p	1	To evaporate 0.623 kg of wastewater
Electricity	Electricity, high voltage {ES} | market for | cut-off, S	kWh	0.040	
		Thermal drying		
Materials	Raw screening waste	kg	1	Moisture of 77.3%
Processes	Trommel drying	p	1	To evaporate 0.623 kg of wastewater
Electricity	Electricity, high voltage {ES} | market for | cut-off, S	kWh	0.560	
		Trituration		
Materials	Dry screening waste	kg	0.377	Moisture of 15%
Processes	Chipper, stationary, electric {GLO} | chipper production, stationary, electric | cut-off, S	p	1	A water loss of 0.3% is considered
Electricity	Electricity, high voltage {ES} | market for | cut-off, S	kWh	0.014	
		Densification		
Materials	Non-densified SRF	kg	0.376	
Processes	Pelletiser [45]	p	1	A water loss of 3% is considered
Electricity	Electricity, high voltage {ES} | market for | cut-off, S	kWh	0.001	
Diesel	Diesel {Europe without Switzerland} | market for | cut-off, S	kg	0.004	

2.4. Life Cycle Impact Assessment

In this phase of the LCA, the significance of the potential environmental impacts is evaluated by using the life cycle inventory results and associating the inventory data with specific impacts [46]. These results are translated into the environmental impacts derived from each proposed scenario.

In this study, the methodology used for calculation was CML-IA baseline v3.08 (midpoint system) [47], which focuses on the following 11 impact categories: abiotic depletion (ADP), abiotic depletion fossil (ADP fossil), global warming potential (GWP100a), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP), photochemical oxidation (PO), acidification potential (AP) and eutrophication potential (EP). These impact categories were selected after an extensive literature review and based on their application in environmental impact assessments of energy recovery process of municipal solid waste [48–50].

3. Results and Discussion

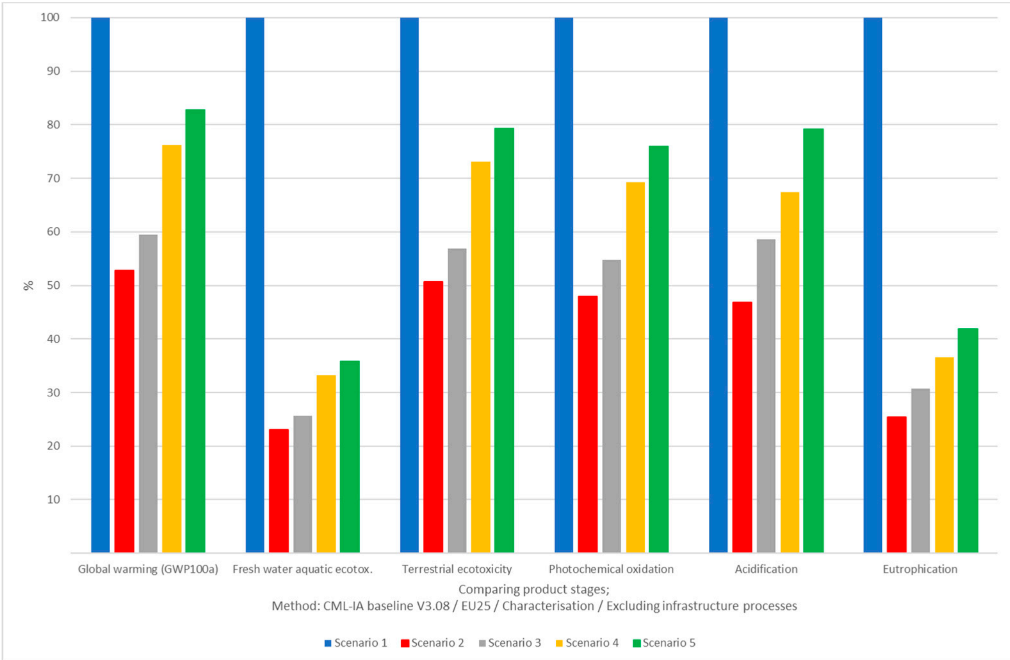
In the context of the waste hierarchy established by Directive 850/2018 [6], it is noted that waste disposal in landfills has the highest environmental impact concerning the disposal of such waste. On the other hand, SRF production processes are placed at a higher level than "other types of recovery, including energy recovery", as established in the directive above. The production of SRF involves the transformation of nutrients, in this case, waste from screening waste, for their incorporation into the value chain. This practise exemplifies the paradigm of the circular economy, whose primary objective is to extend the useful life of resources in the production cycle as much as possible, thus minimising waste generation and promoting environmental and economic sustainability.

The LCA results for each impact category for the five proposed scenarios are presented in Table 3. To enhance clarity, the results for each impact category are normalised against the scenario that exhibits the highest impact within that specific category (Figure 4).

Table 3. Life cycle characterisation results.

Impact Category	Unit	S1	S2	S3	S4	S5
ADP	kg Sbeq	4.40×10^{-6}	1.33×10^{-5}	35×10^{-5}	1.93×10^{-5}	1.95×10^{-5}
	%	6.3	19.1	19.3	27.5	27.8
ADP (fossil)	MJ	29.0	28.8	30.6	41.7	43.6
	%	16.7	16.6	17.6	24.0	25.1
GWP100a	kg CO_2eq	2.41	1.27	1.43	1.83	1.99
	%	26.9	14.2	16.0	20.5	22.3
ODP	kg CFC-11eq	5.05×10^{-7}	1.56×10^{-6}	1.56×10^{-6}	2.25×10^{-6}	2.26×10^{-6}
	%	6.2	19.1	19.2	27.7	27.8
HTP	kg 1.4-DBeq	5.19×10^{-1}	6.43×10^{-1}	7.06×10^{-1}	9.28×10^{-1}	9.90×10^{-1}
	%	13.7	17.0	18.6	24.5	26.2
FAETP	kg 1.4-DBeq	2.11	4.87×10^{-1}	5.42×10^{-1}	7.02×10^{-1}	7.56×10^{-1}
	%	45.9	10.6	11.8	15.3	16.5
MAETP	kg 1.4-DBeq	1.40×10^{3}	1.35×10^{3}	1.60×10^{3}	1.94×10^{3}	2.19×10^{3}
	%	16.5	15.9	18.9	22.9	25.8
TETP	kg 1.4-DBeq	3.18×10^{-3}	1.61×10^{-3}	1.81×10^{-3}	2.32×10^{-3}	2.52×10^{-3}
	%	27.8	14.1	15.8	20.3	22.0
PO	kg C_2H_4eq	6.30×10^{-4}	3.02×10^{-4}	3.45×10^{-4}	4.36×10^{-4}	4.79×10^{-4}
	%	28.7	13.8	15.7	19.9	21.8
AP	kg SO_2eq	9.94×10^{-3}	4.65×10^{-3}	5.82×10^{-3}	6.69×10^{-3}	7.86×10^{-3}
	%	28.4	13.3	16.6	19.1	22.5
EP	kg PO_4eq	4.93×10^{-3}	1.26×10^{-3}	1.52×10^{-3}	1.80×10^{-3}	2.07×10^{-3}
	%	42.6	10.9	13.1	15.6	17.8

Note: Values refer to functional unit of 1 kg of raw screening waste. ADP: abiotic depletion; ADP fossil: abiotic depletion fossil; GWP100a: global warming potential; ODP: ozone layer depletion potential; HTTP: human toxicity potential; FAETP: freshwater aquatic ecotoxicity potential; MAETP: marine aquatic ecotoxicity potential; TETP: terrestrial ecotoxicity potential; PO: photochemical oxidation; AP: acidification potential; EP: eutrophication potential.



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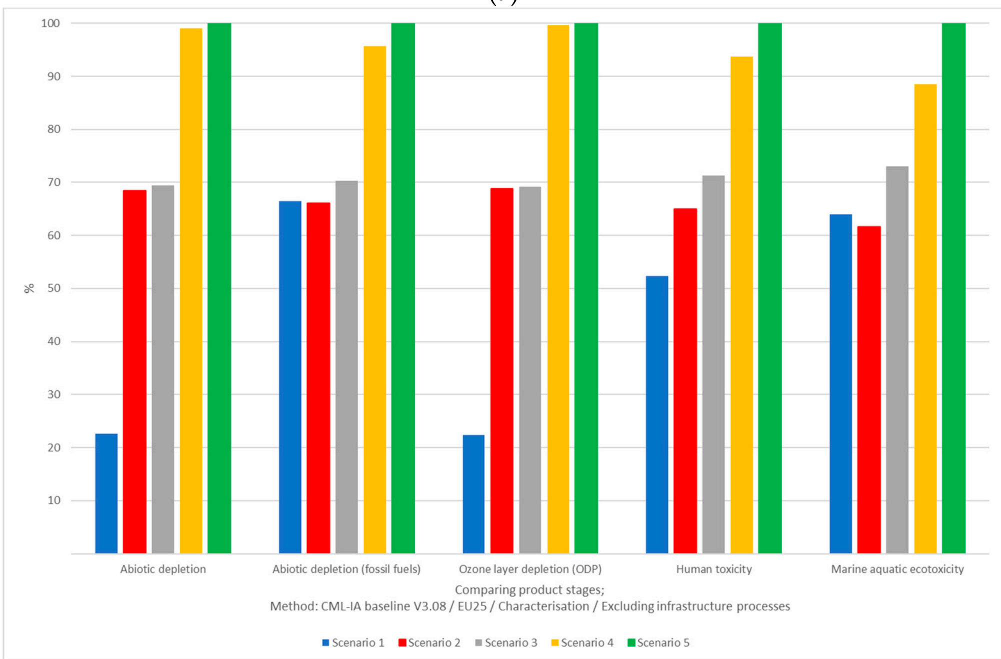

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Figure 4. (**a**,**b**) Comparison of impact assessment of the various scenarios according to the CML-IA baseline v3.08 methodology.

It can be seen that landfill disposal generates the most significant impact in six of the 11 categories proposed by the CML-IA baseline v3.08 method, with noteworthy differences in FAETP and EP. The most negative impact in the rest of the categories corresponds to scenario S5, which has very similar data to S4. The categories on the depletion of natural resources (ADP and ADP fossil) stand out, in which the impact of the increased electricity production required for the processes is exposed. On the other hand, scenario S2, the production of SRF without densification through solar drying, is the most environmentally viable alternative, with the lowest impact index in eight of the 11 categories.

The different categories of impacts shown in Table 3 and Figure 4 are analysed below:

ADP and ADP fossil categories are determined by extracting minerals and fossil materials [51]. The highest impacts recorded in ADP and ADP fossil are 1.95 × 10^{-5} and 43.6 kg Sbeq (Table 3), respectively, corresponding to S5 (densified SRF with thermal drying). It can be observed that the scenarios with densification (S4 and S5) have the most significant impact on these categories due to the increased consumption of fossil fuels (such as coal and natural gas) for electricity production, as necessary for the densification process [52]. In these cases, the densification represents an increase of approximately 30% with respect to the scenarios that produce SRF without densification (S2 and S3). Landfill disposal (S1) presents the lowest values for ADP, due to the absence of utilisation of any mineral/elements during landfilling [53]. The results for fossil ADP for S1 are very similar to those of S2 and S3 and represent an increase with respect to ADP due to diesel transportation, as has been demonstrated in a study concerning the treatment of municipal solid waste in Sakarya [46].

GWP100a represents, in general terms, the increase in temperature due to greenhouse gas (GHG) emissions such as CO_2, CH_4, N_2O and CFCs [26] over a time horizon of 100 years. As expected, Table 2 shows that landfill disposal (S1) contributes the most to this category, with 2.41 kg CO_2eq per kg of raw waste, values higher than the 0.90 kg CO_2eq identified for the landfill disposal of MSW in Brazil [53] and 0.63 kg CO_2eq for the same treatment in Thailand [54]. These results would be far removed from those obtained in another recent study in Brazil, where MSW landfill disposal emissions reach up to 267.44 kg CO_2eq [55]. Such high impact is due to atmospheric emissions, mainly of CO_2, CH_4 and N_2O, which in general terms are generated in the degradation of organic matter in landfill [56], accounting for 60.5% of this waste [15]. The amount of kg CO_2eq per kg of raw waste for the rest of the scenarios is higher for S4 and lower for S2. GWP100a in the alternative scenarios is derived from emissions from fossil combustion for energy production in the SRF process [57]. This assertion is corroborated in Table 1, which shows that the energy consumption of each process in the scenarios is related to the impact on this category.

ODP impact is mainly caused by the emission of methane bromotrifluoro-Halon 1301 resulting from the production of oil and natural gas [58]. In this case, scenarios with higher energy consumption (S4 and S5) have the most significant environmental impact in this category, with 2.25 × 10^{-6} and 2.26 × 10^{-6} kg CFC-11eq, respectively (Table 3), which is about 30% more than S2 and S3 and consistent with the results of a study on wood pellet production [59]. This densification-driven increase is similar to that shown in the abiotic depletion categories, demonstrating that all three categories (ADP, fossil ADP and ODP) are proportionally linked to fossil resource expenditure, as Lourenço and Nunes [60] pointed out in an LCA on wastewater treatment, in which he concluded that ODP is entirely dependent on electricity production. Landfill disposal of waste is not directly related to ozone depletion.

HTP measures human exposure to toxicity from elements such as lead, zinc and other contaminants within dichlorobenzenes [61]. Table 3 exposes that the highest impact values are for densification scenarios, with 9.28 × 10^{-1} and 9.90 × 10^{-1} kg 1.4-DBeq, for S4 (solar drying) and S5 (thermal drying). Comparing the results with the production of non-densified SRF, values of 5.19 × 10^{-1} and 6.43 × 10^{-1} kg 1.4-DBeq are observed for scenarios S2 (solar drying) and S3 (thermal drying), respectively, which represent values 43% and 35% lower, owing to the extra energy consumption in densification [29]. In this category, the impact of S1, which is 50% lower than the highest figure, is determined by transportation; however, compared with the other scenarios, it has a smaller footprint due to the difference in energy expenditure. This assertion aligns with an LCA on alternatives to landfilling for MSW, in which this type of disposal also did not have the most significant impact on HTP [51]. However, landfills can release toxic substances and pollutants, which could affect human health through groundwater contamination and the emission of toxic compounds into the air. This can lead to health risks for people living near or working at landfills.

Regarding the ecotoxicity categories, it can be seen that the scenarios' impact is caused by the emission of contaminants into water, whether to oceans and seas, or to rivers and to the soil [62]. S1 causes the most significant impact on FAETP and TETP with values of 2.11 and 1.40 $\times$ 10^{-3} kg 1.4-DBeq (Table 3), possibly due to contaminants such as nickel, arsenic, lead, zinc, mercury and barium, which are discharged during landfill disposal [59]. The maximum for the MAETP category corresponds to S5, with 3.18 $\times$ 10^{-3} kg 1.4-DB eq (Table 3). The normalised values of the alternative scenarios to landfill for these categories show that their differences follow a similar progression. The percentages for FAETP are 23, 26, 33 and 36% for scenarios S2, S3, S4 and S5, respectively. For MAETP impact, the values are, respectively, 62, 73, 89 and 100%, while for TETP, the results reach 51, 55, 73 and 77% (Figure 4). Analysing these values, it can be observed that the differences between solar drying and thermal drying for both non-densified and non-densified SRF are practically the same across the three categories. Thus, in these categories, thermal drying negatively affects 3% of FAETP, 12% of MAETP and 5% of TETP.

PO defines the reaction of nitrogen oxides with volatile organic compounds to produce tropospheric ozone [26]. In this case, landfill disposal is considered the worst scenario, with a value of 6.30 $\times$ 10^{-4} kg C_2H_4eq (Table 3), mainly due to methane emissions and volatile organic compounds and nitrogen compounds that react in the atmosphere and contribute to the formation of tropospheric ozone, a harmful pollutant [46]. As also asserted by Abeliotis [63] in a paper on MSW management in Athens. The other scenarios have little impact on this category, in line with Edwards et al. [58] research on the environmental impact of a mechanical-biological treatment plant for food waste.

The production of SO_x, NO_x, H_2S, HF, HCl and HNO_3 causes environmental acidification potential and consequent damage to continental ecosystems [64]. Landfill disposal (scenario S1) has the most significant impact, with 9.94 $\times$ 10^{-3} kg of SO_2 eq (Table 3), due to sulphur emission [64]. Regarding SRF production, the most significant impact is caused by the scenario with thermal drying and densified fuel production (S5) [65]. Densification represents an increase of 26% for scenarios with thermal drying (S3 and S5) and 31% for solar drying (S2 and S4).

The impact on EP is where nitrogen and phosphorus affect terrestrial and aquatic systems [66]. In this category, there is the most noteworthy difference between the results of the proposed scenarios—58.13%—between landfill disposal with 4.93 $\times$ 10^{-3} kg PO_4eq and the following most impactful scenario (S5) with 2.07 $\times$ 10^{-3} kg PO_4eq (Table 3). The percentages of increase implied by densification in this category for the rest of the scenarios are very similar to those for AP: 27% and 30% between the scenarios with thermal and solar drying, respectively.

4. Conclusions

Given the need to find alternative means of managing screening waste and, under the premise that the production of SRF from such waste is technically feasible, the use of LCA can provide valuable insights to guide decision-making processes towards more environmentally and economically viable options. The results of this LCA study, performed for the treatment of screening waste, show that landfill disposal has the most damaging environmental impact among the waste management options evaluated. This is due to the release of various contaminants, such as heavy metals, organic pollutants and greenhouse gases, during the decomposition of screening waste in landfill. These pollutants can have significant impacts on air, water and soil quality as well as on human health and ecosystems.

Producing SRF from screening waste, especially without densification and with solar drying, is the most environmentally viable process among the scenarios evaluated here. This process has lower environmental impacts compared to landfill disposal, as it avoids the emissions of pollutants during landfill decomposition and reduces reliance on fossil fuels for energy production, suggesting practical applications for integrating renewable energy resources into waste management systems. However, it is worth noting that the scenarios describing the production of densified SRF showed lower environmental impacts compared to landfill disposal but proved less environmentally viable than the non-densified SRF scenarios. Considering the above, the results of this study emphasise the need to move away from landfill disposal and towards more sustainable waste management practises.

Integrating SRF into energy systems is a key aspect of this transition, contributing to broader efforts in sustainability and resource efficiency.

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