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# Analyzing the production, quality, and potential uses of solid recovered fuel from screening waste of municipal wastewater treatment plants

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ABSTRACT

Over time, wastewater management evolves into a circular model, producing energy and moving towards zero waste. The usual screening waste treatment is the elimination, with no energy recovery processes. As an alternative, the production of solid recovered fuel (SRF) from screening has been studied, both non-densified and densified, in pellet form. The densification was developed, taking as variables the input moisture and size of the die, obtaining 20 different samples. The optimum pelletizing conditions are an input moisture content of 10% and dies with a compression ratio of 6/20, 6/24 and 8/32. SRF properties have been evaluated based on a quality proposal presented in this paper, which has been developed given the lack of uniformity in the existing SRF standards. The SRF produced complies with fuel quality requirements, such as lower calorific value, with values between 13.37 and 25.65 MJ/kg; Cl and Hg content, with maximums of 0.066% and $1.0 \times 10^{-5}$ mg/MJ, respectively; and ash content, between 7.22% and 9.85%. Energy from waste plants could be the destination for all the SRF produced. Its use in cement plants and gasification processes, more restrictive than the previous one, would require manufacturing processes with adequate moisture levels and die size.

## 1. Introduction

The purpose of a municipal wastewater treatment plant (WWTP) is to reduce the pollutant load of water after use and before returning it to the natural environment. Different physical, chemical, and biological treatments are used. At its inlet, wastewater contains a large amount of solid material of varying nature that must be removed to allow the subsequent treatment stages. This solid material generates waste at arrival and during the pre-treatment stage. Among this waste is a fraction consisting of a heterogeneous mixture of organic matter, paper, sanitary waste, and plastics, among others, classified under EWC code 19 08 01, described as *Screening*. It is included in subchapter 19 08 *Wastes from wastewater treatment plants not specified* in chapter 19 *Wastes from waste management facilities, off-site wastewater treatment plants, and from the preparation of water intended for human consumption and water for industrial use* (Europeo, 2014).

The typical composition of screening waste reported in the literature is characterized by the predominance of sanitary textiles, whose presence has been progressively increasing over the years with changes in society's habits (Wid and Horan, 2016), going from 25% in 1996 (Clay et al., 1996) to an average value of 50% today (Gregor et al., 2013). However, percentages of 87% have been reported (Le Hyaric et al., 2009). Paper and vegetables also have a significant presence in waste, with differences depending on the treatment plant, varying between 1.3% and 13.1% by weight (Le Hyaric et al., 2009). The company of fines, i.e., particles less than 20 mm in diameter that are very difficult to separate, varies between 7.6 (Wid and Horan, 2016) and 15.2% (Le Hyaric et al., 2009), and, finally, the set of plastics, metals and non-biodegradable materials do not exceed values between 3.1 (Wid and Horan, 2016) and 9.7% (Le Hyaric et al., 2009).

The amount of this screening waste produced in WWTPs accounts for about 2% of the total waste generated during the process (Le Hyaric et al., 2010), with values in dry matter ranging from 0.08 kg/yr.heq (Le Hyaric et al., 2010) to 1.1 kg/yr.heq (Kaless et al., 2016). The amount is affected by factors such as rainfall, as a meteorological factor (Canler and Perret, 2004), the design of the pre-treatment and the screen passage span used (Le Hyaric et al., 2009), or the compaction process

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**Nomenclature**

| | |
|---|---|
| SRF | Solid recovered fuel. |
| WWTP | Wastewater treatment plant. |
| EWC | European waste catalogue. |
| WRRF | Wastewater resource recovery facility. |
| Dd | Diameter of pelletizing die. |
| Lc | Compression length of pelletizing die. |
| Dd/Lc | Compression ratio of pelletizing die. |
| MSW | Municipal solid waste. |
| LHV | Lower heating value. |
| N.S. | Not specified. |
| EfW | Energy from waste plants. |
| Dp | Pellet diameter. |
| Lp | Pellet length. |
| DP | Pellet density. |
| BD | Bulk density. |
| DU | Pellet moisture. |
| Mp | Pellet moisture. |
| M | Non-densified SRF moisture. |
| HD | Hardness. |
| NR | Not recommended. |

frequently used to eliminate the amount of water contained, which in addition reduces its volume (Clay et al., 1996).

The production of screenings is low, for example, if compared to the generation of other fractions produced in the purification process, such as sludge, which can reach values between 19 and 31 kg/yr.heq in dry matter (Granados, 2015). This low amount has been the main reason why scientific research on screenings has received little interest to date, especially in terms of finding an alternative to their disposal in a landfill (Granados, 2015), the most common destination for this type of waste (Wid and Horan, 2018). This solution generates environmental problems. It also involves a high cost in transporting the waste, given its high moisture content. At the same time, there are possible problems regarding the admission of waste to a landfill due to its organic matter and moisture content (Cadavid-Rodriguez and Horan, 2012). On the other hand, waste disposal by landfilling is bound to disappear since, with the new restrictions raised in Directive 850/2018 (Europeo et al., 2018) in 2035, the amount by weight of municipal waste landfilled will have to be reduced to a maximum of 10% (MITECO, 2020). The few papers published on alternatives to landfilling in the screening treatment of urban wastewater treatment plants have mainly focused on anaerobic digestion and co-digestion of the same (Boni et al., 2021). Studies have been conducted to determine the methane production potential of screenings under different conditions, such as reactor type, presence of solids, and retention time. Results have shown a potential range of methane production from 0.19 (Le Hyaric et al., 2010) to 1.04 L $CH_4$/g VS (Boni et al., 2021). A study about using screenings waste to produce free sugars to obtain different products, including bioethanol, was also carried out (Ballesteros et al., 2022).

For all these reasons, WWTP management companies need to look for alternatives to the current disposal of screening wastes in landfills, thus contributing to circularity in their role as resource producers. In recent years, the consideration of this type of facility as a resource recovery factory has been gaining ground, and it is now common to use terms such as wastewater resource recovery facilities (WRRFs) in the US or biofactories in Santiago de Chile (Donoso-Bravo et al., 2020).

Among the possible alternatives to be considered is energy recovery, which, through the biofuel production (Shehata et al., 2022), should play a relevant role as an alternative to the use of fossil fuels (Yan et al., 2021). Even more so and inevitably, after the impact on the global energy sector caused by COVID-19 and aggravated by February 2022, when Russia invaded Ukraine, creating significant concerns in the energy supply (Esfandabadi et al., 2022). The objective of solid recovered fuel (SRF) production is to decrease the reliance on fossil fuels in combustion, gasification, and pyrolysis processes (Nasrullah et al., 2014). By doing so, the densification of the final product not only lowers the environmental footprint associated with managing waste (Hettiarachchi et al., 2019), but also cuts the expenses of handling, transporting, and storing wood-based products along the supply chain (Whittaker and Shield, 2017). Furthermore, pelletizing in agro-biowaste compost has the potential to reduce the environmental impact by over 63% (Sarlaki et al., 2021). The feasibility of the SRF production and utilization process must be studied in economic, social and environmental terms. For improved decision-making, cost/benefit analyses have been developed for SRF from MSW for use in cement plants (Iacovidou et al., 2018) or gasification processes (Arena et al., 2015). In the environmental and social aspects, an analysis with more variables of the environmental impact derived from the exposed processes is necessary (Aghbashlo et al., 2022). Life Cycle Assessment (LCA) is one of the most useful and established methodologies (Ferrari et al., 2021) being a powerful computerized tool that, in the case of SRF, analyzes impacts derived from its production (Grosso et al., 2016) and use (Breckel et al., 2013).

In this sense and concerning alternatives to current disposal of the screening waste, even though its composition is similar to that of municipal waste (Dong et al., 2010), no studies have been reported that analyse the possible use of WWTP screenings for energy recovery through the production of SRF. Thus, among the wastes that Sarc et al (Sarc et al., 2014). consider suitable for SRF production, as the most commonly used, are rejects from biological treatment of municipal waste (Jędrczak and Suchowska-Kisielewicz, 2018) and construction and demolition by-products (Nasrullah et al., 2015a) with EWC codes 19 12 12 and 17 09 04, respectively. Screening wastes (EWC code 19 08 01) do not appear among them. However, ISO 21640:2021 (AENOR, 2021a), which in 2021 updated the specifications and classes of EWCs, already considers "*solid waste from urban wastewater treatment*" as a possible origin.

The present works aim to study the utilization of screening waste from WWTPs to produce non-densified and densified SRF as an alternative to its problematic disposal in landfills. The determination of the properties of the SRF generated, and the evaluation of its quality has been developed based on an exhaustive study of the existing regulations on SRF and densified biofuels for evaluating the feasibility of using SRF as an alternative to fossil fuels in combustion or gasification processes. To the best of our understanding, this is the first time that solid fuel production from this waste has been evaluated.

## 2. Materials and methods

The work developed to achieve this set of objectives includes the following four stages (Fig. 1) which are described in the following sections: (i) production of SRF at a laboratory scale; (ii) basis for establishing the quality of the SRF produced; (iii) determination of the quality of the SRF; (iv) determination of the potential uses of the SRF.

### 2.1. SRF production at a laboratory scale

In this study, laboratory-scale production of SRF from screenings has been carried out. Both non-densified and densified SRF were produced. For this purpose, the production process shown in Fig. 1, described below, was followed.

#### 2.1.1. Collection of material

The screenings used came from the Biofactoría Sur of Granada (Spain). To work with the most representative material possible, several samples were taken. Specifically, 16 samples of approximately 8 kg were taken from the output of the screen compactor. Two pieces per week, throughout October and November 2021, were collected on random

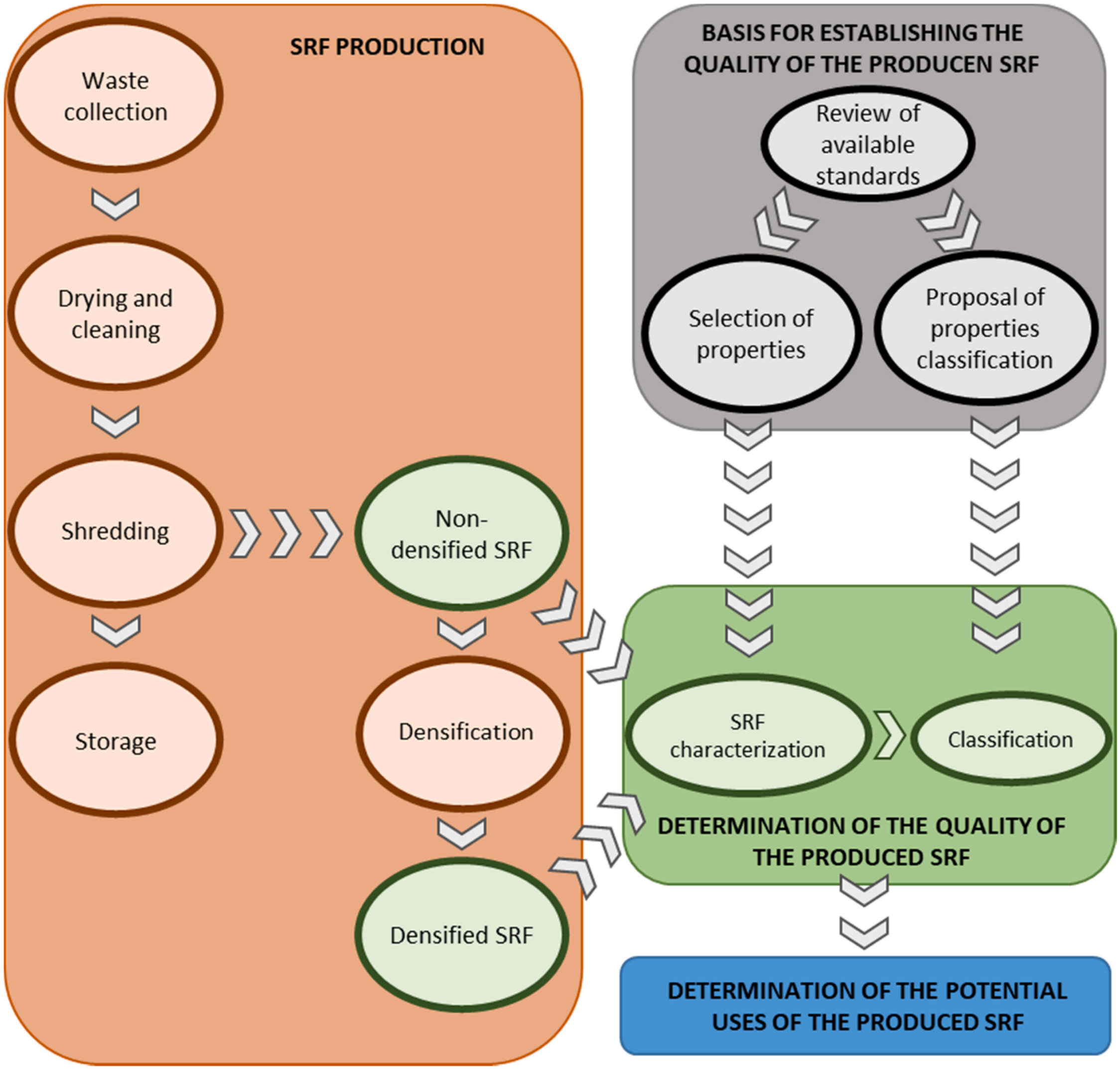



**Fig. 1.** Study phases for Solid Recovered Fuel (SRF).

days of the week and during daytime and night-time hours (Fig. 2a).

### 2.1.2. Drying and cleaning

Once each sample was received in the laboratory, it was dried. For this purpose, the sample was spread on metal trays, and after 24 h in an oven at 105 °C, it was mixed to be introduced again in the oven at the same temperature for another 24 h. Once dry, the undesirable fractions that could affect the process, especially those of an inert nature, were removed and prepared for crushing (Fig. 2b).

### 2.1.3. Shredding

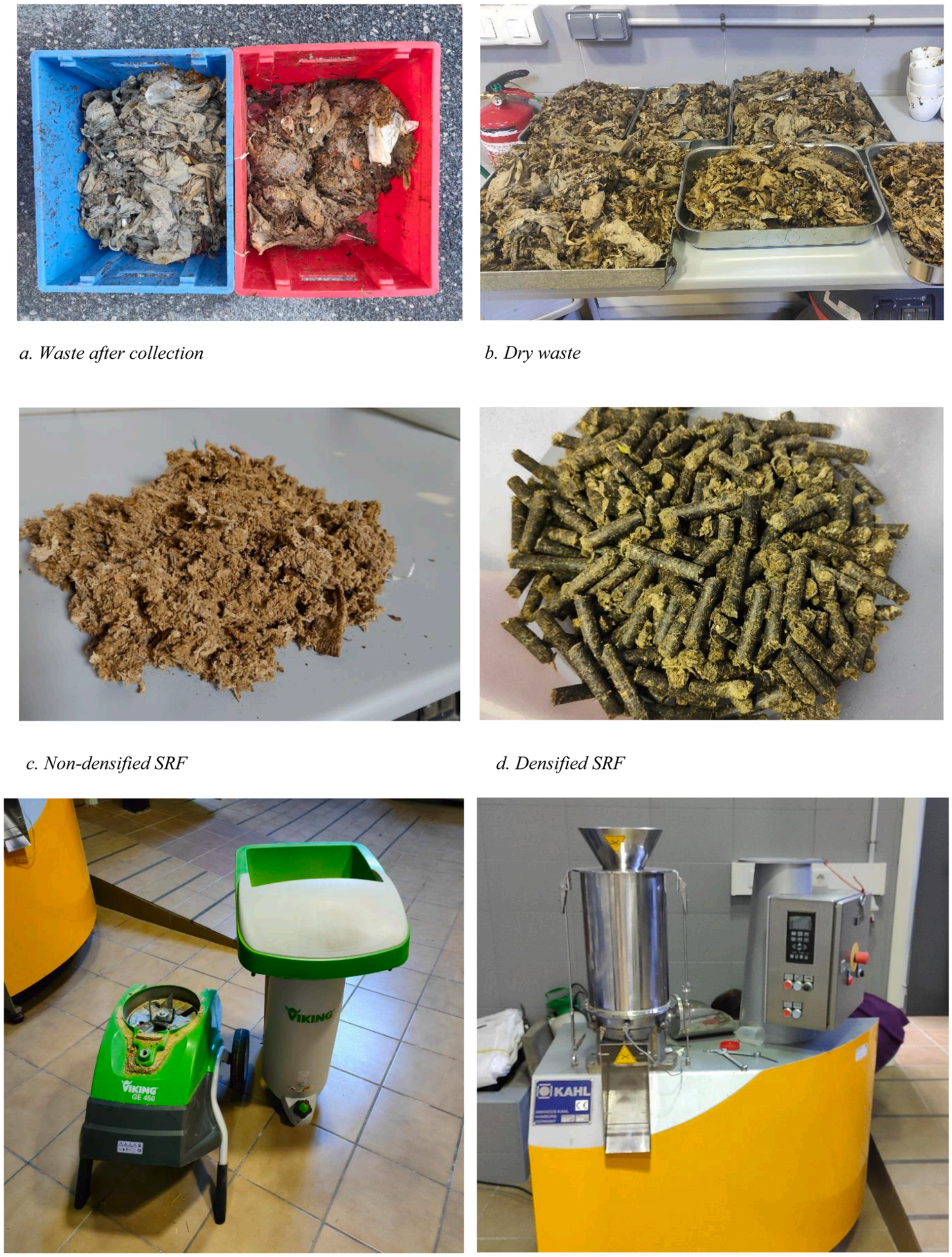
The dry waste was shredded using a Viking GE450 garden bio-shredder with a power of 2500 W (Fig. 2e), which yielded the non-densified SRF, shown in Fig. 2c, characterized by a light matrix and a cottony appearance, due to the high content of sanitary textiles.

### 2.1.4. Storage

A portion of the SRF produced was stored at room temperature for characterization. The rest was used for the production of densified SRF.

### 2.1.5. Densification

Finally, to produce the densified SRF, non-densified SRF was quartered to obtain a homogeneous sample and pelletized using a flat die type press, KAHL 14–175, with a drive power of 3 kW and a feed capacity of 50 kg/h (Fig. 2f). The pelletizing process is subject to input variables including particle size, moisture, the diameter and compression length of the die, temperature (Garcia-Maraver et al., 2015), and the presence of additives (Said et al., 2015). After preliminary tests, and because of the low density of the residue due to the content of sanitary textiles, work was carried out at intensities lower than 7 A and temperatures that did not exceed 29 °C. Likewise, the homogeneity in the particle size of the sample was not considered a variable. Therefore, three operating variables were considered for the pelletizing process: moisture of the inlet stream and the die`s diameter and compression length. In the case of moisture, studies of the pelletization of rejects from biological and mechanical treatment of municipal waste were taken as a reference, with maximum moisture percentages of 45% (Zafari and Kianmehr, 2014), which allowed establishing four operation values, 10%, 20%, 30% and 40%. These values were achieved by spraying the dry sample, obtained after the drying and shredding processes, with water until reaching the values required for each test, taking into account for this purpose the moisture value of the stored non-densified SRF, obtained in its characterization at the time of its use. In terms of diameter (Dd) and compression length (Lc) of the pelletizing dies, which determines their compression ratio (Dd/Lc), five available dies were used with diameters of 6 or 8 mm and compression lengths of 16, 20-, 24-, 32- or 48-mm. Table 1 shows the designation and characteristics of the five dies used. Finally, to lower production costs, and given that




a. Waste after collection

b. Dry waste

c. Non-densified SRF

d. Densified SRF

e. Bio shredder Viking GE450

f. KAHL 14-175 Pelletizer

**Fig. 2.** Non-densified and densified Solid Recovered Fuel (SRF) production process. a) Waste after collection. b) Dry waste. c) Non-densified SRF. d) Densified SRF. e) Bio shredder Viking GE450. f) KAHL 14–175 Pelletizer.

studies of pellet production from urban waste showed the possibility of manufacturing them without the need to add additives (Rezaei et al., 2020), it was decided not to use additives for the densification of the material. As a result, 20 pellet samples were obtained, whose designations are given in Table 1, which were stored at room temperature for.

### 2.2. Basis for establishing the quality of the SRF produced

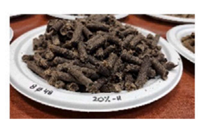
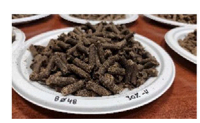
The quality of the SRF produced was established based on the classification of the set of properties that characterize it. These characteristics are related. On one hand, is its use as fuel, as well as its final use, regardless of its presentation in densified form or not, taking into account economic, technical, and environmental aspects. On the other hand, in the case of densified SRF, it is necessary to consider other properties directly related to its densified form and which affect its storage, transport, and feeding in the thermochemical processes in which it can be used.

Given the diversity of existing reference standards, as well as the absence of specific standards to classify pellets generated from screening or similar wastes (e.g., municipal solid waste), it was decided to develop our proposal to organize the identified properties based on a set of existing standards which were used to determine the optimal conditions to produce densified SRF in the form of pellets. For this purpose, the following stages were followed Fig. 1: (i) review of the available standards; (ii) selection of properties for the characterization of the produced SRF; (iii) proposal of properties classification. These stages are described below.

#### 2.2.1. Review of available standards

In the first place, the review of standards applicable to manufactured

**Table 1**
Denomination of pellet samples produced.

| Pelletizing die identification | Diameter of pelletizing die (Dd) (mm) | Compression length of pelletizing die (Lc) (mm) | Compression ratio (Dd/Lc) | Pelletizer inlet stream moisture (%) | | | |
|---|---|---|---|---|---|---|---|
| | | | | 10 | 20 | 30 | 40 |
| D6L20 | 6 | 20 | 6/20 | P-10-D6L20  | P-20-D6L20  | P-30-D6L20  | P-40-D6L20  |
| D6L24 | 6 | 24 | 6/24 | P-10-D6L24  | P-20-D6L24  | P-30-D6L24  | P-40-D6L24  |
| D8L16 | 8 | 16 | 8/16 | P-10-D8L16  | P-20-D8L16  | P-30-D8L16  | P-40-D8L16  |
| D8L32 | 8 | 32 | 8/32 | P-10-D8L32  | P-20-D8L32  | P-30-D8L32  | P-40-D8L32  |
| D8L48 | 8 | 48 | 8/48 | P-10-D8L48  | P-20-D8L48  | P-30-D8L48  | P-40-D8L48  |

SRF included those properties that evaluate its quality as a fuel. For densified fuel, this was completed with a set of properties to assess the quality of the densified form as pellets. Table 2 and Table 3 list the standards used as a reference to evaluate the quality of the SRF produced as fuel and pellets, respectively, indicating end uses, categories, and requirements concerning their properties.

*2.2.2. Selection of properties for the characterization of the produced SRF*

Based on the review of available standards, the properties considered to characterize the produced SRF were selected and are shown in Table 4, including the standards analytical methods.

In the non-densified SRF, the following were selected: LHV, Cl content, Hg content, ash, and moisture. The first three, which have great relevance from an economic, technical, and environmental point of view, were selected because they are included in ISO 21640:2021 (AENOR, 2021a). Moisture and ash content, although not limited to ISO 21640:2021 (AENOR, 2021a), were incorporated because they are present in most of the standards included in the ISO/TR 21916:2021 report (ISO/TC 300, 2021). The report mentioned above consists of an extensive study on the quality of SRFs based on a literature review and consultations with producers, concluding that in 99% of the exposed cases, the moisture and ash content of the SRFs produced is evaluated. On the other hand, other properties incorporated in some of the standards (Table 2), such as particle size and density, were considered of little relevance for this work since, in addition to being present in only three of the eleven standards reviewed, the product obtained, as indicated above, is difficult to break down into particles. Finally, the content of other heavy metals, in addition to Hg, was not considered due to the nature of the waste obtained.

In the case of densified SRF, a total of eleven properties were used, five of them were included in the characterization of non-densified SRF and six additional ones are related to the conditioning of SRF in pellet form, including diameter, length, pellet density, bulk density, durability, and hardness. Diameter and length are present in all standards; bulk density and durability are in all but one, and pellet density is in half of the revised standards. Finally, hardness was included, despite not being included in any of the standards reviewed (García-Maraver et al., 2011), because it is a property linked to pellet handling and storage (Said et al., 2015), and it has been extensively analysed in numerous studies such as torrefaction analysis (Haykiri-Acma and Yaman, 2022) or the effect of additives in pellets (Nursani et al., 2020), including manuscripts that focus on the relation of hardness to other fuel parameters (Suryawan

**Table 2**
Quality of Solid Recovered Fuel (SRF) as fuel. Reference standards.

| Standard | Application area | Final use | Classes | Included properties | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | LHV[a] | Cl | Hg | Moisture | Ash | Particle size/ density | Heavy metal |
| **ISO 21640:2021 Solid recovered fuels — Specifications and classes (AENOR, 2021a).** | International | N.S.[b] | ✓ | ✓ | ✓ | ✓ | | | | |
| **UNI 9903–1:2004 Non mineral refuse derived fuels - Specifications and classification (Ente Nazionale Italiano di Unificazione UNI, 2004).** | Italy | Cement plants, EfW | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **Arrêté du 23 mai 2016 relatif à la préparation des combustibles solides de r é cupération en vue de leur utilisation dans des installations relevant de la rubrique 2971 de la nomenclature des installations classées pour la protection de l'environnement (L'énergie et de la mer Ministère de l'environnement, 2016).** | France | EfW[c] | | ✓ | ✓ | ✓ | | | | ✓ |
| **RAL-GZ 724 (2008) Quality and test instructions Solid Recovered Fuels (Gütegemeinschaft Sekundärbrennstoffe und und und, G.P. für S. e. V, 2008).** | Germany | Cement plants, lime kilns, EfW | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| **WRAP. A classification scheme to define the quality of waste derived fuels (Waste and Resources Action Programme, 2013).** | United Kingdom | EfW | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **No. 389/2002 in the Incineration Waste, BGBI (BMLFUW, 2002).** | Austria | Cement plant, EfW, Co-incineration | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ |
| **Limit values set by authorities for individual permits for cement plants in Spain (Schorcht et al., 2013).** | Spain | Cement plants | | | ✓ | ✓ | | | | ✓ |
| **Limit values set by authorities for individual permits for cement plants in Belgium (Schorcht et al., 2013).** | Belgium | Cement plants | | | ✓ | ✓ | | | | ✓ |
| **SFS 5875 (2000) Solid Recovered Fuel - Quality Control System (General Industry Federation, 2008).** | Finland | Incineration, Co-incineration | ✓ | | ✓ | ✓ | | | | ✓ |
| **Guidelines on Usage of Refuse Derived Fuel in Various Industries. Draft of July 2018 (Health et al., 2018).** | India | Cement plants | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | |
| **Act on the Promotion of Saving and Recycling of Resources Enforcement Regulation (Addendum 7) (R. of Korea, 2002)** | South Korea | N.S. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

[a] LHV: Lower heating value.
[b] N.S.: Not specified.
[c] EfW: Energy from waste plants

et al., 2022).

As a result of the above analysis, Table 5 and Table 6 show the standards, properties, and the included values applied to the SRF without densification and SRF pellets, respectively. The reference units were taken from ISO 21640 (AENOR, 2021a). It was necessary to convert units for some standards. In the case of Hg content, and given the impossibility of unit conversion, it was decided to include the two units that appear in the standards. On the other hand, it was observed that the reference values used for moisture content for non-densified and densified SRF are different; this is because moisture, unlike LHV, and ash, Cl, and Hg contents, is a property that affects the logistics of SRF, so it was evaluated based on the pellet standards, in addition to being conditioned by the manufacturing process. Finally, hardness was analysed as a relevant property of SRF, but it does not appear in any standard. So, it was compared, based on the literature which considers it a pertinent parameter in pellet quality.

### *2.2.3. Proposed classification of properties*

Given the absence of an SRF property classification applicable to the specific case of the waste under consideration and based on the values established in the standards analysed for the selected properties (Table 4), a proposal will be prepared to lead to a classification that includes four categories, according to the levels indicated below:

- Class 1 (C1). It will correspond to the range of optimum values for the property under consideration and includes those values met in 100% of the standards selected for this study.
- Class 2 (C2). It will correspond to average quality values for the property under consideration and includes a range that met at least 50% of the standards selected for this study without reaching 100%.
- Class 3 (C3). It will correspond to low-quality values for the property under consideration and includes a range that met at least 25% of the standards selected for this study without reaching 50%.
- Not recommended (NR). Finally, if the value of property results in quality outside the limits to be established in the indicated classes, it will be considered unsuitable or not recommended, corresponding to values included in less than 25% of the consulting standards.

## *2.3. Determination of the quality of the SRF produced*

To determine the quality of the SRF produced, the analytical methods listed in Table 6 were applied. Each determination was performed in triplicate to obtain an average value. In the case of densified SRF, to determine the most suitable production conditions, the correlation between the independent variables (initial humidity, compression length, and die diameter) and pellet properties was studied (Table 4) using R (V. 4.1.1), a free programming environment and language with a focus on statistical analysis.

**Table 3**
Quality of Solid Recovered Fuel (SRF) as pellet. Reference standards.

| Standard | Application area | Extraction | Final Use | Classes | Included properties | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Dp[a] | Lp[b] | PD[c] | BD[d] | DU[e] | Mp[f] | Ash | LHV[g] | Chemical elements |
| **ISO 17225:2021 Biocombustibles sólidos. Especificaciones y clases de combustibles (AENOR, 2021b)** | International | Wood or herbaceous biomass | Commercial and residential applications. Industrial. | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **O NORM M7135 (O NORM M, 7135, 2002)** | Austria | Wood or herbaceous biomass | Industrial | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **DIN 51731 and DIN PLUS (Norm, 2002)** | Germany | Wood or herbaceous biomass | Specific boilers for pellets. Industrial | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Agro and Agro+ (Narra et al., 2012)** | France | Agricultural origin | Incineration, boilers or furnaces. | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| **SS187120** | Sweden | N.S. | N.S.[h] | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Pelet Fuel Institute Standards (SS20 Pelet Fuel Institute Standards, 1871, 2014)** | United States of America | Wood | N.S. | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **NY/T 1878–2010 (R.K.L. of R. E. Ministry of Agriculture, 2010)** | China | Wood or herbaceous biomass | N.S. | ✓ | ✓ | ✓ | ✓ | | | ✓ | | | |
| **JAS Standards for Wood Pellets for Non-Industrial Use (F. and F. Ministry of Agriculture, 2021)** | Japan | Wood | Non industrial | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

[a] Dp: Pellet diameter.
[b] Lp: Pellet length.
[c] PD: Pellet density.
[d] BD: Bulk density.
[e] DU: Durability.
[f] Mp: Pellet moisture.
[g] LHV: Lower heating value.
[h] N.S.: Not specified

### 2.4. Determination of the potential uses of the produced SRF

Finally, taking ISO/TR 21916:2021 (ISO/TC 300, 2021) as a reference, three potential uses will be considered for the SRF produced: cement plants, power plants, and gasification. The minimum and maximum values to be taken as reference established for the SRF properties considered in the previous report (LHV, Cl content, Hg content, ash, and moisture) are shown in Table 7.

## 3. Results and discussion

The non-densified and densified SRF were produced at a laboratory scale according to the described procedure. Then we proceeded to establish the basis for defining the classification of its properties, based on which samples were characterized and classified, and their potential use was found. The results obtained are presented, analysed, and discussed below.

### 3.1. Proposed classification of SRF properties

Taking into account the criteria established in the methodology described above and the properties and values included in the revised standards (Table 5 and Table 6), a classification proposal for these properties was prepared, establishing limit values for the different classes defined (Class 1, Class 3, Class 3, and Not recommended). Fig. 3 and Fig. 4 show the proposed ranges, with the limit values established for each class and properties considered for the non-densified and densified SRF.

### 3.2. SRF characterization

Once the SRF was manufactured, it was characterized by determining the properties and analytical methods shown in Table 4. Results are shown in Table 8 and Table 9, which show the values obtained for each property and its class according to the proposed classification. The results are presented and discussed below.

#### 3.2.1. Characteristics of the non-densified SRF

The values determined for the properties of the non-densified SRF samples and their classification are shown in Table 8. For clarity, a colour code, including green, yellow, orange, and red, was used for classes C1, C2, C3, and NR, respectively. Shredding the residue at the laboratory level required very high drying to obtain an SRF with 4.5% moisture, which cannot be considered a realistic option at an industrial scale. To complete the study, results are included based on moisture levels corresponding to the limits established for this property for each proposed class (20%, 25%, and 35%). The results obtained are discussed below.

*3.2.1.1. Lower heating value.* Defined as the economic parameter within the requirements for characterization as SRF (Matignon, 2020), this is a standard that measures the total energy content produced as heat when a substance is burned (Etim et al., 2022). The results for SRF produced at a laboratory scale (Table 8) presented a value of 22.93 MJ/kg for a moisture content of 4.5%. This value decreases with increasing the moisture content to 13.37 MJ/kg for 35% water content. The LHV, on a dry basis, was 24.29 MJ/kg, higher than that referenced for SRF generated from waste treatment plant rejects for incineration or

**Table 4**
Properties analyzed to determine the quality of the manufactured Solid Recovered Fuel (SRF).

| SRF type | | Properties | Unit | Standard analytical method |
|---|---|---|---|---|
| **Densified SRF** | Non-densified SRF | Lower Heating Value (LHV) | MJ/kg | UNE-EN 15400:2011 (AENOR, 2011a) |
| | | Cl Content | % | UNE-EN ISO 10304–1:2009 (AENOR, 2009) |
| | | Hg Content | mg/MJ | UNE-EN 15411:2012 (AENOR, 2012a) |
| | | Ash Content | % | UNE-EN 15403:2011 (AENOR, UNE-EN 3, 1540, 2011) |
| | | Moisture (M, for non densified SRF). (Mp, for densified SRF) | % | UNE-EN 15414–3:2011 (AENOR, 2011b) |
| | | Pellet Diameter (Dp) | mm | UNE-EN 16127:2012 (AENOR, 2012a) |
| | | Pellet Length (Lp) | mm | UNE-EN 16127:2012 (AENOR, 2012a) |
| | | Pellet Density (PD) | $kg/m^3$ | UNE-EN 15150:2012 (AENOR, 2012b) |
| | | Bulk Density (BD) | $kg/m^3$ | UNE-EN 15103:2010 (AENOR, 2010a) |
| | | Durability (DU) | % | UNE-EN 15210–1:2010 (AENOR, 2010b) |
| | | Hardness (HD) | kgf | Determination made by using a manual hardness tester (Amandus Khal mod. 21465) (Garcia-Maraver et al., 2015) |

co-incineration, with values ranging from 20.06 MJ/kg (Montejo et al., 2011) to 22.13 MJ/kg (Edo-Alcón et al., 2016). The results obtained place the SRF produced in class C1 for three of the four samples, with class C2 corresponding to the sample corresponding to 35% moisture.

*3.2.1.2. Cl content.* From the combustion point of view, low Cl content reduces adverse effects such as corrosion, slagging, and fouling in boilers (Rotter et al., 2011). In addition, a study on the emission of nanoparticles by conventional and advanced technology noted that the lower presence of Cl suggesting predominately biodegradable salts, but not toxic metals (Panessa-warren et al., 2022). The Cl percentage was determined dryly, so its content does not vary with humidity, reaching a value of 0.031% (Table 8). The values obtained are lower than those referenced in the case of samples generated from urban waste in the studies of Montané et al (Montane et al., 2013)., Nasrullah (Nasrullah et al., 2015b), and Velis (Velis et al., 2012) who obtained similar values, specifically 0.65%, 0.60%, and 0.69% respectively. The higher Cl content referenced in the studies above is motivated by the more significant presence of rigid plastics such as PVC (Rada and Ragazzi, 2014; Ma et al., 2008). These plastics are practically non-existent in the SRF produced, with a major presence of sanitary textiles which, even though they include plastics in their composition, are mainly composed of synthetic fibres (Marques et al., 2020). With the value obtained, the Cl content complies with the requirements of class C1 (Table 8).

*3.2.1.3. Hg content.* The Hg content represents the environmental factor of the SRF, measuring the possible toxicity caused by its combustion (Iacovidou et al., 2018). Its characterization is performed on a wet basis, providing contents for laboratory-produced SRF that ranged between $1.0 \times 10^{-5}$ and $5.9 \times 10^{-6}$ mg/MJ (Table 8) for samples SD-35 and SD-4.5, respectively. These values are lower than the $6.9 \times 10^{-3}$ mg/MJ reported by Ranieri et al (Ranieri et al., 2017). for SRF produced from municipal waste. If the average Hg content is written concerning the mass of the SRF made, results of $1.3 \times 10^{-4}$ mg/kg are obtained. This is lower than the $9.0 \times 10^{-2}$ mg/kg found in the literature (Ramos Casado et al., 2016). The Hg content would give the SRF generated from screening class C1 (Table 8) in any of the samples produced.

*3.2.1.4. Ash content.* Determination of the amount of ash quantifies the amount of inert materials present in the SRF, which in this study was 9.4% in all samples (Table 8) since it is determined on a dry basis. If this value is compared with that reported in studies of SRF produced from rejects coming from urban waste, it is observed that they are higher, as

**Table 5**
Standards and recommended values for the fuel properties of Solid recovered fuel (SRF)[a].

| | Standard | LHV[b] | Cl | Hg | | Ash | M[c] |
|---|---|---|---|---|---|---|---|
| | | MJ/kg | % | mg/MJ | mg/kg | % | % |
| 1 | ISO 21640:2021<br>Solid recovered fuels — Specifications and classes (AENOR, 2021a). | ≥ 3<br>≥ 25 | ≤ 3<br>≤ 0.2 | ≤ 0.15<br>≤ 0.02 | | | |
| 2 | UNI 9903–1:2004<br>Non mineral refuse derived fuels - Specifications and classification (Ente Nazionale Italiano di Unificazione UNI, 2004). | ≥ 15<br>≥ 25 | ≤ 1 | | ≤ 3 | ≤ 20<br>≤ 15 | ≤ 25<br>≤ 15 |
| 3 | Arrêté du 23 mai 2016 relatif à la préparation des combustibles solides de r é cupération en vue de leur utilisation dans des installations relevant de la rubrique 2971 de la nomenclature des installations classées pour la protection de l'environnement (L'énergie et de la mer Ministère de l'environnement, 2016). | ≥ 12 | ≤ 1.5 | | ≤ 3 | | |
| 4 | RAL-GZ 724 (2008) Quality and test instructions Solid Recovered Fuels (Gütegemeinschaft Sekundärbrennstoffe und und und, G.P. für S. e. V, 2008). | ≥ 13<br>≥ 27 | ≤ 1<br>≤ 0.7 | | ≤ 1<br>≤ 0.5 | ≤ 20<br>≤ 9 | ≤ 35<br>≤ 12.5 |
| 5 | WRAP. A classification scheme to define the quality of waste derived fuels (Waste and Resources Action Programme, 2013). | ≥ 6.5<br>≥ 25 | ≤ 0.8<br>≤ 0.2 | ≤ 0.12<br>≤ 0.04 | | ≤ 50<br>≤ 10 | ≤ 40<br>≤ 10 |
| 6 | No. 389/2002 in the Incineration Waste, BGBI (BMLFUW, 2002). | ≥ 11<br>≥ 25 | ≤ 1.5<br>≤ 0.8 | ≤ 0.075 | | ≤ 35<br>≤ 10 | |
| 7 | Limit values set by authorities for individual permits for cement plants in Spain (Schorcht et al., 2013). | | ≤ 2 | | ≤ 10 | | |
| 8 | Limit values set by authorities for individual permits for cement plants in Belgium (Schorcht et al., 2013). | | ≤ 2 | | ≤ 5 | | |
| 9 | SFS 5875 (2000) Solid Recovered Fuel - Quality Control System (General Industry Federation, 2008). | | ≤ 1.5<br>≤ 0.15 | | ≤ 0.5<br>≤ 0.1 | | |
| 10 | Guidelines on Usage of Refuse Derived Fuel in Various Industries. Draft of July 2018 (Health et al., 2018). | ≥ 12.5<br>≥ 18.5 | ≤ 1<br>≤ 0.5 | | | ≤ 15<br>≤ 10 | ≤ 20<br>≤ 10 |
| 11 | Act on the Promotion of Saving and Recycling of Resources Enforcement Regulation (Addendum 7) (R. of Korea, 2002) | ≥ 12.5<br>≥ 27.2 | ≤ 2<br>≤ 0.3 | | ≤ 1.2<br>≤ 0.6 | ≤ 20<br>≤ 4 | ≤ 25<br>≤ 10 |

[a] The cells with several values show that the standard establishes different classes, so the established limits are included.
[b] LHV: Lower heating value.
[c] M: Moisture of non-densified SRF

**Table 6**
Standards and recommended values for Solid Recovered Fuel (SRF) pellet properties [a].

| | Standard | Mp[b] % | Dp[c] mm | Lp[d] mm | PD[e] kg/m$^3$ | BD[f] kg/m$^3$ | DU[g] % |
|---|---|---|---|---|---|---|---|
| 1 | ISO 17225:2021<br>Biocombustibles sólidos. Especificaciones y clases de combustibles (AENOR, 2021b) | ≤ 10<br>≤ 12<br>≤ 15 | ≥ 6<br>≤ 25 | ≥ 3.15<br>≤ 50 | | ≥ 550<br>≤ 750 | ≥ 96.0<br>≥ 97.7 |
| 2 | O NORM M7135 (O NORM M, 7135, 2002) | ≤ 10 | ≥ 4<br>≤ 10 | ≥ 20<br>≤ 50 | ≥ 1120 | ≥ 540 | ≥ 97.7 |
| 3 | DIN 51731 and DIN PLUS (Norm, 2002) | ≤ 10<br>≤ 12 | ≥ 4<br>≤ 10 | ≥ 20<br>≤ 50 | ≥ 1000 | ≥ 540 | ≥ 97.7 |
| 4 | Agro and Agro+ (Narra et al., 2012) | ≤ 11<br>≤ 15 | ≥ 6<br>≤ 8 | ≥ 10<br>≤ 30 | ≥ 1200<br>≤ 1400 | ≥ 580 | ≥ 92 |
| 5 | SS187120 | ≤ 10<br>≤ 12 | ≤ 25 | ≥ 3.15<br>≤ 40 | | ≥ 500 | ≥ 98.5<br>≥ 99.2 |
| 6 | Pelet Fuel Institute Standards (SS20 Pelet Fuel Institute Standards, 1871, 2014) | ≤ 8<br>≤ 10 | ≥ 5.84<br>≤ 7.25 | ≥ 3.15<br>≤ 38.1 | | ≥ 609<br>≤ 737 | ≥ 95 |
| 7 | NY/T 1878–2010 (R.K.L. of R.E. Ministry of Agriculture, 2010) | ≤ 13 | ≤ 25 | ≥ 3.15<br>≤ 40 | ≥ 1000 | | |
| 8 | JAS Standards for Wood Pellets for Non-Industrial Use (F. and F. Ministry of Agriculture, 2021) | ≤ 10 | ≥ 6<br>≤ 8 | ≥ 3.15<br>≤ 40 | | ≥ 600 | ≥ 96.5 |

[a] The cells with several values show that the standard establishes different classes, so the established limits are included.
[b] Mp: Pellet moisture
[c] Dp: Pellet diameter.
[d] Lp: Pellet length.
[e] PD: Pellet density.
[f] BD: Bulk density.
[g] DU: Durability.

**Table 7**
Maximum and minimum values referenced for the use of the Solid Recovered Fuel (SRF).

| Uses | Properties | | | | |
|---|---|---|---|---|---|
| | LHV[a] (MJ/kg) | Cl (%) | Hg (mg/MJ) | Ash (%) | M[b] or Mp[c] (%) |
| Cement plants | 15.6–32.4 | 0.05–3.89 | N.S.[d] | 5.27–30.60 | 1.4–35.0 |
| EfW[e] | 13.24–32.98 | 0.10–1.16 | 0.001–0.209 | 7.40–23.60 | 3.8–34.1 |
| Gasification | 15.4–25 | 0.26–0.65 | 0.02–0.04 | 6.30–21.20 | 2.5–15.0 |

[a] LHV: Lower heating value.
[b] M: Moisture of non-densified SRF.
[c] Mp: Pellet moisture.
[d] N.S.: Not specified
[e] EfW: Energy from waste plant.

in the case of Velis (Velis et al., 2012) or Dunnu (Dunnu et al., 2010) whose ash percentage was 17.3% and 15.79%, respectively. The ash content obtained allows classifying this property in the SRF produced, class C1 for all samples (Table 8).

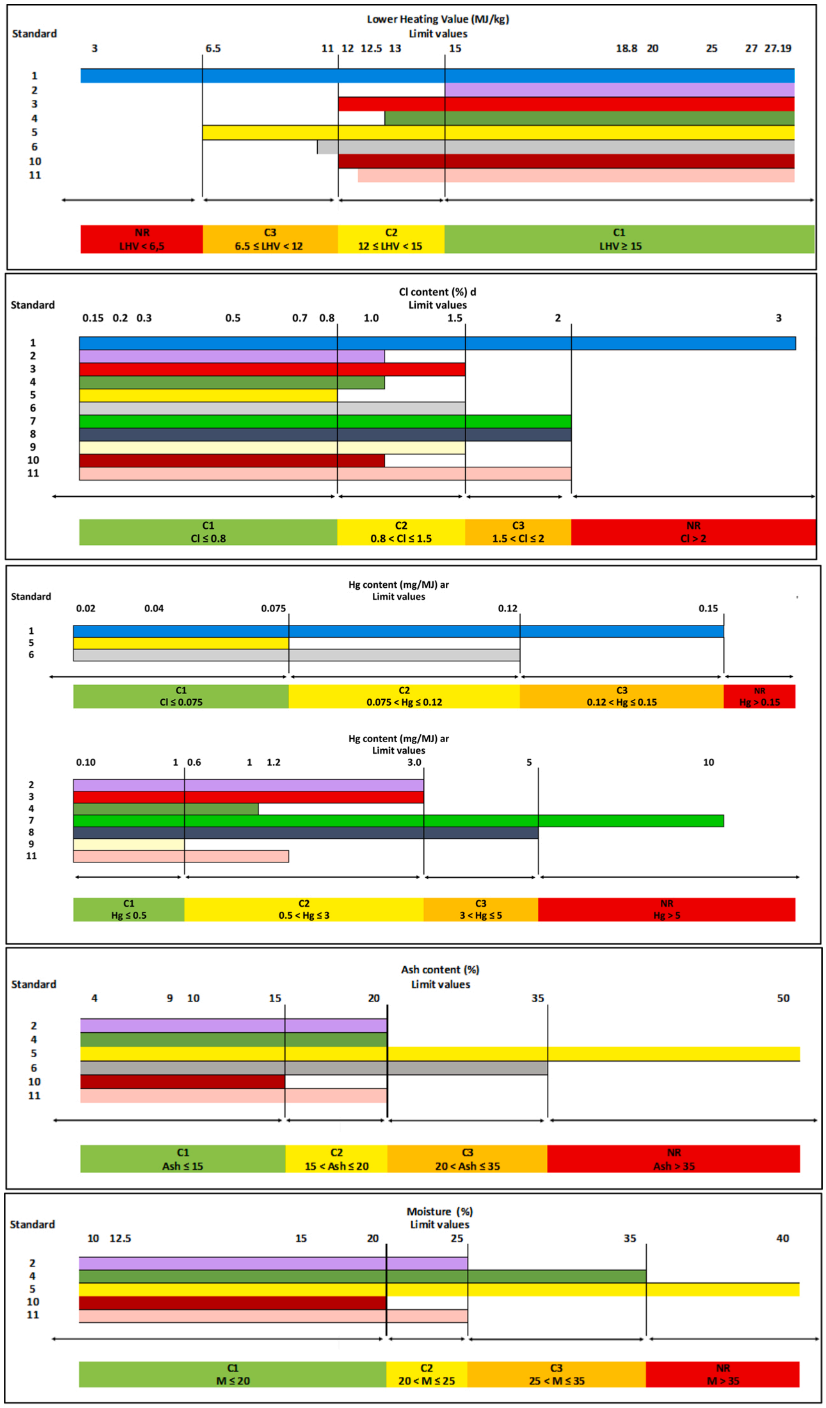
*3.2.1.5. Moisture.* The low moisture content of the SRF allows considerable energy cost savings (Mohammed et al., 2017), as it is directly related to energy value and transportation (Hilber et al., 2007). Due to the need to lower the moisture content as much as possible to facilitate the shredding process, the moisture content of the SRF produced from screening was 4.5% (Table 8), a relatively low value compared to other studies. Studies of SRF made from urban waste have referenced moistures of between 15 (Nasrullah et al., 2015b) and 25% (Rada and Ragazzi, 2014). This implies that, on an industrial scale, it could be produced with higher moisture values, thus reducing production costs, taking as a reference the limits considered for this property, i.e., 20%, 25%, and 35%.

Considering all of the above in the analysis of the different properties that have been included in the characterization of the non-densified SRF, it can be concluded that all the samples produced would comply with the established limits, and none of them would be classified as not recommended. On the other hand, the samples produced with lower moisture values (4.5% and 20%) would have all their properties classified as C1, i.e., they would allow obtaining the fuel with the highest quality. In the case of moisture values of 25%, for the production of SRF, only this property would be affected, and it would be classified in a lower category, C2. Finally, the production of SRF from screening with 35% moisture, classified as C3, would also slightly reduce its quality due to the effect of moisture on its LHV, which would be classified as C2.

### 3.2.2. Characteristics of the densified SRF

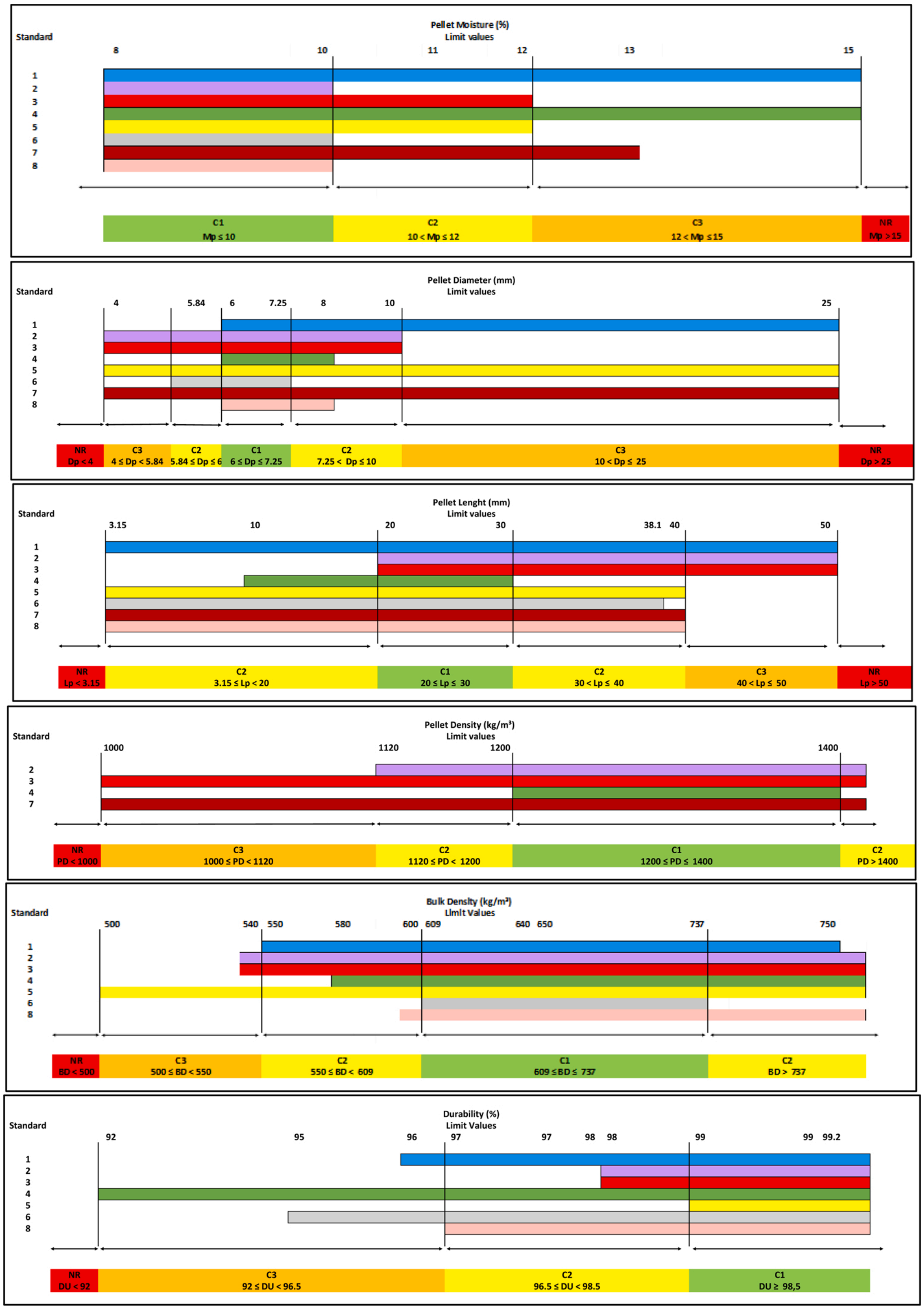
The values and classification of each of the properties analysed for the 20 pellet samples manufactured, the correlation with the process input variables, and the comparison of the results obtained from other studies are presented below. Average values and standard deviation obtained for the properties determined for samples are shown in Table 9, and their classification according to the colour code is described.

Fig. 5 shows the correlation between the input variables (moisture, diameter, and compression length) and the chemical (LHV, Cl, Hg, and ash contents), physical (moisture, diameter, length and density of the pellets, and bulk density), and mechanical (hardness and durability) properties of the pellets produced; the correlation coefficients are shown also. When an increase in one accompanies an increase in the value of another one of the variables, it will be considered a positive or direct correlation, represented in Fig. 5 with a range of blue colours. Conversely, if a decrease in one variable accompanies an increase in another, the correlation is negative or inverse, represented in a range of red colours. A correlation coefficient of 1 implies a perfect and positive correlation. On the contrary, the value − 1.00 implies an ideal and negative correlation, and finally, the value 0 means that there is no



1. ISO 21640:2021. Solid recovered fuels — Specifications and classes.
2. UNI 9903-1:2004. Non mineral refuse derived fuels – Specifications and classification.
3. Arrêté du 23 mai 2016 relatif à la préparation des combustibles solides de récupération en vue de leur utilisation dans des installations relevant de la rubrique 2971 de la omenclatura des installations classées pour la protection de l'environnement.
4. RAL-GZ 724 (2008) Quality and test instructions Solid Recovered Fuels.
5. WRAP. A classification scheme to define the quality of waste derived fuels.
6. No. 389/2022 in the Incineration Waste, BGBI.
7. Limit values set by authorities for individual permits for cement plants in Spain.
8. Limit values set by authorities for individual permits for cement plants in Belgium.
9. SFS 5875 (2000) Solid Recovered Fuel – Quality Control System.
10. Guidelines on Usage of Refuse Derived Fuel in Various Industries. Draft of July 2018.
11. Act on the Promotion of Saving and Recycling of Resources Enforcement Regulation (Addendum 7)

**Fig. 3.** *Proposed classification[1] for non-densified Solid Recovered Fuel (SRF) properties.*




1. ISO 17225:2021. Biocombustibles sólidos. Especificaciones y clases de combustibles.
2. O NORM M7135
3. DIN 51731 and DIN PLUS
4. Agro and Agro+
5. SS187120
6. Pelet Fuel Institute Standards
7. NY/T 1878-2010
8. Japanese Agricultural Standards

**Fig. 4.** Classification proposal[1] for properties of densified Solid Recovered Fuel (SRF) in pellet form.

**Table 8**
Values and classification of the properties of the non-densified Solid Recovered Fuel (SRF).

| Sample | LHV (MJ/kg) | Cl (%) | Hg (mg/MJ) | Ash (%) | M (%) |
|---|---|---|---|---|---|
| **SD-4.5** | 22.93 | 0.031 | $5.9 \times 10^{-6}$ | 9.4 | 4.5 |
| **SD-20** | 18.15 | 0.031 | $7.5 \times 10^{-6}$ | 9.4 | 20 |
| **SD-25** | 16.58 | 0.031 | $8.2 \times 10^{-6}$ | 9.4 | 25 |
| **SD-35** | 13.37 | 0.031 | $1.0 \times 10^{-5}$ | 9.4 | 35 |

Class 1 (C1)
Class 2 (C2)
Class 3 (C3)
Not recommended (NR)

[1] LHV: Lower heating value. [2] M: Moisture of non-densified SRF. [3] ND: Non-densified

**Table 9**
Average values, standard deviation, and classification of the properties of densified Solid Recovered Fuel (SRF).

| Sample | LHV (MJ/kg) | Cl (%) | Hg (mg/MJ) | Ash (%) | Hp (%) | Dp (mm) | Lp (mm) | PD (kg/m$^3$) | BD (kg/m$^3$) | DU (%) | HD (kgf) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **P-10-D6L20** | 24.41 | 0.037 | $6.4 \times 10^{-6}$ | 7.73 | 9.42 | 5.91 | 25.57 | 1198.03 | 504.65 | 98.47 | 13.00 |
| **P-20- D6L20** | 21.72 | 0.047 | $7.3 \times 10^{-6}$ | 7.78 | 18.07 | 5.84 | 21.87 | 1062.91 | 419.20 | 97.89 | 12.67 |
| **P-30- D6L20** | 18.60 | 0.029 | $8.7 \times 10^{-6}$ | 8.02 | 27.69 | 6.16 | 23.39 | 810.16 | 329.38 | 94.39 | 8.33 |
| **P-40- D6L20** | 15.77 | 0.033 | $1.0\times 10^{-5}$ | 8.42 | 34.80 | 6.02 | 20.82 | 706.50 | 314.87 | 93.62 | 5.67 |
| **P-10- D6L24** | 24.54 | 0.026 | $6.3 \times 10^{-6}$ | 7.94 | 8.81 | 6.13 | 26.62 | 1080.15 | 508.10 | 98.49 | 16.33 |
| **P-20- D6L24** | 21.47 | 0.066 | $7.2 \times 10^{-6}$ | 8.17 | 17.93 | 6.11 | 28.51 | 1025.95 | 456.55 | 97.70 | 16.00 |
| **P-30- D6L24** | 18.90 | 0.034 | $8.3 \times 10^{-6}$ | 9.37 | 25.64 | 6.06 | 22.30 | 858.14 | 408.22 | 97.55 | 11.33 |
| **P-40- D6L24** | 15.86 | 0.026 | $9.9 \times 10^{-6}$ | 8.63 | 33.91 | 6.06 | 22.37 | 753.87 | 346.70 | 94.95 | 9.33 |
| **P-10- D8L16** | 25.65 | 0.041 | $6.2 \times 10^{-6}$ | 9.63 | 7.75 | 8.33 | 36.72 | 958.80 | 426.28 | 99.64 | 12.67 |
| **P-20- D8L16** | 21.84 | 0.036 | $7.2 \times 10^{-6}$ | 9.00 | 17.66 | 8.34 | 36.80 | 833.55 | 380.68 | 97.80 | 9.67 |
| **P-30- D8L16** | 18.65 | 0.031 | $8.2 \times 10^{-6}$ | 7.73 | 25.05 | 8.75 | 23.95 | 691.75 | 347.50 | 97.72 | 7.00 |
| **P-40- D8L16** | 15.55 | 0.033 | $9.4 \times 10^{-6}$ | 7.48 | 31.45 | 9.04 | 29.94 | 606.81 | 301.07 | 88.63 | 4.67 |
| **P-10- D8L32** | 24.80 | 0.023 | $6.3 \times 10^{-6}$ | 9.30 | 8.55 | 8.11 | 21.46 | 1025.94 | 517.53 | 97.91 | 12.33 |
| **P-20- D8L32** | 22.01 | 0.027 | $7.2 \times 10^{-6}$ | 9.85 | 17.18 | 8.22 | 21.72 | 928.46 | 457.70 | 98.15 | 9.67 |
| **P-30- D8L32** | 18.85 | 0.031 | $8.4 \times 10^{-6}$ | 8.02 | 26.02 | 8.46 | 17.79 | 650.32 | 338.62 | 90.08 | 5.67 |
| **P-40- D8L32** | 15.57 | 0.028 | $9.8 \times 10^{-6}$ | 8.14 | 33.54 | 8.66 | 19.35 | 522.61 | 328.17 | 62.63 | 3.33 |
| **P-10- D8L48** | 24.87 | 0.027 | $6.2 \times 10^{-6}$ | 7.63 | 7.91 | 8.17 | 26.82 | 1006.89 | 491.37 | 99.76 | 20.00 |
| **P-20- D8L48** | 21.82 | 0.027 | $6.9 \times 10^{-6}$ | 7.54 | 14.59 | 7.76 | 24.50 | 911.16 | 455.93 | 99.22 | 14.33 |
| **P-30- D8L48** | 18.69 | 0.029 | $8.1 \times 10^{-6}$ | 7.45 | 23.99 | 8.14 | 24.89 | 753.91 | 403.65 | 98.35 | 9.67 |
| **P-40- D8L48** | 15.47 | 0.041 | $9.6 \times 10^{-6}$ | 7.22 | 32.36 | 8.20 | 22.33 | 696.12 | 366.85 | 85.88 | 4.33 |

Class 1 (C1)
Class 2 (C2)
Class 3 (C3)
Not recommended (NR)
Property not subject to classification

[1]LHV: Lower heating value. Mp: Pellet moisture Dp: Pellet diameter. Lp: Pellet length. PD: Pellet density. BD: Bulk density. DU: Durability. HD: Hardness. Mi: Inlet stream moisture. Dd: Diameter of the die. Lc: Compression length of the die.

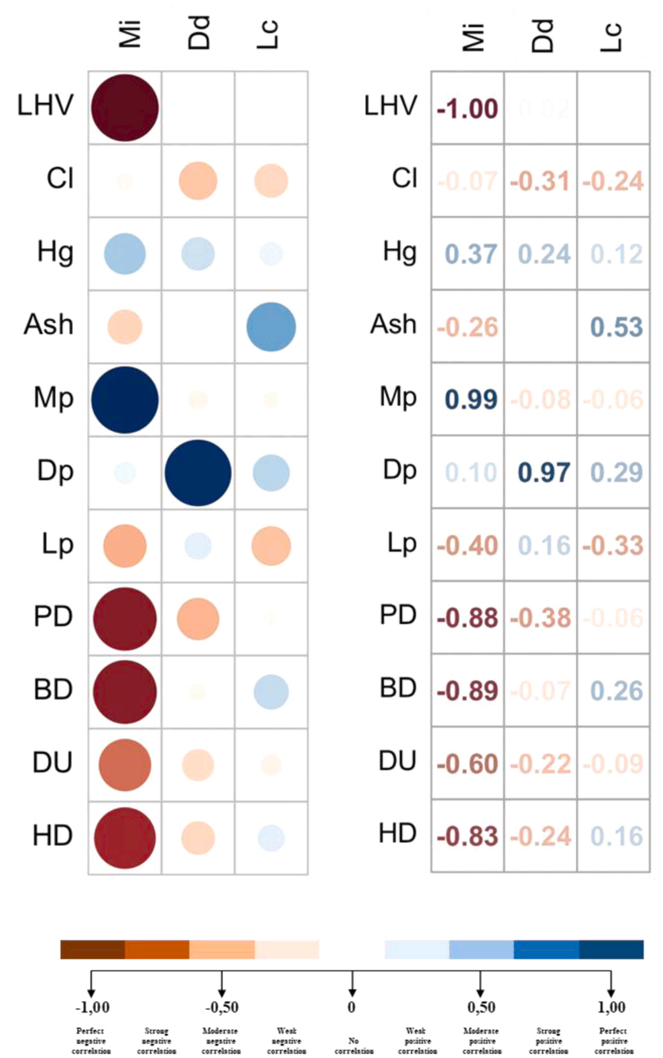



**Fig. 5.** Graphical representation and values of the correlation between production variables and the properties[1] of the pellets produced.

correlation. The diameter of the circles shown in Fig. 5 is proportional to the value of the correlation, so a stronger correlation will imply a larger diameter. Finally, Fig. 6 represents the LHV, Cl, Hg and ash contents, moisture, diameter, length, pellet density, bulk density, durability, and hardness, concerning the inlet stream moisture, for the different dies used in the pellet production process, in addition to the classification intervals, as well as maximum and minimum values reported in other studies included in the discussion.

*3.2.2.1. Lower heating value.* Table 9 and Fig. 6 show the LHV values determined for the densified SRF samples, which ranged from 15.47 to 25.65 MJ/kg for the pellets identified as P-40-D8L48 and P-10-D8L16, respectively, with the value of this property decreasing with that of the input stream moisture. As indicated in Table 9, Fig. 5 shows a perfect inverse correlation between LHV and inlet stream moisture, with a regression coefficient of − 1.00; however, it is observed that there is practically no correlation between this property with the characteristics of the pellet dies, with correlation coefficient of 0.02 for diameter and length.

Comparing the values obtained with those of other studies (Fig. 6), it is observed that for inlet current humidity values of 10%, the LHV obtained varied between 24.41 and 25.65 MJ/kg in the case of samples P-10-D6L20 and P-10-D8L16, respectively. These values are higher than those obtained for municipal solid waste pellets in the studies of Nursani (Nursani et al., 2020) and Ramos Casado et al (Ramos Casado et al., 2016). who recorded 18.24 and 20.34 MJ/kg, respectively, or that of Suryawan et al (Suryawan et al., 2022). in the case of pellets produced from paper, garden and food waste, where the maximum value referenced was 20.41 MJ/kg. The results obtained for inlet humidity values of 20% ranged from 21.47 to 22.01 MJ/kg for samples P-20-D6L24 and P-20-D8L32; these values are still slightly higher than those previously cited (Nursani et al., 2020; Ramos Casado et al., 2016) and also the minimum value of 17.22 MJ/kg recorded by Suryawan et al (Suryawan et al., 2022). in the case of pellets produced from paper, garden, and food waste. Finally, for inlet humidity values of 30%, the LHV results were similar to the lowest values of the mentioned studies, ranging between 18.60 and 18.90 MJ/kg for samples P-30-D6L20 and P-30-D6L24, respectively; the lowest values were reached for the highest inlet stream humidity values (40%), all of them were below 16 MJ/kg and up to 11% lower than the minimum value referenced by Suryawan et al (Suryawan et al., 2022). The LHV results allowed classifying this property in class C1, with no pellet samples of class C2, C3, or not recommended (Fig. 6). Only the five samples corresponding to an inlet current humidity of 40% are close to the limit established by class C2 (15 MJ7kg), ranging between 15.47 and 15.86 MJ/kg.

*3.2.2.2. Cl content.* As indicated in the non-densified SRF, low Cl content reduces adverse effects such as corrosion, slagging, and fouling in the boilers (Iacovidou et al., 2018; Rotter et al., 2011). Since Cl determination is done on a dry weight basis, densification does not influence Cl content, as evidenced by a correlation coefficient of − 0.07 for moisture. (Fig. 5) and values that varied between 0.023% and 0.066% for P-10- D8L32 and P-20- D6L24 respectively (Table 9) An average of 0.034% was obtained for the twenty samples, similar to the results obtained in the case of the SRF without densification.

Comparing these results with other pellet studies, the percentage obtained is similar to those produced with olive wood, which was 0.03% (Garcia-Maraver et al., 2015). This value is lower than that referenced by Ramos Casado (Ramos Casado et al., 2016) and Garcia (García et al., 2021) for SRF produced from household waste, with values of 0.76% in Cl, but higher than the 0.016% determined for those produced from a mixture of sewage sludge and herbaceous biomass (Kliopova and Makarskiene, 2015) or 0.01% for those made from olive leaf (Garcia-Maraver et al., 2015). As a result, this property would be classified in all cases with the highest quality, i.e., with category C1 (Fig. 6).

*3.2.2.3. Hg content.* As in the non-densified SRF, the Hg content must be considered because of its toxicity in the combustion process (Iacovidou et al., 2018). Table 9 and Fig. 6 show the Hg content values determined for the densified SRF samples, ranging from a minimum of 6.2 $10^{-6}$ to a maximum of 1.0 $10^{-5}$ mg/MJ for samples P-10-D8L16 and P-40-D6L20, respectively. Fig. 5 shows a positive correlation of Hg content for the three input variables. Although, as shown in Fig. 5, Pearson's Coefficient values (0.37, 0.24, and 0.24 for Mi, Dd, and Lc, respectively) are rated as weak in all three cases; they are higher in the case of moisture.

The values obtained have results lower than those referenced in other studies in which the Hg content reached values of 0.005 mg/MJ (Ramos Casado et al., 2016) and 0.042 mg/MJ (Kliopova and Makarskiene, 2015) in pellets produced from the rejection of biological treatment of waste and sewage sludge, respectively. This result has allowed classifying all the pellet samples within the limits established for class C1 for this property (Fig. 6).

*3.2.2.4. Ash content.* Since the ash content expresses its results on a dry basis, densification does not influence the results of this property, whose values varied between 7.22% and 9.85% for samples P-40- D8L48 and P-20- D8L32 (Table 11), similar to those obtained in the case of the non-densified SRF (Table 8). Fig. 5 shows that ash content exhibits a weak

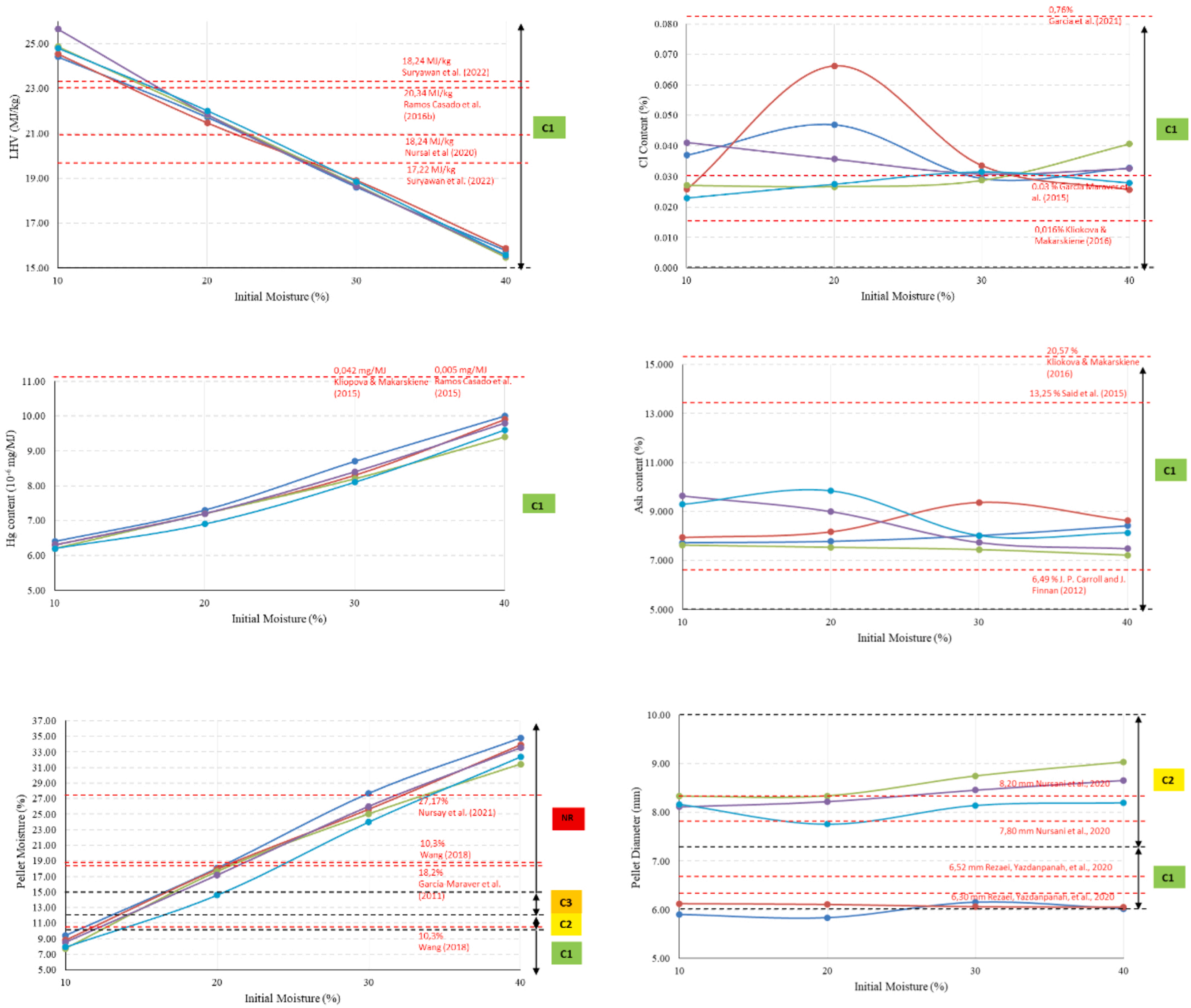



**Fig. 6.** Characteristics of densified solid recovered fue (SRF)l in relation to inlet stream moistures (10%, 20%, 30% and 40%) and for the different matrix used in the pellet production process (M1, M2, M3, M4 and M5). a) Lower Heating Value (LHV). b) Cl content. c) Hg content. d) Ash content. e) Pellet moisture. f) Pellet diameter. g) Pellet length. h) Pellet density. i) Bulk density. j) Durability. k) Hardness.

negative correlation (−0.26) with initial moisture, being null for its relationship with diameter. In contrast, a Pearson's coefficient of 0.53 concerning input length exhibits a moderate positive correlation.

This result is below the 21% referenced in other studies for pellets manufactured from municipal waste treatment plant reject (Ramos Casado et al., 2016), sludge, and biomass waste (Kliopova and Makarskiene, 2015), or 30.5% for SRF from municipal waste (Santamaria et al., 2021). On the contrary, the values obtained are higher than those referenced for pellets produced only from wood or herbaceous biomass which varied between 0.4% for pellets from pine wood (García et al., 2021) and 1.43% for olive wood (Garcia-Maraver et al., 2015). However, the ash content reported by Said et al (Said et al., 2015). for pellets produced from rice straw was higher, with values between 13.25% and 18.66%. A value of 6.49% was obtained from wheat straw, slightly lower than the SRF produced (Carroll and Finnan, 2012). In any case, the values obtained allow classifying this property for all pellet samples produced as class C1 (Fig. 6).

*3.2.2.5. Moisture.* The water content of the produced SRF was evaluated within the framework of quality standards regarding pellet conditioning since safe storage must be ensured to avoid bacterial growth (Lehtikangas, 2001) and degradation of the produced material (Said et al., 2015). Table 9 and Fig. 6 show the moisture values determined for the densified SRF samples, which ranged from 7.75% to 34.80% for samples P-10-D8L16 and P-40-D6L20, respectively. This demonstrated a reduction of 15.27 ± 5.32% concerning the moisture content of the incoming residue, with pelletizing temperatures below 29 °C. Fig. 5 shows a perfect direct correlation between the moisture of the pellet produced and the moisture of the incoming stream, with a correlation coefficient of 1 (Fig. 5). However, in the case of the variables related to the characteristics of the pelletizing dies, the correlation coefficients obtained were − 0.08 and − 0.06 for the diameter and compression length, respectively, which shows that there is practically no correlation between them and the moisture of the pellets produced.

Studies on pellets made from agricultural residues have been consulted to analyse the values obtained. In them, values ranging from 18.2 (García-Maraver et al., 2011) to 27.17% were achieved (Nursani et al., 2020). In a work by Wang (Wang et al., 2018), who produced pellets

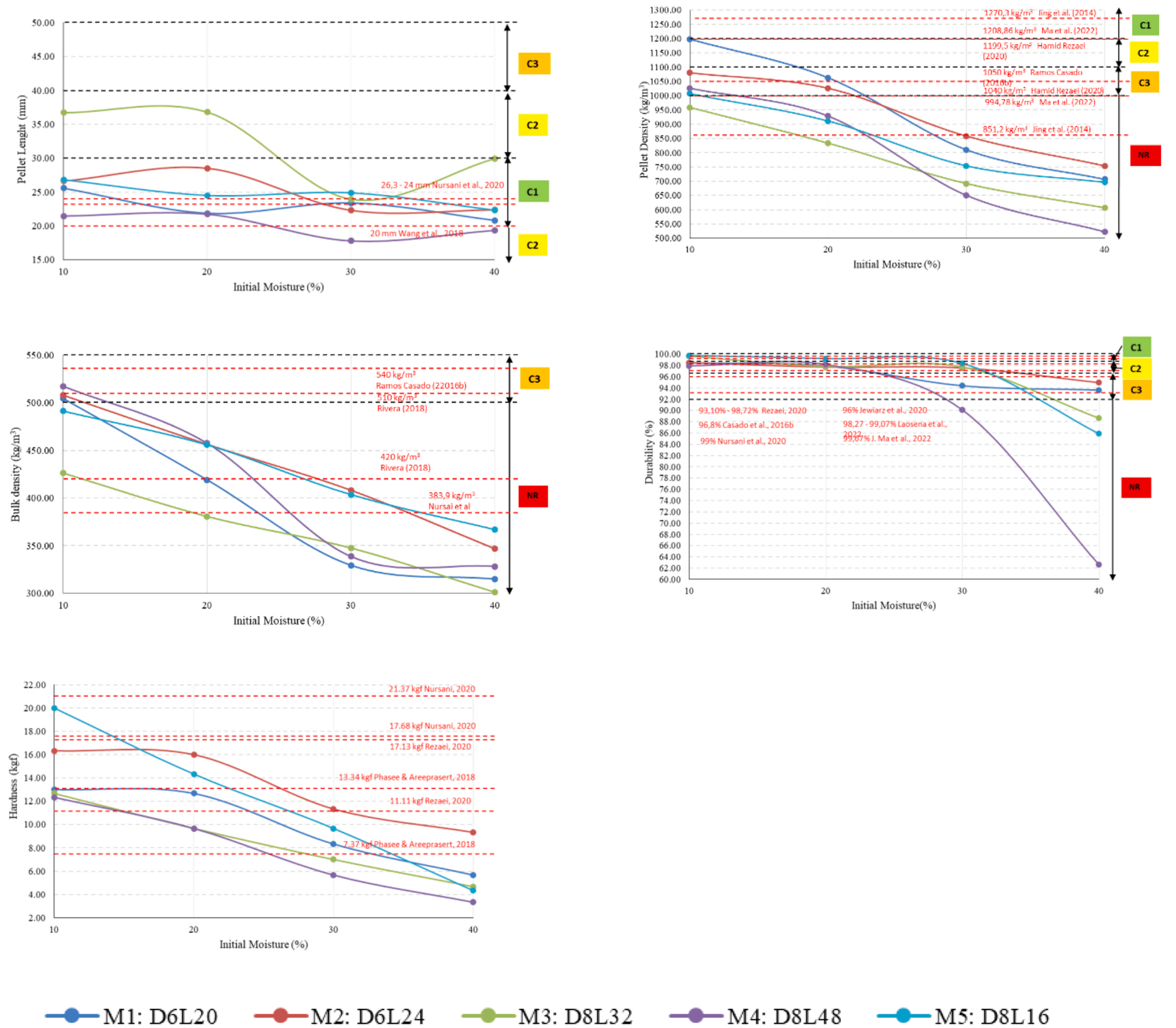



**Fig. 6.** (*continued*).

from MSW, humidity values between 10.3% and 18.9% were obtained. It was observed that for samples produced with an input stream moisture content of 10%, the resulting moisture was always lower than the referenced values. For samples produced with input stream moisture of 20% and 30%, all values, except for sample P-30-D6L20 with an output moisture content of 27.69%, were in the range of the referenced studies. Specifically, in the case of an input moisture of 20%, all pellet samples obtained a moisture value within the limits referenced by Wang (Wang et al., 2018) for densified MSW. Finally, pellet production with input stream moistures of 40% resulted in pellets with moistures above 31%, these values are well above the referenced studies.

The moisture results obtained allowed us to classify this property in the different established classes (Table 9), showing that inlet stream moisture values higher than 10% resulted in pellets with moisture levels that were considered not recommendable. In fact, 14 of the 20 samples manufactured reached moisture values higher than 15%. Five of the samples produced were classified as class C1 concerning this property, all corresponding to samples pelletized with 10% moisture. In addition, none of the samples were classified as class C2, and only one of them, pelletized with an inlet moisture content of 20% with the M5 die, was ranked as class C3.

*3.2.2.6. Pellet size: diameter and length.* Pellet size is a relevant factor in the use phase because combustion is more uniform with smaller diameter pellets, and a high length can hinder the continuous feeding of the plant (Lehtikangas, 2001) and block the hoppers (Grootjes et al., 2015). At the same time, a long pellet is easier to break than a shorter one (Said et al., 2015; Tarasov et al., 2013), affecting the storage and transport phases. In the case of the results obtained in the pellet diameter, the eight samples produced with the 6 mm diameter die present values between 5.84 (P-20-D6L20) and 6.16 mm (P-30-D6L20). On the other hand, the remaining twelve samples, manufactured with 8 mm dies, resulted in pellets with diameters between 7.76 (P-20-D8L48) and 9.04 mm (P-40-D8L16). There is an almost perfect positive correlation between the die inlet diameter and the pellet outlet diameter (Fig. 5), which reaches a correlation coefficient of 0.97 (Fig. 5). However, it is practically not affected by the die compression length and the moisture content of the inlet stream, with coefficients of 0.29 and 0.10, respectively. Regarding the most commonly used diameter in other studies in which pellets were manufactured from urban waste, the use of 6 mm diameter dies predominates, although some studies with larger diameters of 16, 18, and 20 mm have also been referenced (Jewiarz et al., 2020).

The values obtained in the case of length have shown large variability, with a minimum of 17.79 mm (P-30-D8L32) and a maximum of 36.80 mm (P-20-D8L16), as shown in Table 9. Also, there was a weak positive correlation with die diameter, a weak negative correlation with compression length, with a correlation coefficient of − 0.33, and close to moderately negative, with a coefficient of − 0.4, in the case of input moisture (Fig. 5). The effect of inlet moisture is higher, as shown in Table 9, in the case of pellets manufactured with a diameter of 8 mm. Although, in some cases, they are higher, the length values obtained could be considered similar to those of other studies, with values that have varied between 20 (Wang et al., 2018) and 24 mm (Nursani et al., 2020).

The results obtained for the properties that define the size of the pellets made it possible to classify them into several of the established classes. By diameter (Table 9), six of the samples would be classified as class C1, all of them produced by 6 mm diameter dies, while the remaining 14, corresponding to pellets manufactured with 8 mm diameter dies, would be included in class C2. Regarding the length (Table 9), 16 of the 20 samples correspond to Class C1, while the remaining four fall into Class C2. With the M1, M2 and M5 dies, pellets classified as Class C1 were produced. In the case of the M3 and M4 dies, Class C2 pellets were produced with 10% and 20% and 30% and 40% moisture content, respectively.

*3.2.2.7. Pellet density.* Pellet density is a fundamental parameter because low-density pellets are more easily broken and decomposed (Garcia-Maraver et al., 2015; Lehtikangas, 2001). According to the literature reviewed, the use of high-density biofuels generally improves combustion (Jewiarz et al., 2020), gasification (Nixon et al., 2013), and pyrolysis processes (Chen et al., 2014), although there are studies that argue that a very high pellet density could generate combustion problems (Tarasov et al., 2013).

Table 9 and Fig. 6 show the density values of the manufactured pellets, which varied between 522.61 and 1198.03 kg/m$^3$ for samples P-40-M4 and P-10-M1, observing the effect that moisture has on the production process. In fact, Fig. 5 shows a high inverse correlation between pellet density and moisture of the input stream, with a correlation coefficient of − 0.88 (Fig. 5). Also, in the case of the variables related to pellet die characteristics, an inverse correlation is observed in both cases, but it is very weak in the case of compression length and weak for die diameter, with correlation coefficients of − 0.06 and − 0.38, respectively (Fig. 5).

Comparing these results with those referenced in other studies, it becomes clear that they are comparable to those of other studies in the case of pellets produced with low feed stream humidity values (10% and 20%). Thus, Ramos Casado (Ramos Casado et al., 2016) produced pellets from the rejects of mechanical biological treatment plants of municipal waste, reaching a density of 1050 kg/m$^3$. After torrefaction of such waste, Ma et al (Ma et al., 2022). produced pellets with densities that varied between 994.78 and 1208.86 kg/m$^3$, depending on the torrefaction and pelletization temperature. Meanwhile, mixtures of different waste fractions present in MSW were pelletized, reaching values that varied between 1040 and 1199.5 kg/m$^3$. The minimum value corresponded to the composition with a lower percentage of paper (Rezaei et al., 2020). Finally, studies of densification of sewage sludge mixed with biomass allowed obtaining pellets with densities ranging from 851.2 to 1270.3 kg/m$^3$ (Jiang et al., 2014). With increasing inlet stream moisture up to 30% and 40%, pellet density values were reduced to values below the minimum value referenced by Jiang et al (Jiang et al., 2014). for sewage sludge with biomass.

The pellet density results obtained allowed classifying this property in the different established classes (Fig. 6), with a predominance (fourteen of the twenty samples analysed, 75%) of those being classified as not recommended. Furthermore, none of the samples produced was classified as class C1, only one as C2 (pelleted at 10% moisture), and five as C3 (pelleted at 10% and 20% moisture). The low-density values are explained by the use of reference values to establish the classification based on standards applicable to agricultural waste, which usually report higher values such as 1327 kg/m$^3$ for olive wood (Garcia-Maraver et al., 2015), 1260 kg/m$^3$ for rice straw (Said et al., 2015), or 1198 kg/m$^3$ for pellets produced from alfalfa (Sarker et al., 2015). However, the composition of the initial screening is characterized by the high presence of low-density fractions (52.1% of sanitary textiles and 11.7% paper and cardboard). These values could be increased by adding a binder, as reported in the study by Nursani et al (Nursani et al., 2020). which produced pellets with a density between 988 − 1009 kg/ m$^3$ from urban waste.

*3.2.2.8. Bulk density.* Some of the problems derived from the low bulk density of SRF is the need for high storage volumes, increased transportation costs, as well as difficulties in feeding (Lomas Esteban et al., 2001), hence the importance of the analysis of this property, which in this study reached values between 301.07 and 517.53 kg/m$^3$ for samples P-40-D8L16 and P-10-D8L32 (Table 9), respectively. The effect of inlet stream moisture was observed (Fig. 6). This translates into a strong inverse correlation between bulk density and inlet stream moisture, with a correlation coefficient of − 0.89 (Fig. 5). In the case of compression length and die diameter, the observed correlations were weakly positive and very weakly negative, with correlation coefficient values of 0.26 and − 0.07, respectively (Fig. 5).

Comparing these values with those obtained in other MSW pelletizing studies, it becomes clear that they are comparable to those referenced in other studies of those produced with low feed stream moistures (10% and 20%). MSW pelletizing studies show bulk densities that varied between 383.9 (Nursani et al., 2020) and 540 kg/m$^3$ (Ramos Casado et al., 2016). In another study, Rivera (Rivera, 2018) reported values between 420 and 510 kg/m$^3$.

The results for this property, shown in Table 9, allow the samples to be classified into the established classes. None of the samples produced was classified as class C1 and C2 for this property. Three of them, corresponding to an inlet stream moisture content of 10%, were classified as C3, while the remaining 17 (85% of the samples produced) reached bulk densities below 500 kg/m$^3$, and therefore, were classified as not recommended. Again, the low-density values are explained by the presence of low-density fractions in the waste and the use of reference values to establish the classification based on standards applicable to agricultural waste, which usually report higher values. In fact, in the case of pellets produced from various biomasses, according to a review, the density values were found to be higher than 600 kg/m$^3$ (Miranda et al., 2015a). These values were reported for pellets from olive pomace with 780 kg/m$^3$ (Miranda et al., 2012) and oak and Scots pine wood with 678 (Miranda et al., 2009) and 675 kg/m$^3$ (Filbakk et al., 2011), respectively, or wheat straw with a bulk density of 620 kg/m$^3$ (Verma et al., 2012). The values for bulk density could be increased by adding a binder, as reported in some studies certifying that binders strengthen the cohesion between particles and increase the density, both particle and bulk (Ju et al., 2020; ZDANOWICZ and CHOJNACKI, 2017).

*3.2.2.9. Durability.* Durability is an essential parameter concerning transportation and logistics (Jewiarz et al., 2020). It can be considered a reference property for SRF pellet conditioning (Said et al., 2015). High durability is synonymous with high-quality (Zafari and Kianmehr, 2014) as it avoids the generation of fine particles that could increase pollutant emissions and even health risks (Miranda et al., 2015b). Table 9 and Fig. 6 show the durability values of the manufactured pellets, which ranged from 62.63% to 99.76%, for samples P-40-D8L32 and P-10–48, respectively. Fig. 5 shows a strong inverse correlation between durability and inlet stream moisture, with a coefficient of − 0.60. The effect of die diameter and compression length is not significant, with observed correlation coefficient values of − 0.22 and − 0.09, respectively (Fig. 5), also implying an inverse correlation but in this case weak and very weak.

The analyses of durability values obtained in other studies of densified SRF production from MSW show similar values, such as those obtained from MSW rejects with durability of 96.8% (Ramos Casado et al., 2016). In a work where water content was analysed as a variable, 93.10% and 98.72% durabilities were obtained with input stream moisture values of 30% and 15%, respectively (Rezaei et al., 2020). Considering pelletizing temperature as a variable, the maximum durability (96%) was reached at 120 °C (Jewiarz et al., 2020). Higher durability values have been found in the case of torrefied biodegradable products from MSW, with 99.67% (Ma et al., 2022) and up to 99% improving the pellet by adding 6% binder (Nursani et al., 2020). The pellets produced from rubber wood and waste derivative mixtures presented high durability levels (98.27–99.07%) (Laosena et al., 2022).

The durability results concerning the input variables (Fig. 6) allow placing the samples in the established classes, predominantly class C2, which includes 50% of them, followed by C3 with four samples, and C1 with 3. Finally, only 3 of the samples produced were considered not recommended, with values lower than 92%, all of these corresponded to inlet current humidity values of 40%.

*3.2.2.10. Hardness.* As mentioned in the methodology, the importance of this property lies in handling and storage, as well as in the combustion process itself, where adequate hardness is required to avoid crushing and deforming the pellets (Said et al., 2015; Gilbert et al., 2009), which causes difficulties in the boiler operation due to occasional blocking of the screw conveyor, regardless of the thermal boiler load (Garcia-Maraver et al., 2014).

The results obtained for this property in the SRFs screening cover a broad spectrum of values, with a minimum of 3.33 kgf and a maximum of 20 kgf for samples P-40-D8L32 and P-10-D8L48, respectively (Table 9). Regarding the relationship of this property with the input variables, a strong inverse correlation was observed between hardness and input moisture, with a correlation coefficient of − 0.3, which is also evident in Fig. 5. The correlation was also harmful in the case of diameter, although relatively weak (−0.24), while for compression length, it is also soft but positive (0.16) (Fig. 5).

If the results are compared with other studies, the maximum values are similar. However, the minimum value is much lower. Thus, in a study developed to improve the properties of pellets from municipal waste by hydrothermal treatment, hardness values between 7.37 and 13.34 kgf were obtained (Phasee and Areeprasert, 2018). In the case of the pellets produced by Rezaei (Rezaei et al., 2020), the hardness varied between 11.11 and 17.13 kgf for water contents of 15% and 30% respectively. The addition of binder in the pellet manufacturing process increased the hardness up to 17.68–21.37 kgf (Nursani et al., 2020). In any case, it was observed that for moisture below 30%, SRF hardness values can be similar to those found in the literature.

No classes have been established in this case because the property is not contemplated in the reference standards. However, the values obtained are below those recommended in studies for biomass pellets such as wood (Arshadi et al., 2008) and herbaceous or agricultural residues (Carroll and Finnan, 2012; Zamorano et al., 2011), whose optimum hardness, according to the literature, would be 22 kgf (Said et al., 2015).

Taking into account the classifications of the properties considered to establish the quality of the densified SRF in pellet form, shown in Table 9 with the colour code, it is observed that only 3 of the 20 samples produced comply with the limits established for all of the properties, specifically samples P-10-D6L20, P-10-D6L24, and P-10-D8L32. In the rest of the samples, some of the properties were not recommendable, so the quality of the pellets would not be suitable according to the classification proposal. On the other hand, for all the samples, it was observed that the specific properties conducive to evaluating the quality of SRF as fuel reach classes C1 and C2. Moisture, pellet density, and bulk density are the ones that reach values with a lower rate (C3), not even recommendable in most of the density determinations. This result is explained by the use of standards for pellets produced from agricultural residues, with higher density than screening residue, which has a lower density due to its high content of sanitary textiles. For this reason, it is considered that the proposal for quality standards in the future should consider this aspect, as well as the incorporation of hardness, which is not incorporated in the current standards for other types of waste since it is viewed as a property to be included in future pellet quality standards.

On the other hand, concerning the operating variables of the pelletizing process for this residue, the most favourable results were obtained with 10% moisture in the inlet stream, which would imply the need to subject the screening residue, characterized by high moisture, to an intense drying process, which would mean higher production costs. Regarding the dies, the most suitable option would be the 6 mm inlet diameter. With the two compression lengths tested (20 and 24 mm), this 6 mm die makes it possible to obtain convenient pellets (classes C1, C2, or C3). It is also possible to produce pellets with a larger diameter, 8 mm, with a compression ratio of 8/32.

### *3.3. Determination of SRF uses*

The results of the properties produced from screening both densified and non-densified SRF were compared with the reference ranges shown in Table 7 for its uses in cement plants, power plants, and gasification, resulting in the degree of compliance by properties shown overall in Table 10.

Firstly, it can be seen that the Cl, Hg, and ash content of the SRF manufactured was limiting for any of the uses analysed, while LHV limits its application in cement works and LHV and moisture for gasification.

On the other hand, it was observed that the application of manufactured SRF in plants to produce energy from waste does not pose any limitation. In the case of cement plants, the possibility of application is high, since three of the four and fifteen of the twenty samples of non-densified and densified SRF, respectively, comply with all the established limits, which represents 75% of the same. In both cases, the limiting property was the LHV, which shows the difficulty of using SRF produced at humidity values above 35%. Finally, gasification turned out to be the application with the lowest number of samples suitable for use, with only one of the five applicable non-densified SRF samples and six of the twenty in the case of densified, representing 25% and 30%, respectively. In this case, the applicability is limited to SRF produced at humidity values below 20%. The moisture content of the manufactured SRF was the most limiting property since 17 samples did not meet the requirements. These corresponded to the samples of non-densified SRF manufactured with a moisture content of 35% and to all the samples of densified SRF produced with moisture content equal to or higher than 20%, except in the case of one that used a longer compression length (P-20-D8L48), which failed with moisture content values equal to or higher than 30%. In the case of LHV, given its relationship with humidity, six samples were added to the non-compliance list, one in non-densified SRF and five in densified SRF. These cases also corresponded with samples of SRF manufactured with humidity values equal to or higher than 35%.

## 4. Conclusions and further perspectives

Energy recovery from the screening waste would be a definitive step towards achieving the zero waste objective in wastewater treatment, avoiding the economic and environmental costs derived from landfill disposal. The following is a summary of the most relevant conclusions obtained relating to the objectives set out in the study.

In relation to the proposed classification of the SRF produced, based

**Table 10**
Comparative properties of Solid Recovered Fuel (SRF) produced for use in cement, waste to energy, and gasification plants.

| SRF type | Samples | Uses | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cement plants | | | | | | Energy from waste plants | | | | | | Gasification | | | | | |
| | | LHV[a] | Cl | Hg | Ash | M[b] | Suitable | LHV | Cl | Hg | Ash | M | Suitable | LHV | Cl | Hg | Ash | M | Suitable |
| Non densified SRF | ND-4.5 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | ND-20 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | ND-25 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | ND-35 | ⊗ | ✓ | ✓ | ✓ | ✓ | ⊗ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| Densified SRF | P-10-D6L20 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | P-20- D6L20 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | P-30- D6L20 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | P-40- D6L20 | ⊗ | ✓ | ✓ | ✓ | ✓ | ⊗ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | P-10- D6L24 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | P-20- D6L24 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | P-30- D6L24 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | P-40- D6L24 | ⊗ | ✓ | ✓ | ✓ | ✓ | ⊗ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | P-10- D8L16 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | P-20- D8L16 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | P-30- D8L16 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | P-40- D8L16 | ⊗ | ✓ | ✓ | ✓ | ✓ | ⊗ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | P-10- D8L32 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | P-20- D8L32 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | P-30- D8L32 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | P-40- D8L32 | ⊗ | ✓ | ✓ | ✓ | ✓ | ⊗ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | P-10- D8L48 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | P-20- D8L48 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | P-30- D8L48 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ⊗ |
| | P-40- D8L48 | ⊗ | ✓ | ✓ | ✓ | ✓ | ⊗ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ⊗ | ✓ | ✓ | ✓ | ⊗ | ⊗ |

[a] LHV: Lower heating value.
[b] M: Moisture.

on existing regulations on the quality of SRF as a fuel, and on those relating to the quality of the pellet according to its mechanical properties.

- The proposed classification of the properties that affect the quality of non-densified SRF is a reference framework to be considered for future quality standards since it brings together the diversity of existing standards and can be used as a common framework.
- Due to its benefits in handling and use, the interest in densification, in the form of pellets, of SRF from sources such as municipal solid waste or screening waste requires the development of quality standards, depending on its uses, which are currently non-existent. In this sense, the proposed classification of the properties that affect the quality of densified SRF is a frame of reference to be taken into account for future quality standards that can be based on the current standards for agricultural and forestry waste or similar waste. However, it will be necessary to uniquely analyse values that limit properties linked to the characteristics of these wastes derived from their composition and the incorporation of hardness values due to their effects on the handling and use of the pellets.

  The production of SRF at laboratory scale required some conditions, mainly for the experimental design of densified SRF. The input moisture content for densification varied between 10% and 40%, and the compression ratios of the matrices used were 6/20, 6/24, 8/16, 8/32 and 8/48. In light of the results, it can be concluded:
- The production of SRF, both densified and non-densified, is a viable option for screening waste that meets the requirements of the European standard ISO 21640:2021.
- In the case of the production of the non-densified SRF, taking into account the classification proposed for the properties selected to determine its quality, it would be desirable to produce it from screening residues with a maximum of 20% moisture; it is possible to do so up to moisture content of 35%, even if there is a loss in its LHV.
- In the case of the production of densified SRF in the form of pellets, taking into account the classification proposed for the properties selected to determine its quality, it would be desirable to produce it with a residual moisture content of 10%, using a die with a 6 mm inlet diameter with compression lengths of 20 or 24 mm, or a larger diameter, 8 mm, with a compression ratio of 8/32.
- The moisture content of the residue used for the production of SRF is the variable that will condition the process the most since it is necessary to reduce it to values of 35% in the case of non-densified and 10% for the manufacture of pellets, which could affect the economic viability of the product.

  In relation to the uses of the SRF produced:

- The Cl, Hg, and ash content of the SRF manufactured did not limit any of the uses analysed, while the LHV limits its application in cement works, and LHV and moisture were limiting in the case of gasification.
- The use of the SRF produced is not limited in the case of power plants. Cement plants would require production processes with humidity values below 35%, both for non-densified and densified SRF. The major limitation for SRF use is observed in its application for gasification. Non-densified SRF could be used when manufactured with humidity values lower than 35%, reducing this limit to values lower than 20% in the case of densified SRF for samples densified with a high compression ratio die (8/48).

The present study provides evidence of the potential to generate SRF from screening waste. This finding serves as a starting point for scaling up the process and assessing the technical, economic, and environmental viability of industrial-level production.

## Author contributions

The authors contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

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## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Juan Jesus de la Torre Bayo reports financial support was provided by Emasagra.

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