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Study of the variability of physicochemical parameters in different fractions of corn and espartillo intended for the production of solid biofuels

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Abstract
The current context of the energy transition is driving the development of alternative fuels, such as lignocellulosic materials of agricultural origin. This study analyzed the variation in physicochemical parameters in fractions of espartillo (E) and corn stover (RM) according to particle size. It was observed that reducing the particle size in RM increased the ash and extractive content, while E only showed an increase in ash. Pure materials and hybrid mixtures of E/RM 1:1 and 1:3 were evaluated in combustion. The 1:1 mixture reached a higher combustion temperature, exhibited a longer flame duration, and had an optimized heating value, although it had a higher ash content that could be reduced by removing particles smaller than 149 µm. The results obtained demonstrate that E and RM are viable alternatives as solid biofuels through synergistic mixtures and granulometric control, favoring the revaluation of agricultural waste and naturally growing species in the region for energy purposes.

Keywords: corn stover; espartillo; physicochemical characterization; solid biofuels; combustibility.

Estudio de variabilidad de parámetros fisicoquímicos en diversas fracciones de maíz y espartillo destinadas a la generación de biocombustibles sólidos

Resumen
El contexto actual de transición energética impulsa el desarrollo de combustibles alternativos, como los basados en materiales lignocelulósicos de origen agrícola. Este estudio analizó la variación de parámetros fisicoquímicos en fracciones de espartillo (E) y rastrojo de maíz (RM) según granulometría. Se observó que al reducir el tamaño de partícula en RM aumenta el contenido de cenizas y extraíbles, mientras que E solo presentó incremento de cenizas. En la combustión se evaluaron materiales puros y mezclas híbridas E/RM 1:1 y 1:3. La mezcla 1:1 alcanzó una temperatura de combustión superior, mayor duración de llama y poder calorífico optimizado, aunque presentó mayor contenido de cenizas que podría reducirse eliminando las partículas menores a 149 µm. Los resultados obtenidos demuestran que E y RM son alternativas viables como biocombustibles sólidos mediante mezclas sinérgicas y control granulométrico, favoreciendo la revalorización de residuos agrícolas y especies de crecimiento natural de la región para aprovechamiento energético.

Palabras clave: rastrojo de maíz; espartillo; caracterización fisicoquímica; biocombustibles sólidos; combustibilidad.

1 Introduction

The growing need to reduce fossil fuel consumption and diversify energy sources has driven the development of renewable alternatives, including biomass. In this context, the native species espartillo (*Spartina argentinensis*) and the traditional crop corn (*Zea mays*) exhibit suitable properties for producing densified solid biofuels. Espartillo is a perennial

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grass belonging to the *Poaceae* family. This species is mainly found in northeastern Argentina and is notable for its resistance to saline soils and water stress, which gives it high potential for adaptation in marginal regions suitable for energy generation [1]. Espartillo covers more than 2 million ha in the province of Santa Fe, Argentina. As it is a natural grassland, accurate quantification of usable biomass on a national scale requires the use of advanced estimation and monitoring technologies [2] Corn is widely cultivated in the central region of Argentina; however, its cultivation is expanding into colder areas such as northern Patagonia and the Calchaquíes Valleys. Corn is characterized not only by its contribution to food production, but also by its role as an energy crop in bioethanol generation, which produces a considerable volume of residual lignocellulosic stover [3]. Corn stover is typically left on the field surface to serve as organic amendment and to prevent soil erosion. Although this practice is generally recommended, in certain locations with low temperatures, stover decomposition slows down, forming a moist layer that creates favorable conditions for the proliferation of fungi harmful to subsequent crops [4]. These issues, along with the need for pest control, could increase the occurrence of improper practices such as the burning of crop residues [5]. In this context, it is crucial to determine the quantity of corn stover that can be utilized for energy production without compromising soil quality. During the 2024/25 season, Argentina produced around 49 million t of grain. Considering a stover/grain ratio close to 1:1 on a dry basis, the total residual biomass is estimated to be of a similar magnitude. Of this total, around 25 % is used for silage, and of the remainder, between 15 % and 40 % could potentially be used for energy generation without impacting soil functions [6]. Consequently, 5.50–14.40 million t of residual biomass could potentially be used, in accordance with values reported in the literature [7,8]. Both espartillo (E) and corn stover (RM) exhibit physicochemical characteristics that make them suitable raw materials for use as solid biofuels through densification processes (pellets or briquettes). The use of such densified fuel represents an efficient energy alternative for households and industries, due to its storage capacity, low environmental impact and easy transportation. At the same time, it allows for the utilization of resources from marginal soils and the proper disposal of crop residues, thereby promoting the incorporation of these assets into the circular economy.

The production of densified fuels is a process that is still developing in Argentina and has not yet reached its maximum industrial potential. To foster growth, it is essential to understand the quality and energy potential as residual biomass, their combustion behavior, and ways to enhance their performance as fuel. This is why analyzing the interaction between the physical and chemical parameters of the pellet with the combustion process and its residues is important. Therefore, proper characterization of lignocellulosic crops is fundamental for developing an energy-appropriate fuel.

The development of a solid biofuel is influenced by various factors, including crop moisture content. This content can have a significant impact on the densification process, which can lead to higher costs in pellet production [9]. Ash content is another critical factor, as it interferes with combustion quality by reducing the heating value (HV) of the fuel and, when present in large quantities, decreases system efficiency, causing emissions, increasing equipment wear, and causing fouling. This is especially important when pellets are used for combustion in industrial systems because accumulation in tube banks and boiler walls reduces heat transfer and causes maintenance problems [10]. Lignin is a key factor in the palletization process. At high temperatures and pressures, lignin reaches its glass transition temperature, promoting internal particle cohesion and improving the mechanical strength of the pellet without the need for external additives.

Lignin is characterized by its high thermal stability and carbon content, making it more suitable for energy applications due to its higher carbon yield and HV. However, this process often generates large amounts of char and tar. By contrast, hemicellulose has lower thermal stability, contains more oxygen, and undergoes rapid degradation at high temperatures, which reduces its energy yield [11]. Fixed carbon is essential for maintaining energy quality, enabling more stable and prolonged combustion, whereas volatile compounds facilitate rapid but brief ignition [12]. For this reason, biomass materials with high lignin content are preferred the production of efficient solid biofuels [13,14]. There is also evidence linking the extractive content of products to the measured higher heating value (HHV). This suggests that a high extractive content positively affects the combustion process [15] by accelerating pellet flammability [16]. Particle size affects the physical quality of the pellet as well as the energy required for compaction. It affects the total surface area, pore size, and number of interparticle contacts, all of which are essential for achieving product cohesion and durability [17]. Similarly, the size and distribution of particles in the mixture can affect the chemical reactivity of biomass, improving kinetics and flame propagation during combustion. This is particularly important as it enhances heat transfer in solid fuels [18]. Whittaker & Shield [13] recommend using a mixture of particle sizes, as the finer particles fill the gaps left by the larger ones, promoting compaction. This increases pellet's strength and resistance and internal cohesion, but also increases friction during palletization, impacting energy consumption. Thus, an optimal combination of particle sizes guarantees the structural integrity of the pellet obtained, reducing the production of fines during handling and transport. From an energy standpoint, grinding and separation of the raw material are key processes for ensuring both overall performance and the quality of the final product [19].

This study aims to characterize the physicochemical parameters of the E and RM fractions obtained from crushing and screening in a pilot-scale solid fuel production process, to evaluate their performance during densification and subsequent combustion. This integrated assessment seeks to determine the overall energy potential and viability of these agricultural wastes as sustainable solid fuel feedstocks, and to examine whether the composition of the different fractions exhibits significant differences in key physicochemical properties. By identifying which fractions are equally viable or necessary for efficient energy generation, the study provides a comprehensive understanding of the role of each component in the production and combustion processes, thus contributing to the development of efficient and sustainable alternatives for industrial-scale energy generation.

2 Methodology

E was obtained from natural esparto grass cut in the La Francia region, while RM was obtained from harvest residue deposited on the ground in El Tío, near the esparto grass fields. Both locations are situated in the central-eastern part of the province of Córdoba, Argentina. The collected materials were then washed in running drinking water to remove solid contaminants that could be carried over from the harvesting process. The materials were subsequently dried in a fluid bed flash dryer (SR-HGJ 400, Zhengzhou Share Machinery Co.) to reduce moisture content and enable storage.

The conditioned waste was ground in a blade mill (CID 75, 1.5 hp) with a 3 mm mesh outlet and then sieved to separate the particles using a series of 20, 35, and 100 mesh (Tyler) sieves. Based on this procedure, the particle size fractions used throughout the study were defined in Table 1.

The ash content (ASTM 1102), moisture content (ASTM E 871-82), volatile matter (ASTM E 872), and fixed carbon (FC) were determined in the various fractions obtained, with FC being calculated as the difference between the previous values. In turn, the bulk density of the fractions (ISO 17828:2015), extractive matter content (TAPPI T 204 cm 97), and insoluble lignin by Klason method (TAPPI 222:om-21) were determined.

Several authors have developed equations correlating HHV determined by bomb calorimetry, with the structural components of biomass. Among them, Demirbas [15] reported that, in non-woody species, HHV correlates with lignin (Lg) content while also noting that the extractives (Ex) index exerts a positive influence in both woody and non-woody species. Based on the work of Demirbas and other authors, Telmo [20] suggests that the most accurate correlation is obtained by considering both extractives and lignin, as this better reflects the HHV measured in wood species with high *Ex* content (Equation 1; R = 0.915).

$$HHV\left[\frac{MJ}{kg}\right] = 14.3377 + 0.1228(Lg) + 0.1353(Ex) \quad (1)$$

Non-woody species such as E and RM tend to exhibit high *Ex* content; therefore, although Telmo's equation was originally formulated for wood, it is considered suitable for the theoretical estimation of HHV in this work. It should be emphasized that HHV values tend to be highly variable due to the edaphological conditions of the samples. While this makes the values useful for the comparative analysis conducted here, they cannot be extrapolated directly to other sampling contexts.

Table 1.
Definition of particle size fractions used in this study

	>841 µm	841-500 µm	500-149 µm	<149 µm
Espartillo	E_1	E_2	E_3	E_4
Corn stover	RM_1	RM_2	RM_3	RM_4

Source: Own elaboration

Combustion tests were also carried out using a methodology adapted from Dula *et al*. [21], as there are no specific regulations for the combustion of pellets in open grills. The objective of this test was to record the flame time, the characteristics of the process, and the duration of combustion. For this purpose, a fixed-bed grill was employed, supported in a glass-covered, closed gas extraction hood with natural convection air circulation. In order to prevent material loss, combustion residues were meticulously collected in an ash pan positioned below the grill. Ignition was performed manually using a minimal amount of ignition material (0.2 mL of 96 % ethyl alcohol, PORTA). In the experimental setting, comparable quantities of densified pellets of E, RM, and mixtures in E/RM ratios of 1:1 and 1:3 were combusted during the test. The pellets were constructed from material ground before fraction separation, and their densification was achieved through manual compacting using a 15 kN press. The thermochemical process was recorded in two stages: I) Ignition and combustion: this phase begins when a spark is generated and a visible flame is sustained and ends when the flame is extinguished; II) Post-combustion: commences when the flame is no longer visible and continues until the material ceases to emit smoke. The time for each stage was measured, with t_1 representing the time for the first stage and t_2 representing the total time for both stages.

Furthermore, an observational study of the residues was conducted, and the percentage of mass loss for each fuel was determined. The experiment was recorded using stopwatches and a thermal imaging camera (Fluke Ti 105).

3 Results

3.1 Fractionation and physicochemical evaluation

Fig. 1 shows the E and RM crops before and after the chopping process. Table 2 shows the results of the physicochemical characterization obtained for the different fractions of E and RM. These results were obtained by taking the average of analytical measurements made in triplicate.

Figure 1. Materials before and after grinding, a) E; b) RM.
Source: Own elaboration.

Table 2.
Physicochemical parameters of RM and E fractions.

	Moisture (%; n=3) (1)	Ash $_{DB}$ (%; n=3) (1)	Volatiles $_{DB}$ (%; n=3) (1)	Fixed Carbon $_{DB}$ (%; n=3) (1)	Extractives (%; n=3) (1)	Lignin (%; n=3) (1)	Bulk density (kg/m^3; n=3) (1)	HHV(2) (MJ/kg; n=3) (1)
E1	7.76 ± 0.39	5.49 ± 0.42	79.19 ± 1.88	15.32 ± 1.67	14.05 ± 0.25	23.15 ± 0.79	165.94 ± 3.18	19.08 ± 0.06
E2	9.81 ± 0.16	10.22 ± 0.17	73.19 ± 1.33	16.59 ± 1.50	7.37 ± 0.28	25.53 ± 0.32	239.38 ± 1.91	18.47 ± 0.04
E3	9.61 ± 0.25	10.35 ± 0.13	71.99 ± 1.07	17.66 ± 1.48	8.37 ± 0.63	24.96 ± 0.24	285.00 ± 1.27	18.54 ± 0.07
E4	9.49 ± 0.12	21.86 ± 0.14	65.97 ± 2.45	12.17 ± 2.58	14.89 ± 0.22	25.60 ± 0.35	302.82 ± 2.23	19.50 ± 0.04
RM1	7.62 ± 0.48	3.57 ± 0.31	88.65 ± 2.56	7.78 ± 2.29	10.57 ± 0.80	6.04 ± 0.12	104.00 ± 4.04	16.51 ± 0.10
RM2	6.64 ± 0.12	5.18 ± 0.05	87.32 ± 1.78	7.50 ± 1.79	14.33 ± 0.61	6.93 ± 0.37	121.23 ± 6.56	17.13 ± 0.13
RM3	8.58 ± 0.18	8.50 ± 0.78	81.80 ± 2.63	9.70 ± 2.90	16.26 ± 0.65	7.05 ± 0.17	124.31 ± 3.48	17.40 ± 0.09
RM4	7.53 ± 0.78	17.02 ± 0.59	74.20 ± 2.10	8.78 ± 2.59	21.83 ± 0.86	6.88 ± 0.30	257.08 ± 6.42	18.14 ± 0.13

Source: Own elaboration
(1) Mean ± standard deviation
(2) HHV obtained from equation 1

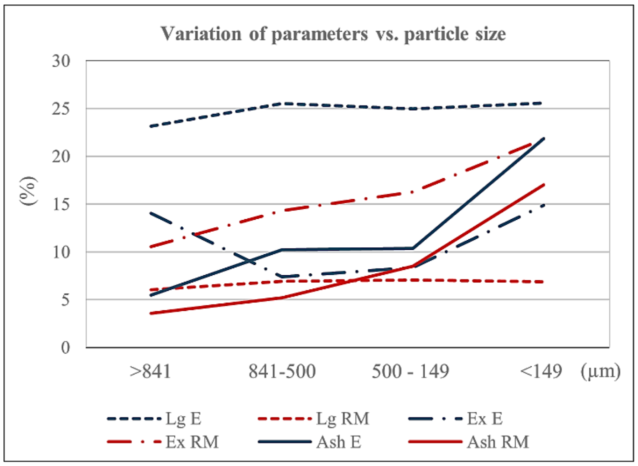

Figure 2. Variation of physicochemical parameters asparticle size decreases.
Source: Own elaboration.

As demonstrated in Table 2, the moisture values for all fractions of each material analyzed were found to be similar. *Ex* are secondary non-structural components of plants, which are usually soluble in various polar solvents. These are predominantly located in the plant's parenchyma, though they can also be found in vessels, fibers, or specialized cells [22]. The composition and distribution of the subject are dependent on a number of factors, including the species, age, health status, and the environmental conditions during the growth period. Li *et al*. [23] investigated the chemical composition of the leaves, pith, and bark of the stem separately. They found that the content of *Ex* soluble in benzene-alcohol was higher in the pith region than in the bark, while *Ex* in water was similar in the pith and leaves, and higher than in the bark. Furthermore, it was observed that the disparities in morphology are a consequence of a specific chemical composition, determined by the levels of lignin, cellulose and hemicellulose, where the stem exhibits a slightly higher level of lignin in comparison to the other structures. In relation to this, and as illustrated in Table 2, an inverse relationship is evident between the *Ex* content in RM and particle size. This trend is less pronounced in E. Therefore, it can be inferred that, due to the morphological differentiation of the fractions, they exhibit different responses to the shear effect of grinding. Consequently, depending on the species, fractions with a higher concentration of certain morphological structures would be obtained, which could be reflected in a higher proportion of *Ex* or *Lg*. As a result, it could be assumed that the spongier structures of the stem pith, rich in hemicellulose, can achieve a smaller particle diameter during grinding, thus exposing their larger surface area to the extraction of organic compounds; this effect is compounded by the higher concentration of *Ex* in the pith region [23]. This is consistent with the incremental extractive content observed as particle size decreases, mainly in RM, which also coincides with the findings of Ottone & Baldwin [24] on yellow poplar sawdust particles and with Miranda *et al*. [25] when analyzing the link between *Ex* and particle size in sawdust from various pine species. This trend is less pronounced in E, possibly because the morphological variation in the hollow stem structure of this species is less than in RM. Thus, the variation in the composition of the fractions may influence the compaction effect, since *Ex* includes waxes, resins, and phenolic compounds that could act as lubricants in the matrix. This lubricating effect reduces mechanical friction and material jams during the production process, therefore reducing energy consumption. However, it also decreases the mechanical properties of the pellets obtained [26]. In turn, the *Lg* content does not show significant variation depending on particle size. Nevertheless, the contribution of both *Lg* and *Ex* content to HHV causes it to vary slightly in RM as particle size decreases, and it remains relatively stable in the E fractions. Fig. 2 shows how the relationships between the variables change as the particle size in the fraction decreases.

The bulk density of the fractions, which is defined as the mass per unit volume, takes into account the empty spaces between particles and internal porosity. It varies depending on the size, shape, particle size distribution and porosity of the particles, which can be influenced by the duration, technology and grinding conditions. Additionally, internal porosity is related not only to the morphology of the species, but also to growth conditions, which can modify pore distribution and closure [27,28]. These factors impact the mechanical, physical and thermal properties of densified lignocellulosic materials. It is well known that the compaction of spongy particles, such as those of RM, is complex [29,30]. Thus, the production of hybrid biofuels can improve processing and combustion characteristics [31]. As

Table 3.
Combustion test results

	t_1 (s)	t_2 (s)	Average flame temperature* (°C)	Volatiles (%)	Solid combustion waste (%)	Ash (%)	Extractives (%)	Lignin (%)	Observations
E	45	320	152.3	72,58	21,14	11,98	11,17	24,81	Incomplete combustion. Sintering and dark ashes. Lights quickly, struggles to keep the flame alive, tries to go out, even though it stays lit and smokes.
RM	55	195	183.2	82,99	8,40	8,57	15,75	6,73	Complete combustion, lighter ashes. Larger flame than E. Tends to go out but remains lit and smoldering.
1:1	90	150	275.0	77,79	13,66	10,28	13,46	15,77	Complete combustion. The flame lasts longer and is larger, with a lot of smoke.
1:3	80	130	186.9	80,39	11,12	9,42	14,60	11,25	Complete combustion. Flame similar to 1:1, combustion with a lot of smoke.

* The average flame temperature was obtained using SmartView® 3.5.31.0 software (Fluke Corporation), based on the analysis of the temperatures across the entire surface of the fuel captured by the thermal imaging camera.
Source: Own elaboration.

shown in Table 2, the reduction in particle size enables fine particles to fill the spaces between larger particles, thereby increasing the apparent density. This is expected to enhance adhesion and compaction during the pelletization process.

Regarding ash content, it is notable that it increases significantly in both species as the particle size of the fractions decreases (Table 2). It is well known that ash content in fuels is linked to problems during combustion, as the high temperatures reached can melt the ash and cause overheating and slag accumulation on the walls of boilers and burners [10]. In turn, the generation of fine particles during pellet handling can cause faster combustion that achieves higher temperatures, thus accelerating the melting of ash [13].

From a solid fuel processing perspective, incorporating fine particles into the mixture helps to mechanically stabilize the resulting pellet. Located on the free surface between coarse particles, these particles increase the density of the product, minimize pores and improve adhesion and cohesion mechanisms, thereby increasing durability [19,32]. However, according to the results obtained, a significant percentage of ash is added through this same incorporation of small particles when the particle size is between 35 and 100 mesh for both materials. In both E and RM, the ash content approximately quadruples when the particle size is reduced, but half of this increase occurs when the particle size is further reduced below 149 µm. The highest percentage of *Ex* is also observed in this fraction. The exclusion of particles that pass through the #100 mesh in both products would result in a mixture that still contains small particles. These particles improve the mechanical performance of the pellet, while substantially reducing fuel ash generation and exhibiting a lower *Ex* content. The latter could potentially hinder the compaction process, but it would also enhance pellet stability and HHV development by enabling a higher proportion of fractions with high *Lg* content. These combinations must then be considered in terms of the available materials and critical production parameters, with the aim of achieving a balance between production efficiency, pellet quality and combustion performance.

3.2 Combustion

Tests were carried out on the various combinations of raw materials to establish the combustion properties of compacted pellets of E, RM, and combinations thereof. The results obtained in this test are shown in Table 3.

As shown in Table 3, pure densified E has a shorter flame time (t_1) and a longer total combustion time (t_2) compared to RM, the latter of which includes both the flame time and the post-combustion time. Both materials tend to have low active flame capacity and burn internally with excessive smoke release. However, E exhibits sintered residual material and a higher percentage of residue after combustion. In the case of RM, the residue obtained is light grey, powdery and proportionally similar to the ash content of the original fuel. When combustion is analyzed in hybrid E and RM pellets, higher t_1 values are obtained compared to pure fuels, although lower t_2 values are obtained. Fig. 3 illustrates the relationship between the combustion times of the different fuel samples, while Fig. 4 shows the variability of the physicochemical parameters of the evaluated fuels.

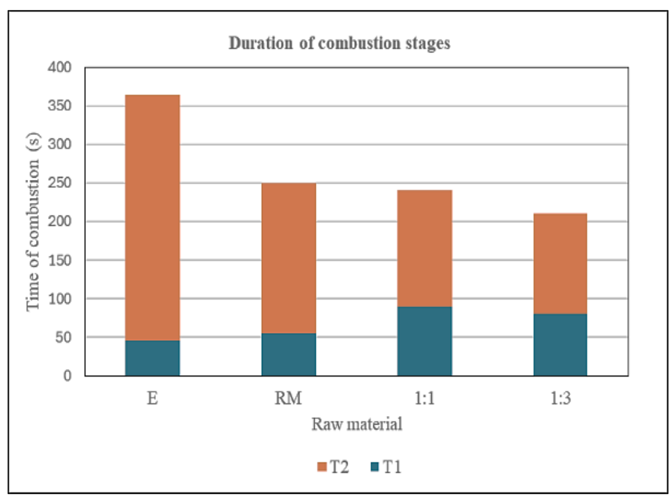

Figure 3. Combustion times for densified solid fuels
Source: Own elaboration.

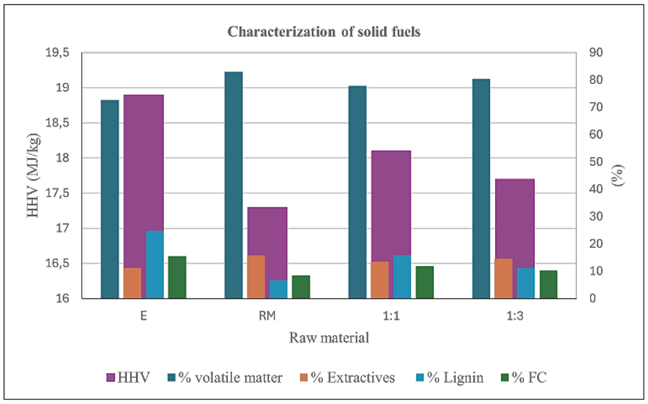

Figure 4. Relationship between physicochemical parameters in solid fuels
Source: Own elaboration.

As shown in Table 3 and illustrated in Figs. 3 and 4, the lower t_1 exhibited by E is consistent with its lower volatile and *Ex* content. However, its high *Lg* and FC concentrations favor prolonged combustion over time. In contrast, RM exhibits a higher t_1 due to its higher percentage of volatiles and *Ex* than that of E. However, its low *Lg* and FC content limits the total duration of the combustion process. This is because the content of volatile materials, which are mainly associated with hemicellulose and *Ex*, favors rapid ignition and lower starting temperatures. However, although these components generate intense combustion, it is short-lived due to their rapid consumption [12].

Likewise, mixtures of E and RM in different proportions exhibit synergistic behavior during the combustion phases, as evidenced by an increase in visible flame time (t_1) that is even greater than that of pure materials. This phenomenon can be attributed to the relative increase in volatiles and *Ex* from the RM, but it also suggests the existence of a complementary effect between particles of different natures present in E and RM. Thus, it can be assumed that greater particle cohesion, favored by diverse sizes, compositions and morphologies, improves heat transfer within the fuel. This allows for higher temperatures to be reached, based on an appropriate balance between generating an active flame easily and sustaining combustion over time. Better ignition of the material in the mixtures, as evidenced by an increase in t_1, is crucial for combustion and energy generation, with holocellulose and *Ex* demonstrating greater potential in this regard [12]. On the other hand, there is a notable decrease in t_2 compared to pure fuels, which seems to be a consequence of this improvement in combustion capacity during the initial stage, producing more energy and promoting faster and more efficient fuel consumption. This increase in energy is linked to the higher average temperatures reached at the point of maximum combustion; with the highest value being obtained in the E/RM 1:1 mixture. This finding is consistent with the reduction in the fraction of residue from the combustion process, which reached values similar to its ash content. Fig. 5 shows the thermographic images, providing visual evidence of the observed differences in combustion times. Pure materials display highly localized high-temperature zones; for instance, E shows a small, confined flame region,

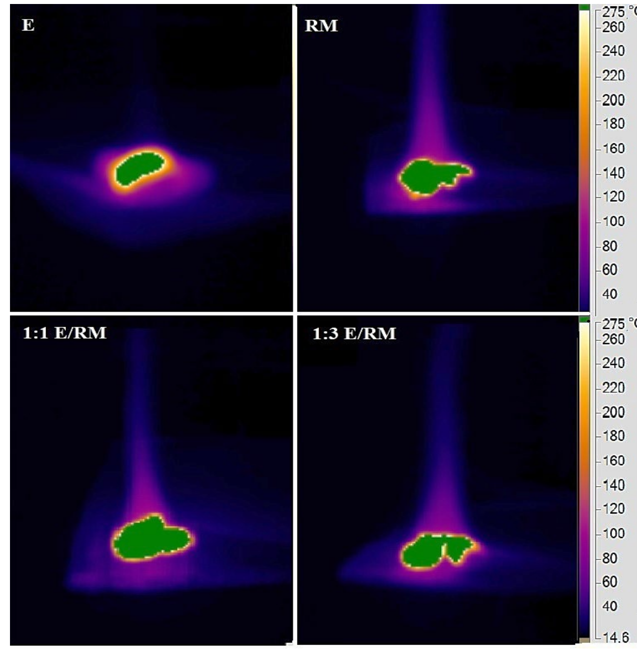

Figure 5. Thermographic images taken during stage I of combustion.
Source: Prepared by the authors.

consistent with its lower t_1. In contrast, RM exhibits a more intense initial heat release, in line with its higher volatile and extractive content. The E/RM blends, however, demonstrate more uniform temperature distribution and a stable flame structure, corresponding to an increased t_1. This also accounts for the faster fuel consumption reflected in the shorter t_2 values. Overall, these thermographic patterns indicate a more efficient heat transfer and combustion process in the blends, reinforcing the synergistic behavior inferred from the combustion time analysis.

In the 1:1 mixture, the prolongation of t_2 with respect to the 1:3 ratio is linked to the higher *Lg* content, whose high carbon content and the nature of the chemical bonds between its monomers provide high thermal resistance and improve carbonization performance, resulting in a consequent increase in temperature. Due to the high energy requirements for their decomposition, lignins exhibit a low ignition rate. Consequently, the ignition of the material must be ensured by other components, while lignin ensures continuous and prolonged combustion [12]. This combination of variables appears to be more balanced in the 1:1 (E:RM) ratio, suggesting more efficient combustibility parameters compared to the 1:3 (E:RM) ratio, although with a slightly higher ash content. However, this increase in ash, which would be detrimental to combustion processes, can be mitigated by removing particle size fractions, smaller than 149 µm, from these mixtures.

The findings presented thus far indicate that a suitable combination of raw materials enhances the combustion capacity of densified solid fuels, achieving a balance between the factors that favor greater heat generation and more complete combustion. Nevertheless, when selecting the appropriate materials, certain critical factors - such as their physicochemical properties - have the potential to exert a negative influence on both the densification process and the quality of the fuel, as well as the dynamics of combustion. Consequently, effective technical management of grinding and particle separation, founded upon the analysis of these parameters, would facilitate strategic intervention in the production process, leading to the elimination of problematic fractions and the optimization of the quality of the final product. This alternative also facilitates the incorporation of non-traditional agricultural resources such as E or RM, whose use has been limited until now, thus expanding the range of raw materials available for the production of solid fuel.

Finally, it should be mentioned that the present study employed an experimental methodology adapted for densified pellet combustion tests, with the purpose of conducting a thermal evaluation of the process through thermographic recording. Consequently, the results should be expanded through a more in-depth analysis of the combustion process, incorporating both gas and residue sampling. Thus, the comparison of these and other properties in mixtures of E and RM, with and without exclusion of the smaller fraction, will provide statistical and experimental support for the trends shown in this study. These objectives have not been incorporated into this study for two main reasons. Firstly, modification of the combustion chamber would be necessary in order to take gas samples. Secondly, these new results would lead to a second stage of analysis, already linked to the comparative production of pellets, the efficiency of the production process and its subsequent combustion. The information thus obtained would be relevant and would form part of future studies.

4 Conclusions

The need to decarbonize the energy matrix is driving the development of novel alternative fuels. Within this framework, the integration of unconventional lignocellulosic materials -particularly those of agricultural origin - poses a challenge for the production of solid biofuels. The present study examined the variation in physicochemical parameters during the fractionation of corn stover (RM) and espartillo (E), as well as the feasibility of direct combustion of pure materials (E, RM) and synergistic blends (E/RM at ratios of 1:1 and 1:3).

The findings indicate an increasing trend in extractives and ash content as particle size decreased for RM, while E exhibited a comparable upward trend in ash content under analogous conditions. Hybrid mixtures demonstrated enhanced combustion performance. From a technical standpoint, the results of this study suggest that E/RM blends at a 1:1 ratio, with particle sizes above 149 µm, represent a favorable configuration for direct combustion applications. This mixture exhibited higher mean combustion temperatures, extended flame duration, and improved HHV relative to the other formulations evaluated.

The findings of this study indicate that the incorporation of RM and E into combustion processes constitutes a viable alternative when production is designed around synergistic blending and granulometric optimization to minimize adverse effects. This strategy is oriented toward the valorization of agricultural residues from an energetic perspective, while simultaneously contributing to the diversification of energy sources in rural regions characterized by limited access to the electrical grid.

Subsequent research endeavors will encompass the exploration of additional combinations of these materials, along with the incorporation of another residual biomass. This will be undertaken to develop blends with higher HHV, with the objective of optimizing key physicochemical parameters to enhance combustion efficiency.

References

[1] Jozami, E., Di-Leo, N., Barbona, I., and Feldman S., Modelos predictivos para la estimación de biomasa de "*Spartina argentinensis*", Ciencias Agronómicas, 45(25), art. e047, 2025. DOI: https://doi.org/10.35305/agro45.e047

[2] Jozami, E., Sosa, L.L., and Feldman, S.R., *Spartina argentinensis* as feedstock for bioethanol, ATI - Appl. Technol. Innov., 9(2), pp. 37–44, 2013. DOI: https:// doi.org/10.15208/ati.2013.8

[3] García-Stepien, E.L., Variabilidad del germoplasma de Maíz (*Zea mays* L.) en Argentina: la aptitud forrajera asociada a la producción de bioetanol lignocelulósico, Phd Thesis, Universidad Nacional de la Plata, La Plata, Buenos Aires, Argentina, 2020.

[4] Montemarani, A., Sartori, M., Nesci, A., Etcheverry, M., and Barros, G., Influence of crop residues, matric potential and temperature on growth of Exserohilum turcicum an emerging maize pathogen in Argentina, Lett. Appl. Microbiol. 67, pp. 614–619, 2018. DOI: https://doi.org/10.1111/lam.13076

[5] Kumar, P., Kumar, S., and Joshi, L., The extent and management of crop stubble, springer briefs in environmental science (Ed.), Springer, Nueva Delhi. [online]. pp. 13–34, 2015. Available at: https://link.springer.com/chapter/10.1007/978-81-322-2014-5_2

[6] Idígoras, G., Prospectiva tecnológica al 2025 del complejo de semillas, Análisis tecnológicos y prospectivos sectoriales, Ministerio de Ciencia, Tecnología e Innovación Productiva, Buenos Aires, Argentina, [online]. 2016. Available at: https://www.argentina.gob.ar/sites/default/files/5._agro_atypsii_semillas.pdf

[7] Menéndez, J.E., and Hilbert, J.A., Cuantificación y uso de Biomasa de residuos de cultivos en Argentina para bioenergía, Inf. Técnicos Bioenergía, 2(4), 2013, 48P.

[8] Richmond, S.N., and Rillo, P.F., Caracterización de la dinámica de incorporación de residuos de cosecha al suelo en un sistema agrícola en siembra directa en el centro-oeste de Buenos Aires, LACS, IPNI Informaciones Agronómicas Hisp., [online]. 43, pp. 22–26, 2009. Available at: https://fertilizar.org.ar/wp-content/uploads/2009/09/22.pdf

[9] Lopez, L., Vega, L., Rendon, C., y Tobon, S., Aprovechamiento de residuos madereros, Corporación Universitaria de Remington, Medellín, Colombia, [online]. 2019. Available at: https://www.uniremington.edu.co/wp-content/uploads/libros-de-investigacion/aprovechamiento-de-residuos-madereros.pdf

[10] Granada-Álvarez, E., Febrero-Garrido, L., Eguía-Oller, P., Regueiro Pereira, A., y Patiño-Vilas, D., Análisis del "fouling" procedente de la combustión de pellet de pino y pellet de paja en una caldera de baja potencia: influencia de los parámetros de combustión, IX Congr. Nac. Ing. Termodinámica, Cartagena, Colombia, pp. 1226–1234. art. 9941, 2024. DOI: https://doi.org/10.31428/10317/9941

[11] Wang, S., Zou, C., Lou, C., Yang, H.M., and Mei-Jing, H., Effects of hemicellulose, cellulose and lignin on the ignition behaviors of biomass in a drop tube furnace, Bioresour. Technol., 310, art. 123456, 2020. DOI: https://doi.org/10.1016/j.biortech.2020.123456

[12] Vieira, T.A.S., Trugilho, P.F., Carabineiro, S.A.C., Zanuncio, A.J.V., Carvalho, A.G., and Branco-Vieira M., Impact of chemical composition on eucalyptus wood clones for sustainable energy production, Forests, 14(11), pp. 1–12, 2023. DOI: https://doi.org/10.3390/f14112240

[13] Whittaker, C., and Shield, I., Factors affecting wood, energy grass and straw pellet durability–A review, Renew. Sustain. Energy Rev. 71, pp.1–11, 2017. DOI: https://doi.org/10.1016/j.rser.2016.12.119

[14] Montenegro-Mateos, L., PhD Thesis, Determinación del riesgo de auto-combustión en almacenamiento de biomasas para la producción de gas mediante gasificación. Escuela Técnica Superior de Ingenieros de Minas y Energía, Universidad Politécnica de Madrid, España, 2014.

[15] Demirbas, A., Relationships between heating value and lignin, moisture, ash and extractive contents of biomass fuels. Energy Explor. Exploit. 20, pp. 105–111, 2002. DOI: https://doi.org/10.1260/014459802760170420

[16] Beltrón-Vinces, I.C., Palacios Bravo, H.E., y Rosero Delgado, E., Evaluación energética de biocombustibles sólidos elaborados a partir de mezclas de biomasa lignocelulósica, RIEMAT. [online]. 4, pp. 33–38, 2019. Available at: https://revistas.utm.edu.ec/index.php/Riemat/article/view/2192

[17] Kirsten, C., Lenz, V., Schröder, H., and Repke, J., The influence of particle size reduction on their physical–mechanical quality and energy demand during production, Fuel Process. Technol. 148, pp. 163–174, 2016. DOI: https://doi.org/10.1016/j.fuproc.2016.02.013

[18] Mlonka, A., Magdziarz, A., Dziok, T., and Nowak, W., Laboratory studies on the influence of biomass particle size on pyrolysis and combustion using TG-GC/MS, Fuel, 252, pp. 635–645, 2019. DOI: https://doi.org/10.1016/j.fuel.2019.04.091

[19] Correa-Méndez, F., Carrillo-Parra, A., Rutiaga-Quiñones, J.G., Márquez-Montesino, F., González-Rodríguez, H., Ybarra, E.J., and Garza-Ocañas, F., Granulometric distribution in timber byproducts for potential use in pellets and briquettes. Rev. Mex. Ciencias For. [online]. 5, pp. 52–63, 2014. Available at: https://www.scielo.org.mx/scielo.php?pid=S2007-11322014000500005&script=sci_abstract&tlng=en

[20] Telmo, C., and Lousada, J., The explained variation by lignin and extractive contents on higher heating value of wood, Biomass and Bioenergy. 35, pp. 1663–1667, 2011. DOI: https://doi.org/10.1016/j.biombioe.2010.12.038

[21] Dula, M., Kraszkiewicz, A., and Parafiniuk, S., Combustion efficiency of various forms of solid biofuels in terms of changes in the method of fuel feeding into the combustion chamber, energies, 17, pp. 1–21, 2024. DOI: https://doi.org/10.3390/en17122853

[22] Hillis, W.E., Distribution, properties and formation of some wood extractives, Wood Sci. Technol. 5, pp. 272–289, 1971. DOI: https://doi.org/10.1007/BF00365060

[23] Li, Z., Zhai, H., Zhang, Y., and Yu, L., Cell morphology and chemical characteristics of corn stover fractions, Ind. Crops Prod. 37, pp. 130–136, 2012. DOI: https://doi.org/10.1016/j.indcrop.2011.11.025

[24] Ottone, S.P., and Baldwin, R.C., The relationship of extractive content to particle size distribution in milled yellow-poplar. Wood and Fiber, [online]. 13(2) pp. 74–85, 1981. Available at: https://share.google/p5Ih9QgC5tF4Ewk4p

[25] Miranda, I., Gominho J., Mirra I., and Pereira, H., Chemical characterization of barks from picea abies and pinus sylvestris after fractioning into different particle sizes. Ind. Crops Prod. 36, pp. 395–400, 2012. DOI: https://doi.org/10.1016/j.indcrop.2011.10.035

[26] Nielsen, N.P.K., Gardner, D.J., and Felby C., Effect of extractives and storage on the pelletizing process of sawdust, Fuel. 89, pp. 94–98, 2010. DOI: https://doi.org/10.1016/j.fuel.2009.06.025

[27] Li, S.X., Huang, and R., Zheng, Xylem plasticity of root, stem, and branch in Cunninghamia lanceolata under drought stress: implications for whole-plant hydraulic integrity, Front Plant Sci, 15, Art. 1308360, 2024. https://doi.org/10.3389/fpls.2024.1308360.

[28] Sun, S., Ahmad, N., Callenius, H., Uslu, V.V., Rey, J.C., Zhao, F., and Rajab, H., "The plastid cysteine synthase complex regulates ABA biosynthesis and stomatal closure in Arabidopsis," Nat. Comun., 16(8960), Art. 3, 2025. DOI: https://doi.org/10.1038/s41467-025-64705-3.

[29] Djatkov, D., Martinov, M., and Kaltschmitt, M., Biomass and Bioenergy Influencing parameters on mechanical–physical properties of pellet fuel made from corn harvest residues, Biomass and Bioenergy, 119, pp. 418–428, 2018. DOI: https://doi.org/10.1016/j.biombioe.2018.10.009.

[30] Mani, S., Tabil, L.G., and Sokhansanj S., Specific energy requirement for compacting corn stover, Bioresour. Technol., 97, pp. 1420–1426, 2006. DOI: https://doi.org/10.1016/j.biortech.2005.06.019.

[31] Kaliyan, N., and Morey, R.V., Densification characteristics of corn stover and switchgrass, ASABE, 52(3), pp. 907–920, 2009. DOI: https://doi.org/10.13031/2013.21202.

[32] Crawford, N.C., Ray, A.E., Yancey, N.A., and Nagle, N., Evaluating the pelletization of "pure" and blended lignocellulosic biomass feedstocks, Fuel Process. Technol. 140, pp. 46–56, 2015. DOI: https://doi.org/10.1016/j.fuproc.2015.08.023

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