resources

Article

Biomass Densification to Improve Management Efficiency and to Obtain High Value Products in México

Rigoberto Rosales-Serna [1], Artemio Carrillo-Parra [2,*], Julio César Ríos-Saucedo [1], Damián Reyes-Jáquez [3], Donaji Sierra-Zurita [1], Saúl Santana-Espinoza [4], Rafael Jiménez-Ocampo [1], Pablo Alfredo Domínguez-Martínez [1,*] and Cynthia Adriana Nava-Berumen [2]

[1] Campo Experimental Valle del Guadiana, Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Carretera Durango—El Mezquital km 4.5, Durango 34170, Mexico; rosales.rigoberto@inifap.gob.mx (R.R.-S.); rios.julio@inifap.gob.mx (J.C.R.-S.); sierra.donaji@inifap.gob.mx (D.S.-Z.); jimenez.rafael@inifap.gob.mx (R.J.-O.)

[2] Instituto de Silvicultura e Industria de la Madera (ISIMA), Universidad Juárez del Estado de Durango (UJED), Boulevard del Guadiana Núm. 501, Colonia Torre de Institutos, Durango 34120, Mexico; c_nava@ujed.mx

[3] Posgrado en Ingeniería Bioquímica-Instituto Tecnológico de Durango-TecNM, Felipe Pescador 1803, Col. Nueva Vizcaya, Durango 34080, Mexico; damianrj2002@yahoo.com

[4] Campo Experimental La Laguna, Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Boulevard José Santos Valdéz 1200, Matamoros 27440, Mexico; santana.saul@inifap.gob.mx

* Correspondence: acarrilloparra@ujed.mx (A.C.-P.); dominguez.pablo@inifap.gob.mx (P.A.D.-M.)

Abstract: In México, the utilization of fast-growing plant species for biomass production presents transportation-related issues such as freshness reduction, the transportation of large volumes with minimal weight due to low density, limited storage availability, and logistical challenges. To enhance understanding in this field, the research aimed to evaluate the densification potential of a variety of organic materials, with a specific emphasis on the biomass derived from eight species of rapidly growing plants, three animal species' manure, and concentrated feed. After conditioning, 100 g samples underwent particle size analysis and were categorized into seven sizes. Pellets and briquettes (40 g, 10% moisture, 15 MPa pressure, 5 min processing, 80 °C temperature) were produced and evaluated for bulk density (BD) and pellet (PD) and briquette durability (BDU). The predominant particle sizes were 0.850 mm and 0.425 mm. Original biomass bulk density (OBBD) varied notably, with ovine manure (0.50 g cm^{-3}) and cattle feed (0.49 g cm^{-3}) exhibiting the highest values. Caprine manure (0.83 g cm^{-3}) and ovine manure (0.78 g cm^{-3}) yielded the densest pellets at 1.76 and 1.84 g cm^{-3}, respectively. Apple tree pellets achieved premium quality with the highest hardness (97.9%). Cattle manure (1.25 g cm^{-3}) and cattle feed (1.25 g cm^{-3}) had the densest briquettes, with notable BBD/OBBD ratios in pine sawdust (4.6) and corn (4.5). Caprine manure and *Acacia* biomass briquettes showed premium quality with the highest hardness (99.1%), emphasizing densification variations and the need for tailored approaches based on organic material characteristics.

Keywords: bioenergy; biofertilizers; industry; productivity; sustainability

Citation: Rosales-Serna, R.; Carrillo-Parra, A.; Ríos-Saucedo, J.C.; Reyes-Jáquez, D.; Sierra-Zurita, D.; Santana-Espinoza, S.; Jiménez-Ocampo, R.; Domínguez-Martínez, P.A.; Nava-Berumen, C.A. Biomass Densification to Improve Management Efficiency and to Obtain High Value Products in México. *Resources* **2024**, *13*, 48. https://doi.org/10.3390/resources13030048

Academic Editor: Francesco Patuzzi

Received: 25 January 2024
Revised: 6 March 2024
Accepted: 7 March 2024
Published: 20 March 2024

1. Introduction

In México, fast-growing plant species and crops that produce valuable byproducts for increasing biomass availability have been identified [1]. Biomass could be used to produce value-added products such as engineered wood, biofuels, cattle feed, and organic fertilizers. Increasing biomass availability for biofuel production will reduce costs in energy generation at domestic, commercial, and industrial levels. Some biomass primarily produces forage and dietary supplements for meat- and milk-producing cattle.

The wood and paper industry requires biomass inputs to produce engineered wood, pellets, briquettes, and pulp for paper. Therefore, identifying alternative and sustainable sources of lignocellulosic biomass contributes to forest conservation, strengthens the sustainability of forestry production, and improves environmental services provided by forest masses. It is also necessary to consider the biomass requirement for sustaining trophic chains and thereby maintaining balance in the different ecosystems observed in México.

Tree felling has led to a reduction in the diameter classes of trees extracted excessively, particularly in the case of pine (*Pinus* spp.), oak (*Quercus* spp.), mesquite (*Prosopis* spp.), and other timber and non-timber species present in the forest masses of México's forests, shrublands, and jungles. Excessive felling, combined with the pressure exerted by livestock producers, has caused a significant increase in the surface area of secondary vegetation (disturbed areas) in temperate forest ecosystems, pine-oak forests, and microphyllous shrublands. In the case of cattle production, there is an excess of livestock population that far exceeds the productive capacity of grasslands (grazing response index), forests, shrublands, and other ecosystems. Most of the agricultural soils in the semiarid highlands have low organic matter content (<1.5%), which reduces their fertility and productivity [2]. Low organic matter content results from not incorporating crop residues, manure, and other organically produced soil amendments. The efficient and rational use of available plant biomass in México's productive systems will reduce pressure on ecosystems while strengthening family economies and forestry, agricultural, and industrial production. Some of the included studies have determined the quality of different materials in producing interesting solid biofuel. For instance, the residues from agricultural and industrial production, including fibrous materials derived from Agave [3] and sotol, as well as agricultural residues [4], represent an option for maintaining adequate soil organic matter levels. Additionally, evidence shows that invasive wild plants (*Dodonaea viscosa*) and cultivated ones (*Pennisetum* sp., *Ricinus communis*) exhibit accelerated biomass accumulation.

However, the biomass of most fast-growing plant species exhibits high volume and low density due to its fibrous nature, making its collection, storage, and use a severe challenge for input management. Technology for the densification of plant-based matrices is available, which can significantly aid in the efficient and extensive use of biomass in homes, agricultural production, industry, and other economic activities. Biomass densification facilitates its handling and use, although it is essential to identify technological options that maintain or improve the natural properties of the original organic matter. Currently, the most popular densification technologies include the production of granules, pellets, briquettes, and extrudates. The efficient use of biomass would contribute to the sustainability of various economic activities by reducing the negative environmental impact observed today. This study aimed to assess the densification levels that different organic materials can achieve to facilitate their handling and enhance the sustainability of agricultural and forestry production in México.

2. Materials and Methods

2.1. Sources of Biomass

The biomass was collected in the semiarid highlands of México and divided into four groups: Group 1: Agricultural products and crop residues, including biomass from king grass (*Pennisetum* sp.), common bean straw (*Phaseolus vulgaris*), and corn stubble (*Zea mays*). Group 2: Domestic livestock manure, which includes manure from bovine (*Bos taurus*), goat (*Capra aegagrus*), and ovine (*Ovis orientalis*) cattle. Group 3: Woody materials such as pruning residues from apple trees (*Malus domestica*) and pecan trees (*Carya illinoensis*), branches from huisache (*Acacia farnesiana*), mesquite (*Prosopis laevigata*), and pine sawdust (*Pinus* sp.). Group 4: This group includes a concentrated feed for domestic cattle.

2.2. Biomass Treatment

Pruning residues from apple and pecan trees, as well as branches from huisache and mesquite were chipped using TFS 420, XKJ* equipment to accelerate biomass drying. King grass and corn stubble were processed through a hammer mill, powered by the tractor's power take-off, to reduce particle size before final grinding. Lastly, all materials, except sawdust and concentrated animal feed, were ground using SM 300 equipment to homogenize particle size. Finally, the materials were naturally dried in the shade and open-air until reaching 10 to 12% moisture content.

2.3. Granulometric Study

Firstly, 3 kg ground biomass samples were taken and conditioned for approximately one month at room temperature (20 to 30 °C), and at a relative humidity of 60 to 70%. After that the percentage of biomass particles for each size was determined in accordance with the UNE-EN-15149-2 standard [5]. This involved calculating the weight percentage of particles retained at each size after 10 min using a vibrating sieve; this procedure was performed in quadruplicate. The minimum size per replication was 100 g of biomass, and each biomass source had four replications.

The percentage of biomass particles capable of passing through a vibrating sieve, as established in the UNE-EN-15149-2 standard [5]. The seven sieves used in this test retained particles of the varying sizes, as depicted in Table 1; classification was carried out independently for the groups presented in Table 1.

Table 1. Particle size distribution and classification.

Number of Sieve	Sieve Size (mm)	Particle Classification
20	0.850	Large
40	0.425	Large
50	0.300	Medium
60	0.250	Medium
80	0.180	Medium
100	0.150	Small
200	0.075	Small

2.4. Production of Pellets and Briquettes

After conducting tests on pellet production to identify the optimal moisture content for each material, the moisture content employed for all types of biomasses ranged from 10% to 12%. The pellets were mechanically produced using a commercial machine (ZLSP-R400, GEMCO, Anyang, China). The pelletizer used produces pellets at a rate of 350–450 kg h^{-1} and was operated using a flat disc with channels of 8 mm in length and 6 mm in diameter [6]. The production of briquettes with the different types of biomasses included in the study was carried out with a standard moisture level of 10% and a pressure of 15 Mpa, with 15 replications for each biomass source. The briquette production process was performed using 40 g of biomass from each species and the necessary laboratory equipment (Lippel model LB32, Agrolândia, Brazil), with a processing time of 5 min and a temperature of 80 °C.

2.5. Variables Evaluated

The original biomass moisture content was adjusted to 10 to 12% through natural dehydration when the biomass exceeded the moisture limit or by spraying distilled water when moisture condition was low. The moisture content was determined using an Ohaus MB 200 moisture analyzer. After stabilizing the moisture content (48 h), the bulk density (UNE-EN 15103 solid biofuels) [7] of the original material, pellets, and briquettes was determined before expansion affected the results [8]. For this, a container with a known volume (5 L) and a digital balance with an accuracy of 1 g was used to weigh the original biomass sample, pellets, and briquettes.

Particle density was determined one day after pellet fabrication. Using a digital caliper, the diameter, length, and volume of each pellet were measured, and the weight of individual pellets was recorded on a digital scale. The particle density value was calculated using Equation (1)

$$PD = Wt/Vol \quad (1)$$

where PD = Particle density, Wt = weight of each pellet, and Vol = volume of each pellet.

The ratio between original biomass bulk density (OBBD) and the value of pellets (PBD) and briquettes (BBD) was obtained using the equation DR = PBD/OBBD, where DR = density ratio, PBD = pellets bulk density (briquettes = BBD), and OBBD = bulk density of the original biomass.

Friability (impact resistance) was measured through the number of pieces formed when each pellet and briquette was dropped three times from a height of two meters onto the ground [9,10].

An additional friability test was conducted by dropping 20 pellets twice from a height of 1.8 m onto a ceramic floor and recording how many parts they broke into (two, three, or more parts) according to ASTM D440-86 [11]. The friability value was then calculated using Equation (2).

$$RF = Nf/Ni \quad (2)$$

where RF = resulting friability (dimensionless), Ni = number of pellets at the beginning of the experiment, and Nf = number of intact pellets at the end of the experiment.

2.6. Statistical Analysis

The obtained data were analyzed using descriptive statistics, normality tests, and goodness of fit. Additionally, an analysis of variance (ANOVA) was performed in a completely randomized design, with a variable number of replications (from 4 to 20) depending on the analyzed variable. Four replications were conducted for the particle size study, six for bulk density, and twenty replications for pellet dimensions and resistance tests (number of parts at break, biomass loss, and friability). When significant differences were observed among biomass materials, Tukey's test ($p \leq 0.05$) was applied for multiple mean comparisons. Statistical analysis was performed using SAS® v. 9.4 [12].

3. Results and Discussion

3.1. Particle Size Distribution

The particle distribution of the biomass showed a tendency toward statistical normality for each of the four sizes present in all evaluated materials. Highly significant differences ($p \leq 0.01$) were detected for particle size in each of the species included in the study (Table 2). The particle sizes with the highest prevalence were 0.850 mm (mesh 20) and 0.425 mm (mesh 40) (Figure 1). All materials were considered as a mixture of particles of different sizes, which, combined with other attributes such as variations in composition and proportions, may complicate the application of a homogeneous treatment to the organic matter collected in México. Based on this, it is advisable to perform morphological and chemical characterization of each material to establish its suitability for producing pellets, briquettes, or extrudates for various uses.

Table 2. Normality tests and goodness of fit for four predominant particle sizes in organic materials collected in México.

Sieve Size	Lilliefors Normality Test		Kruskal-Wallis Test	
	Statistic	*Probability*	Chi-Square	*Probability*
0.850 mm (20)	0.145	0.02 **	42.18	0.01 **
0.425 mm (40)	0.165	0.01 **	41.31	0.01 **
0.300 mm (50)	0.236	0.01 **	40.58	0.01 **
0.250 mm (60)	0.235	0.01 **	39.52	0.01 **

** highly significant ($p \leq 0.01$).

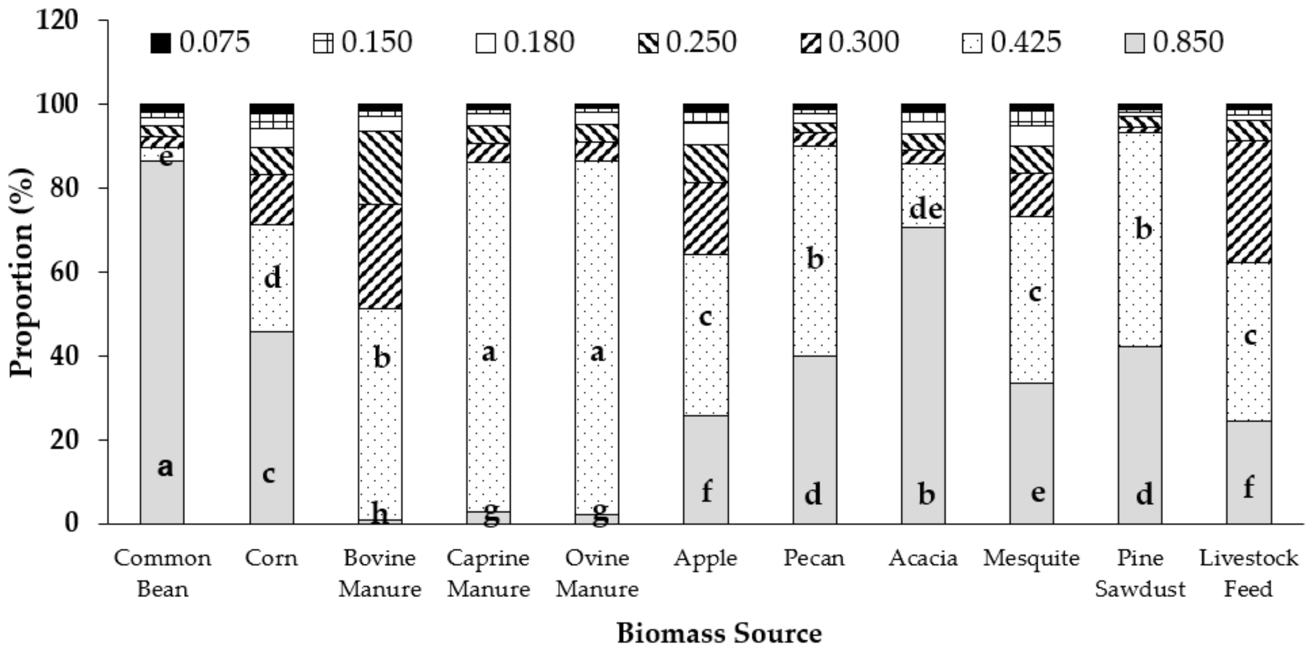

Figure 1. Particle size distribution (mm) of different organic materials collected in México. Different letters in each column and between columns indicate that they are statistically different based on Tukey's test ($p \leq 0.05$).

The common bean plant residues showed a predominance of the 0.850 mm particle size, significantly surpassing other species such as mesquite and corn stubble. Caprine and ovine manure exhibited predominance of the 0.425 mm particle size, significantly surpassing bovine manure and the rest of the evaluated materials. Particles 0.300 mm in size were abundant in livestock feed and bovine manure. The results indicated that the particle size resulted from the type of material and the handling applied for its use as raw material in producing pellets and briquettes. Based on this, organic material collection, grinding, and sieving should undergo careful management to obtain particle sizes that optimize biomass densification for each species.

Particle size divergence affects the compression strength of pellets used in energy generation [13]. Other studies established that the quality of pine briquettes was influenced by particle size distribution, and the use of small particles (<0.430 mm) favored density and compression strength [14]. It is necessary to establish the most important traits that biomass should have when used to produce specific densified products. Results showed that uniformity in particle size would contribute to optimizing the quality of pellets and briquettes produced for various purposes.

3.2. Physical Properties

3.2.1. Ground Biomass

The bulk density of the original biomass, ground material, and then used to produce pellets and briquettes showed statistically significant differences ($p \leq 0.01$) among the materials included in the study (Table 2). The highest bulk density value was observed for ovine manure (0.50 g cm^{-3}) and livestock feed (0.49 g cm^{-3}). On the other hand, king grass, corn, common bean, and pine sawdust showed the lowest values (ranging from 0.18 to 0.19 g cm^{-3}) (Figure 2). The latter materials must increase their density to a higher level to reduce storage and transportation costs. Livestock feed has unique requirements due to the interest in optimizing its use and avoiding particle loss caused by the animal's breathing and belching when feeding at troughs.

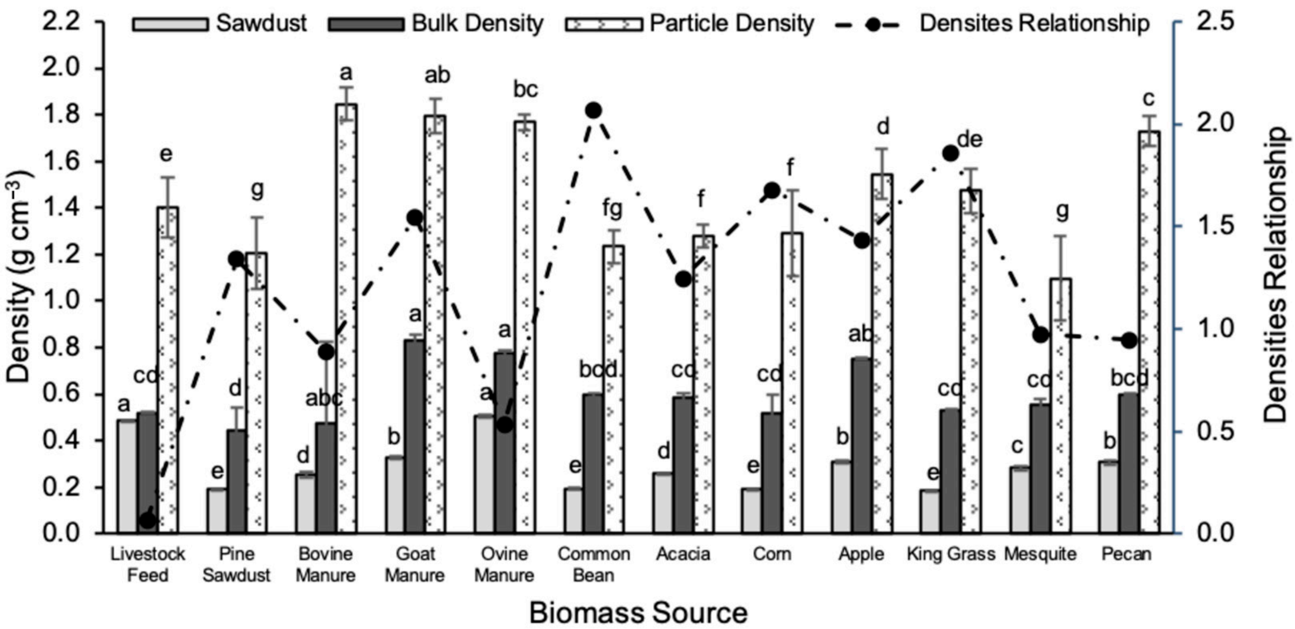

Figure 2. Densification variables assessed in organic materials collected in México and pellets. Different letters between columns indicate that they are statistically different ($p \leq 0.05$). (Change letter type in the Graphic).

3.2.2. Pellets

The bulk density of the pellets showed highly significant statistical differences ($p \leq 0.01$) among organic materials (Table 3). Caprine (goat) manure pellets (0.83 g cm^{-3}) showed the highest bulk density, resulting statistically similar to ovine manure pellets (0.78 g cm^{-3}) and apple tree residues (0.75 g cm^{-3}). This group was superior to the rest of the materials evaluated in the present study. Pine pellets (0.45 g cm^{-3}) had the lowest density values, as well as those made with bovine manure (0.48 g cm^{-3}) (Figure 2). The bulk density of pellets from some species, such as king grass and pine, was lower than previously recorded values (0.67–0.69 g cm^{-3}) [15].

Table 3. Results of the normality test, analysis of variance, and goodness-of-fit test for the evaluated variables in organic materials and pellets.

Variables	Kolmogorov-Smirnov		ANOVA		Kruskal-Wallis Test	
	Statistic	[1] p	Statistic	p	Chi-Square	p
Biomass density	0.178	0.181	689.5	0.01 **	-	-
Pellets particle density	0.119	0.002	-	-	196.2	0.01 **
Pellets bulk density	0.211	0.082	12.92	0.01 **	-	-
Pellets hardness	0.33	0.001	-	-	32.0	0.01 **

** Highly significant ($p \leq 0.01$), [1] p = probability.

Bovine, caprine, and ovine manure pellets exhibited the highest particle density, with levels between 1.76 and 1.84 g cm^{-3}. On the other hand, significantly lower values were found in mesquite (1.09 g cm^{-3}) and pine pellets (1.20 g cm^{-3}). Lower particle density is due to the use of biomass from branches and secondary twigs in the case of mesquite and sawdust from multiple pine individuals, as well as the inclusion of bark remnants showing low density. Lignification, fiber breakdown, bark, tracheid, and vessel elements reduced the wood densification capacity in mesquite and pine. In previous studies, the density of organic materials from different plant species decreased as the vessel diameter and cell wall thickness were modified [16].

The relationship between the bulk density of pellets (PBD) and the original biomass (OBD) was also highly variable among the materials analyzed. The highest value for this relationship was observed in common bean (2.07), king grass (1.87), and corn (1.68). In contrast, livestock feed (0.06) and bovine manure (0.53) showed the lowest (PBD/OBD) density relationship. Biomass with the highest relationship also had a higher level of densification, primarily due to the anatomy of the vascular tissue, which has been linked to plant physiology and the natural density of biomass [16].

3.3. Quality

3.3.1. Pellets

Highly significant statistical differences ($p \leq 0.01$) were registered among the materials for pellet hardness (Table 3). Only three species showed levels close to the optimum established for pellet hardness, with those made from apple sawdust having the highest value (97.9%), although it was statistically equal to corn stalks (97.2%) and ovine manure (96.6%) (Figure 3). Despite this, only apple sawdust pellets exceeded the threshold of 97.8%, which is considered optimal (A1) for energy pellets by the ENPlus certification scheme. Other materials, such as corn, common bean, and bovine manure, produced pellets with acceptable hardness in the 96.0 to 97.1% range.

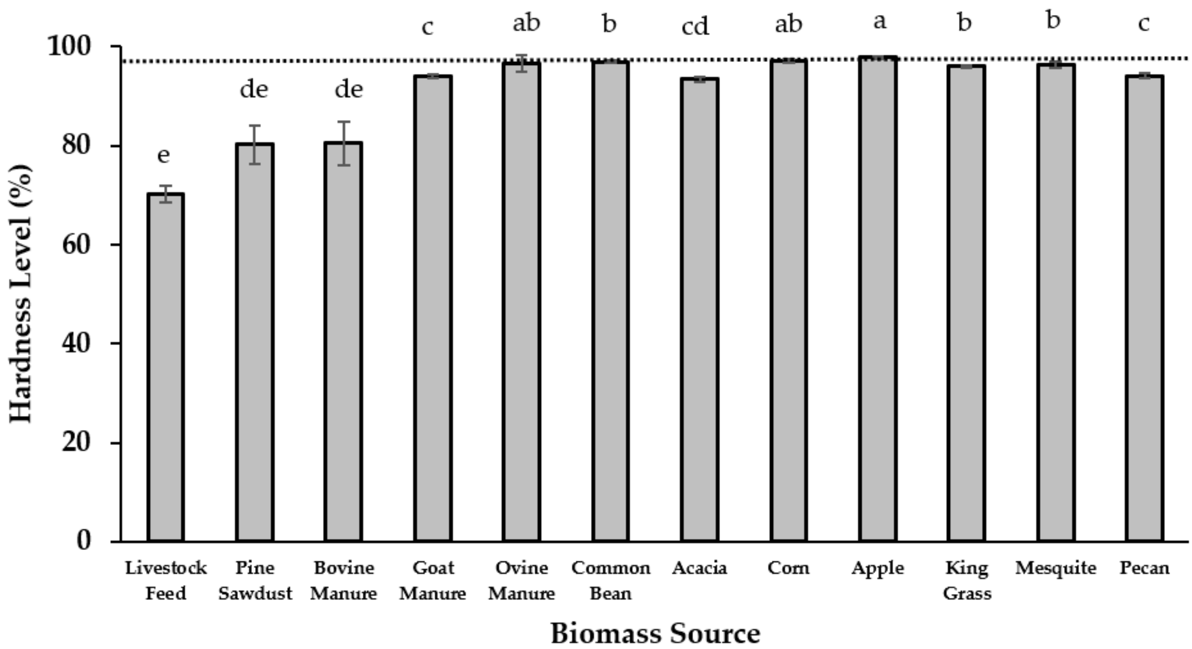

Figure 3. Hardness of pellets made from organic materials collected in México. The dashed line indicates the optimal value established for energy pellets by ENPlus. Different letters indicate statistically significant differences (Tukey's test, $p \leq 0.05$) between pellets.

Pellets made from livestock feed exhibited the lowest hardness levels (70.3%), also registering the lowest density relationship compared to the original biomass; these attributes are related to its composition and conditioning for pellet production. Additionally, these pellets are primarily intended for use in livestock feed, although the values were lower than those shown in previous studies, where one method showed values between 89.7 and 95.3%. However, the alternative method (Holmen) showed lower values (51.0 to 78.0%). These studies demonstrated that pellet size and the site of their manufacture on the pelletizer's disc (plate) significantly influence hardness. On the other hand, using molasses as an additive (agglutinant) improves durability without increasing pellet hardness [17]. Most of the pellets obtained in this study showed friability values like those reported previously, ranging from 80 to 90% [10].

In some cases, it is possible to use agglutinants and a mixture of different types of biomass and particle sizes to increase pellet hardness, although this could affect its nutritional quality and its energetic value in the case of bioenergy pellets. This aspect represents a significant challenge in pellet production, as it seeks to balance the necessary hardness for handling and consumption and preserve its nutritional value as food, especially in the case of animal feed.

3.3.2. Briquettes

Particle density in the briquettes showed highly significant differences ($p \leq 0.01$) among the evaluated materials (Table 4). Bovine manure showed the highest density (1.25 g cm^{-3}), although it was statistically equal to livestock feed (1.25 g cm^{-3}) and mesquite biomass (1.18 g cm^{-3}). King grass biomass showed low effects during briquette production, resulting in the lowest density briquettes (1.00 g cm^{-3}) (Figure 4). This value was higher than that observed in other grasses, where bulk density values of briquettes ranged from 407 to 501 kg m^{-3} [18], i.e., 0.407 to 0.501 g cm^{-3}. There is potential to increase the briquettes' densities, obtained from the different materials included in the study, by improving the available information on biomass properties, conditioning requirements and operational adjustment of the equipment for process optimization.

Table 4. Results of the normality test, analysis of variance, and goodness-of-fit test for variables evaluated in briquettes and original biomass collected in México.

Variables	Kolmogorov-Smirnov		ANOVA		Kruskal-Wallis Test	
	Statistic	[1] p	Statistic	p	Chi-Square	p
Particle density	0.095	0.65	25–37	0.01 **	-	-
Hardness	0.287	0.01	-	-	31.721	0.01 **

** Highly significant ($p \leq 0.01$), [1] p = probability.

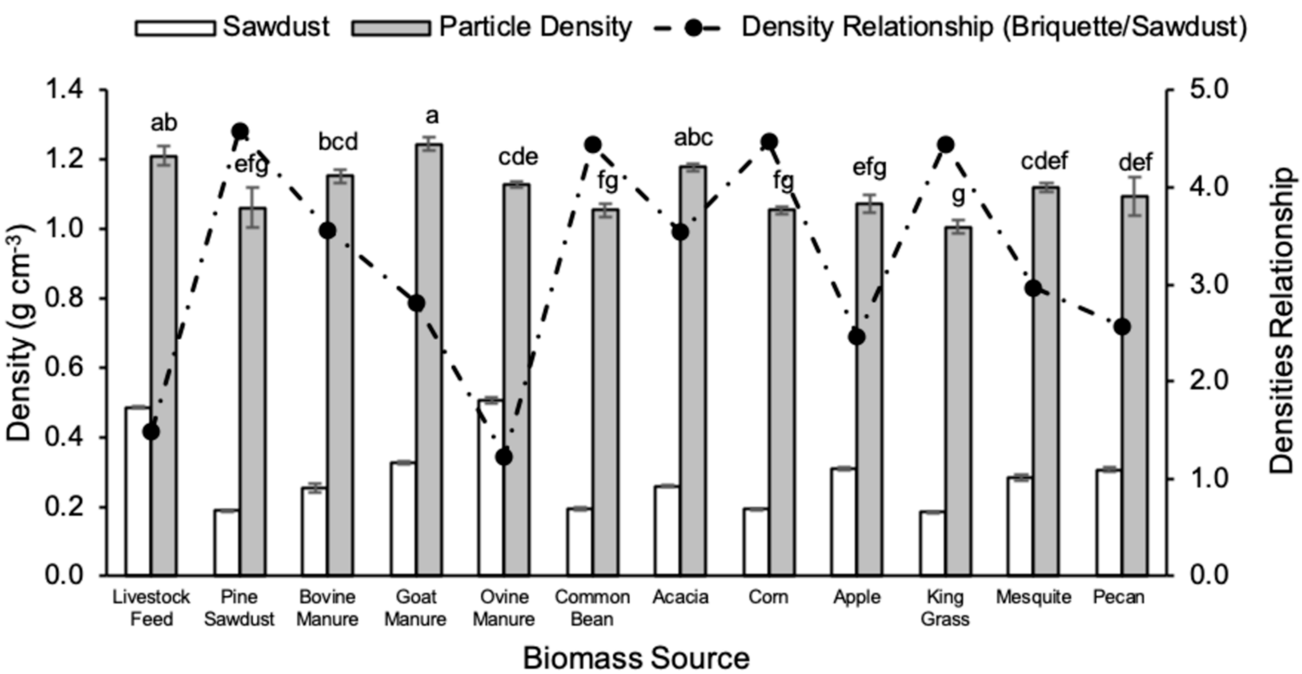

Figure 4. The density of briquettes compared to the original biomass and the ratio of briquette density to particle/original material density in organic materials collected in México. Different letters between columns indicate that they are statistically different ($p \leq 0.05$). (Change letter type in the Graphic, both axis).

The briquette bulk density/original biomass bulk density ratio (BBD/OBBD) was also different, with the residues showing higher values being pine dust (4.6), corn (4.5), common bean (4.4), and king grass (4.4). Biomass showing lower BBD/OBBD ratio were ovine manure (1.2) and cattle feed (1.5). The density ratio tended to increase as the bulk density of the original biomass decreased. Some organic materials, such as pine sawdust, corn, common bean, and king grass, increased their bulk density by more than 3.4 times and reduced their volume by more than 60% when briquettes were produced.

3.4. Hardness

The hardness of the briquettes showed significant ($p \leq 0.05$) differences among the biomass sources evaluated (Table 4). Briquettes made from caprine manure and mesquite had higher hardness levels, both with 99.1% of the requirement established for this type of product on EN 14961-2, 2012 [19]. Other organic materials that resulted in briquettes with high levels of hardness were mesquite (98.1%), bovine manure (97.1%), and ovine manure (96.9%). Pecan and apple tree biomass generated briquettes with acceptable hardness in the 95.7% to 97.1% range. On the contrary, briquettes made from livestock feed exhibited the lowest hardness level, reaching a percentage of 45.6% compared to the recommended level. Lower briquette hardness reinforces the need to include additives, such as molasses, in this helpful input for animal feeding to achieve greater cohesion between particles (Figure 5).

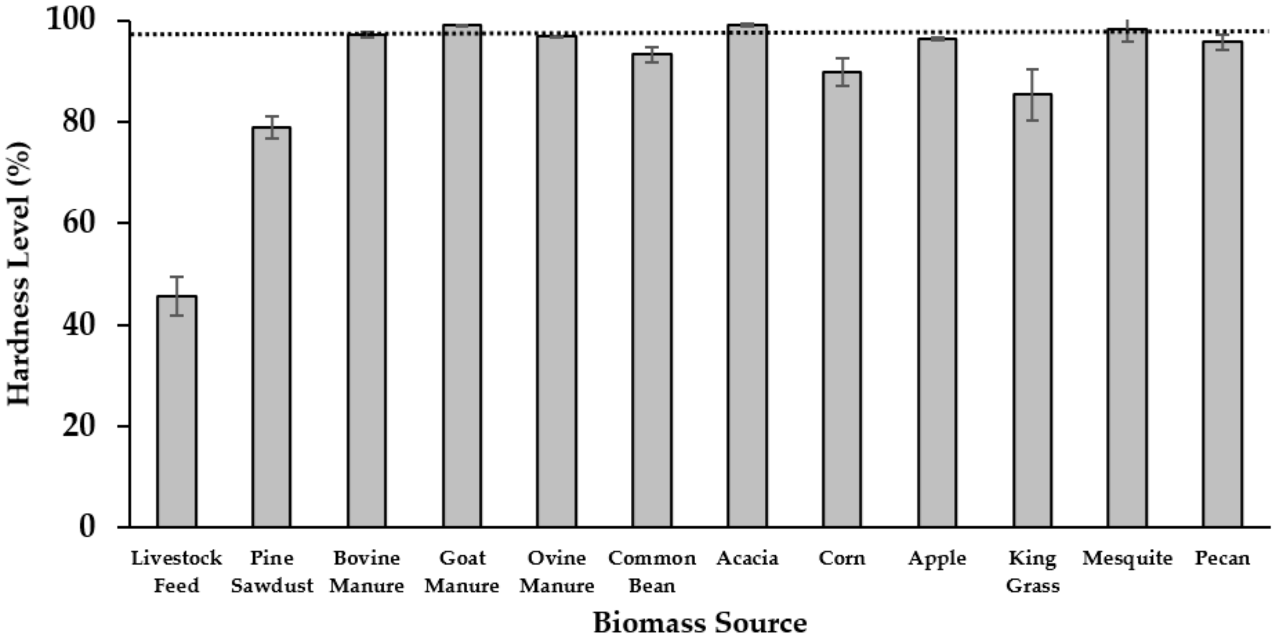

Figure 5. Hardness of briquettes made from organic materials collected in México. The dashed line indicates the value of the established optimum (97%) for briquettes used in energy generation by ENPlus.

The particle density with pellets increased from 65% in concentrated feed to 88% in the case of king grass (Figure 6). In the production of briquettes, values ranged from 55% with bovine manure to 82% when king grass was used. This increase in particle density supports the reduction in the volume of organic waste to facilitate its handling and storage.

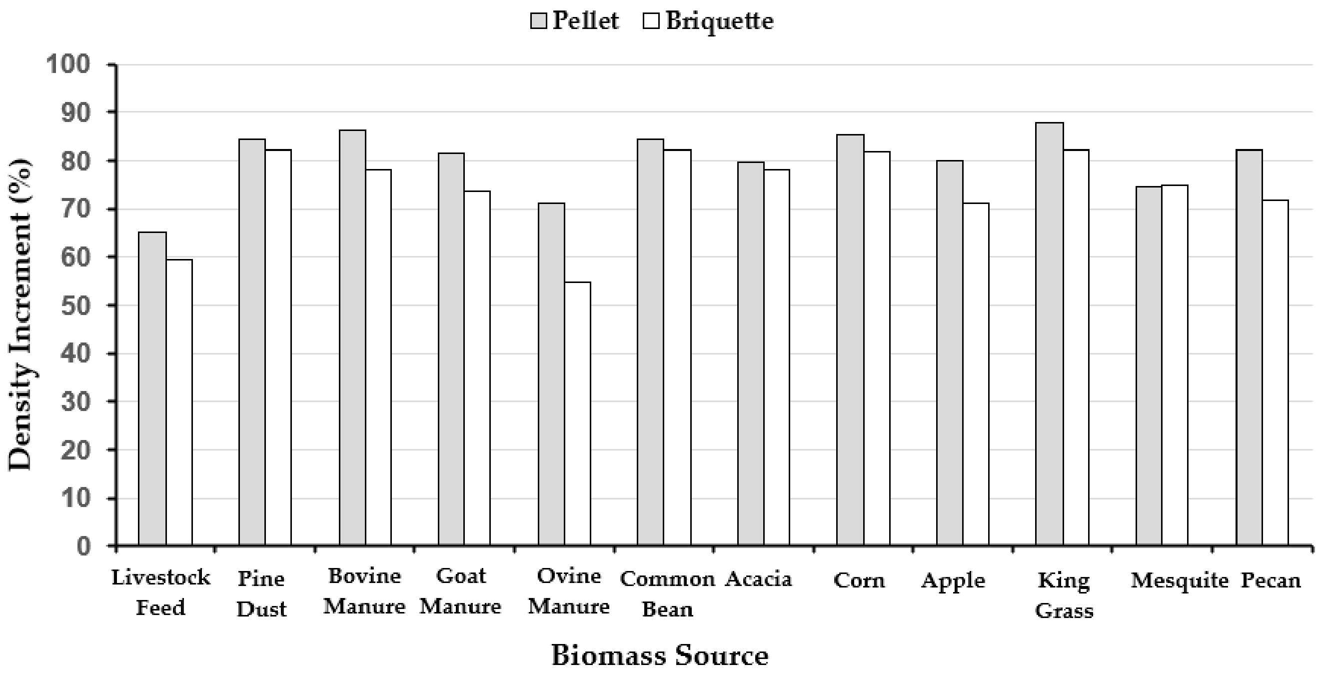

Figure 6. Increase in density due to the effect of two densification treatments of the original biomass of organic materials collected in México. (Change the letter type in the Graphic, Y axis).

3.5. The Influence of Densification Degree on the Practical Application

Densification showed significant increases between 65% and 88% in pellet density and between 55% and 82% in briquette production compared to the original biomass. The foregoing would imply the optimization of resources, which can translate into greater efficiency in storage, improved logistics, and reduced costs associated with the transportation of these materials. Densification not only promises higher profitability for those involved in the production and marketing of densified biomass, but also suggests environmental benefits since densification facilitates the integration of biomass into economic activities.

4. Conclusions

Considerable variation was observed among the evaluated biomass sources in the original material and during its use in pellet and briquette production. All materials were characterized as a mixture of particles with different sizes and densities. Densification was higher in materials with low-density levels in the original biomass. Densification levels increased between 65% and 88% in the case of pellets, while briquette production increased between 55% and 82%, compared to the original biomass. Densification is a process that facilitates the storage, transport, and use of different organic materials useful for various economic activities. In México, the densification of biomass could be promoted by collaborating with community members through various activities, such as educational programs, events, workshops, and demonstrations. Additionally, diverse communication channels, including social media and radio programs, could be utilized to explain the environmental benefits of biomass densification in a clear and accessible manner.

Author Contributions: Conceptualization, R.R.-S., A.C.-P. and D.R.-J.; Formal analysis, D.R.-J., D.S.-Z., R.J.-O. and C.A.N.-B.; Funding acquisition, S.S.-E. and R.J.-O.; Methodology, A.C.-P.; Project administration, C.A.N.-B.; Resources, P.A.D.-M.; Software, D.R.-J.; Supervision, R.R.-S. and J.C.R.-S.; Validation, J.C.R.-S., D.S.-Z. and S.S.-E.; Visualization, R.R.-S. and P.A.D.-M.; Writing—original draft, R.R.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All the data generated and analyzed during the present study were included in this published article. Data sharing is not applicable to the article.

Acknowledgments: The authors gratefully the infrastructure, equipment and support provided by INIFAP, ISIMA-UJED and UPIDET (Unidad de Posgrado, Investigación y Desarrollo Tecnológico) -ITD.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Serna, R.R.; Saucedo, J.C.R.; Parra, A.C.; Ocampo, R.J.; Espinoza, S.S.; Zurita, D.S. Balance Preliminar Fuente/Demanda de Biomasa Para Diferentes Usos En El Norte de México. In *Optimización de los Procesos de Extracción de Biomasa Sólida Para uso Energético*; Cuadernos de la Red IBEROMASA: Valencia, Spain, 2022; pp. 125–152.
2. Reyes, R.C.M.; Rosales, S.R.; Rosales, A.S.B.; Ríos, S.J.C.; Ortíz, S.I.A.; Santana, E.S.; Domínguez, M.P.A. Niveles Observados Para La Degradación de Las Propiedades Químicas En Suelos Usados Para La Producción Agrícola. *Agrofaz* **2019**, *1*, 21–31.
3. Moreno, A.O.; Cloutier, A.; Rutiaga, J.G.; Wehenkel, C.; Rosales, S.R.; Rebolledo, P.; Hernández, P.C.E.; Carrillo, P.A. Use of Agave Durangensis Bagasse Fibers in the Production of Wood-Based Medium Density Fiberboard (MDF). *Forests* **2022**, *13*, 271. [CrossRef]
4. Reyes, M.L.; Camacho, V.T.C.; Guevara, H.F. Rastrojos Manejo, Uso y Mercado En El Centro y Sur de México. INIFAP-CIRNOC-C.E. Pabellón. Pabellón de Arteaga, Ags., México. 2013. Available online: https://chapingo.orex.es/cgi-bin/koha/opac-detail.pl?biblionumber=108251 (accessed on 6 March 2024).
5. *UNE-EN 15149-2*; Biocombustibles Sólidos. Determinación de la Distribución de Tamaño de Partícula. Parte 2: Método del Tamiz Vibrante con Abertura de Malla Inferior o Igual a 3,15 mm. Asociación Española de Normalización y Certificación (AENOR): Madrid, Spain, 2010; pp. 1–15.
6. Núñez, R.V.D.; Rosales, S.R.; Prieto, R.J.Á.; Wehenkel, C.; Carrillo, P.A. Improving the Physical, Mechanical and Energetic Properties of Quercus Spp. Wood Pellets by Adding Pine Sawdust. *PeerJ* **2020**, *8*, e9766. [CrossRef]
7. *UNE-EN-15103*; Biocombustibles Sólidos, Determinación de la Densidad a Granel. Asociación Española de Normalización y Certificación (AENOR): Madrid, Spain, 2010; pp. 1–13.
8. Križan, P.; Matú, M.; Šooš, L'.; Beniak, J. Behavior of Beech Sawdust during Densification into a Solid Biofuel. *Energies* **2015**, *8*, 6382–6398. [CrossRef]
9. Rajaseenivasan, T.; Srinivasan, V.; Qadir, G.S.M.; Srithar, K. An Investigation on the Performance of Sawdust Briquette Blending with Neem Powder. *Alex. Eng. J.* **2016**, *55*, 2833–2838. [CrossRef]
10. Buliah, N.; Jamek, S.; Ajit, A.; Abu, R. Production of Dairy Cow Pellets from Pineapple Leaf Waste. *AIP Conf. Proc.* **2019**, *2124*, 020048.
11. *ASTM D440-86*; Standard Test Method of Drop Shatter Test for Coal. ASTM: West Conshohocken, PA, USA, 2002.
12. SAS Institute Inc. *Help for SAS Management Console 9.4*; SAS Institute Inc.: Cary, NC, USA, 2013.
13. Núñez, R.V.D.; Wehenkel, C.; Vega, N.D.J.; García, Q.J.; Carrillo, P.A. The Bioenergetic Potential of Four Oak Species from Northeastern Mexico. *Forests* **2019**, *10*, 869. [CrossRef]
14. Zepeda, C.C.O.; Goche, T.J.R.; Palacios, M.C.; Moreno, A.O.; Núñez, R.V.D.; Heya, M.N.; Carrillo, P.A. Effect of Sawdust Particle Size on Physical, Mechanical, and Energetic Properties of Pinus Durangensis Briquettes. *Appl. Sci.* **2021**, *11*, 3805. [CrossRef]
15. Ríos, S.J.C.; Rosales, S.R.; Jiménez, O.R.; Domínguez, M.P.A.; Carrillo, P.A.; Valenzuela, N.L. Calidad de Pélets a Partir de Biomasa de Ocho Especies Dendroenergéticas de Crecimiento Rápido. *Agrociencia* **2021**, *55*, 557–568. [CrossRef]
16. Echeverría, A.; Petrone, M.E.; Segovia, R.A.; Figueroa, A.V.A.; Olson, M.E. The Vessel Wall Thickness–Vessel Diameter Relationship across Woody Angiosperms. *Am. J. Bot.* **2022**, *109*, 856–873. [CrossRef] [PubMed]
17. Winowiski, T. Measuring the Physical Quality of Pellets. KSU and NCSU. USA. 2005, pp. 1–6. Available online: https://img.feedstrategy.com/files/base/wattglobalmedia/all/document/2019/09/fs.5-20_Measuring_the_physical_quality_of_pellets.pdf (accessed on 6 March 2024).
18. Muntean, I.; Ţîţei, V.; Gudima, A.; Armaş, A.; Gadibadi, M. Biomass quality of some poaceae species and possible use for renewable energy production in Moldova. *Sci. Papers Ser. A Agron.* **2018**, *61*, 497–502.
19. *CEN/TS, 14961*; Solid Biofuels. Fuel Specifications and Classes. Comité Européen de Normalisation (cen). iTeh, Inc.: Brussels, Belgium, 2005.