SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V12I6P103

Volume 12 Issue 6, 21-33, June 2025

Review Article

A Systematic Review of Densified Biofuel Production in Peru: Insights into Briquettes and Pellets

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Received: 06 April 2025 Revised: 08 May 2025 Accepted: 06 June 2025 Published: 30 June 2025

Abstract - *Densified biofuels are increasingly vital for renewable energy systems due to their high energy density and homogeneity. This study presents a systematic review of densified biofuel production in Peru, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. A review of international databases, such as Scopus, and national databases, including RENATI and ALICE, selected 28 scientific publications after a four-stage identification, screening, eligibility, and inclusion process. The results revealed that most studies focused on briquette production and their energy feasibility as replacements for conventional fuels, with woody biomass-based briquettes being the most studied and reporting calorific values ranging from 17.51 to 22.38 MJ/kg. Rice husk-based briquettes were the second most studied, with reported calorific values of 16.78 to 18.92 MJ/kg. Although less frequently studied, pellets exhibited higher calorific values, ranging from 41.79 to 48.26 MJ/kg. In the compaction process, cassava starch was identified as the most used binder, followed by corn starch, while small-scale densification technologies, such as wooden briquette presses and manual screw presses, were commonly employed. While pellets demonstrated superior calorific values compared to most briquettes, making them a more energy-dense option for biofuel applications, their versatility in material combinations and production methods highlights significant potential for further optimization in renewable energy production.*

Keywords - *Biofuels, Densification, Briquette, Pellet, Densified biomass, Biomass.*

1. Introduction

The rising global energy demand increases the use of fossil fuels, which emit large amounts of CO2, causing environmental pollution and climate change [1]. The Sustainable Development Goal (SDG) number seven seeks to provide access to affordable, clean, and reliable energy and double the improvement rate in energy efficiency [2]. Among the available renewable energy sources, biomass energy offers the advantage of maintaining a closed carbon cycle, with no net increase in atmospheric carbon dioxide [3]. This is achieved through replanting operations following each harvest, where new crops absorb the emitted carbon dioxide during their growth cycle.

Biofuels are energy carriers obtained from various biomass sources through mechanical, thermal, or biological conversion processes [4]. Lignocellulosic biomass, encompassing energy crops, woody biomass, agricultural residues, the organic fraction of municipal solid waste, and forest residues, represents abundant sources for solid biofuel production [5]. These solid biofuels can range from unprocessed biomass (e.g., fuelwood) and minimally processed biofuels (e.g., wood chips and sawdust) to densified biofuels (e.g., briquettes and pellets) and thermochemically upgraded biomass (e.g., biochar, torrefied biomass, and torrefied pellets) [6]. Agricultural residues, in particular, offer substantial volumes of biomass with relatively consistent properties. However, their low density often impedes economically viable transport to energy production sites. Consequently, densification processes are an effective pre-treatment to overcome this limitation and facilitate their use as a solid biofuel [7].

Many densification processes have been developed to improve biomass's low bulk density properties, mainly using mechanical processes [8]. Briquetting and pelleting densification techniques are highlighted for the high energy content per unit volume of the obtained solid biofuels, briquettes and pellets. In addition, considering the usually large distance between the production sites and the end use, the high-density solid biofuels significantly improve the logistics and decrease the storage capacity [9]. Briquettes present a higher diameter, 50-100 mm, in contrast to 6-8mm pellets. Also, briquettes are not limited to cylindrical form, as square, rectangular and polygonal briquettes also exist [10].

With enhanced energy density, structural homogeneity, and compatibility with automated boiler systems, pellets and briquettes are widely utilized for residential and industrial heating and electricity generation. Their application as feedstock for heating and power systems also plays a key role in reducing greenhouse gas emissions [11]. Consequently, the production, distribution, and use of densified biofuels have been increasing globally [12].

In certain Latin American countries, densified biofuels remain an emerging market despite significant production potential [13, 14]. A systematic review and exploratory Life Cycle Assessment (LCA) of biomass briquettes and pellets in the region conducted in [15] revealed that most publications originated from Brazil, Colombia, Chile, Mexico, and Costa Rica. The study found pellet production generally exhibits lower environmental impacts than briquettes, with dedicated production systems being more sustainable than multifunctional ones. These findings highlight the potential of densified biofuels to contribute to emission trading systems within and beyond Latin America.

A technical energy potential of 46,000 GWh/year was estimated for Peru's agro-industrial and livestock residual biomass, which could potentially satisfy 88% of the country's electricity demand [16]. This assessment indicated that sugarcane residues, rice straw, and cattle manure represent the largest contributors to this potential. Effectively harnessing this biomass could foster sustainable development through clean energy production and contribute to reductions in CO2 emissions. Similarly, a study evaluated the energy potential of lignocellulosic biomass in Peru as a sustainable alternative to fossil fuels [17]. Their analysis revealed that sugarcane bagasse, wood waste, and coffee husk have the highest calorific values, while wood residues, rice husk, and quinoa stalk are more suitable for bioethanol conversion.

To the authors' knowledge, no previous study has reported on the current state of densified biofuels production in Peru, including the common biomass sources used in their fabrication. Therefore, this study reviews pellet and briquette production and the prevalent biomass sources used. Furthermore, it reports the calorific value of the most produced densified biofuels, alongside the binders employed and the small-scale densification technologies utilized.

2. Methodology

The current review of densified biofuels production in Peru covers English and Spanish studies from 2013 to 2024. The review process follows the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) statement, which was developed to facilitate transparent and complete reporting of systematic reviews [18].

2.1. Identifying the Research Questions

Driven by the growing interest in densified biofuels in Peru and the increasing number of publications on briquettes and pellets, this study addresses the following research questions.

2.1.1. RQ1

What is the current state of pellets and briquettes production in Peru, focusing on production methods and technologies, based on a systematic review of the existing scientific literature?

2.1.2. RQ2

Based on the existing scientific literature in Peru, what are the most promising biomass sources for densified biofuels production, considering factors like calorific value, availability, and suitability for densification?

It is hypothesized that the recent scientific literature will show a significant increase in both pellet and briquette research in Peru.

2.2. Identifying Relevant Studies

This systematic review was based on Scopus, ALICIA, and RENATI data to address the research questions. Scopus is a prominent international database of peer-reviewed scientific literature. For national data, this review utilized two key Peruvian databases: ALICIA, the Peruvian National Digital Repository for Science, Technology, and Innovation, which provides open access to Peru's intellectual heritage; and National Repository for Academic and Professional Degrees and Titles (RENATI), a collector repository that registers research work submitted for academic degrees and professional titles in Peru, including recognized foreign degrees and titles. Together, these platforms ensured comprehensive access to Peruvian scientific advancements and academic contributions.

For this systematic review, searches were performed in all selected databases (Scopus, ALICIA, and RENATI) using the following terms: "briquette", "pellet", "briqueta", "briquetas", and "pellets" to account for variations in English and Spanish. The searches were limited to publications with a geographical focus on Peru and excluded the thematic area and title of Health Sciences. This process yielded a list of documents that were reviewed for further evaluation.

2.3. Selecting Studies

According to the PRISMA guideline, the selection of studies is comprised of four stages: (i) identification, (ii) screening, (iii) eligibility, and (iv) inclusion. The initial searches yielded 389 publications from Scopus, 721 from RENATI, and 777 from ALICIA. These results were then subjected to a title screening process to remove irrelevant documents. Publications with misleading titles (e.g., "food pellet" or "plastic pellet") were excluded.

This process reduced the number of documents to 32 from Scopus, 60 from RENATI, and 50 from ALICIA. After removing duplicate publications, a total of 104 documents remained. Based on abstract, conclusions, and methodological rigor, a final quality assessment further reduced this to 28 selected documents focused on densified biofuel production. This selection process is illustrated in Figure 1.

2.4. Charting the Data

Charting, also called data extraction in systematic reviews, is a method for organizing and synthesizing data by categorizing and sorting information. For this study, the included articles were organized into an Excel sheet containing the following information for each document: authors' information (authors and year), type of densified biofuel (briquette or pellet), dimensions of the densified biofuel, biomass source or raw material, calorific value, moisture content, ash content, densification technology, compaction load, and language (English or Spanish).

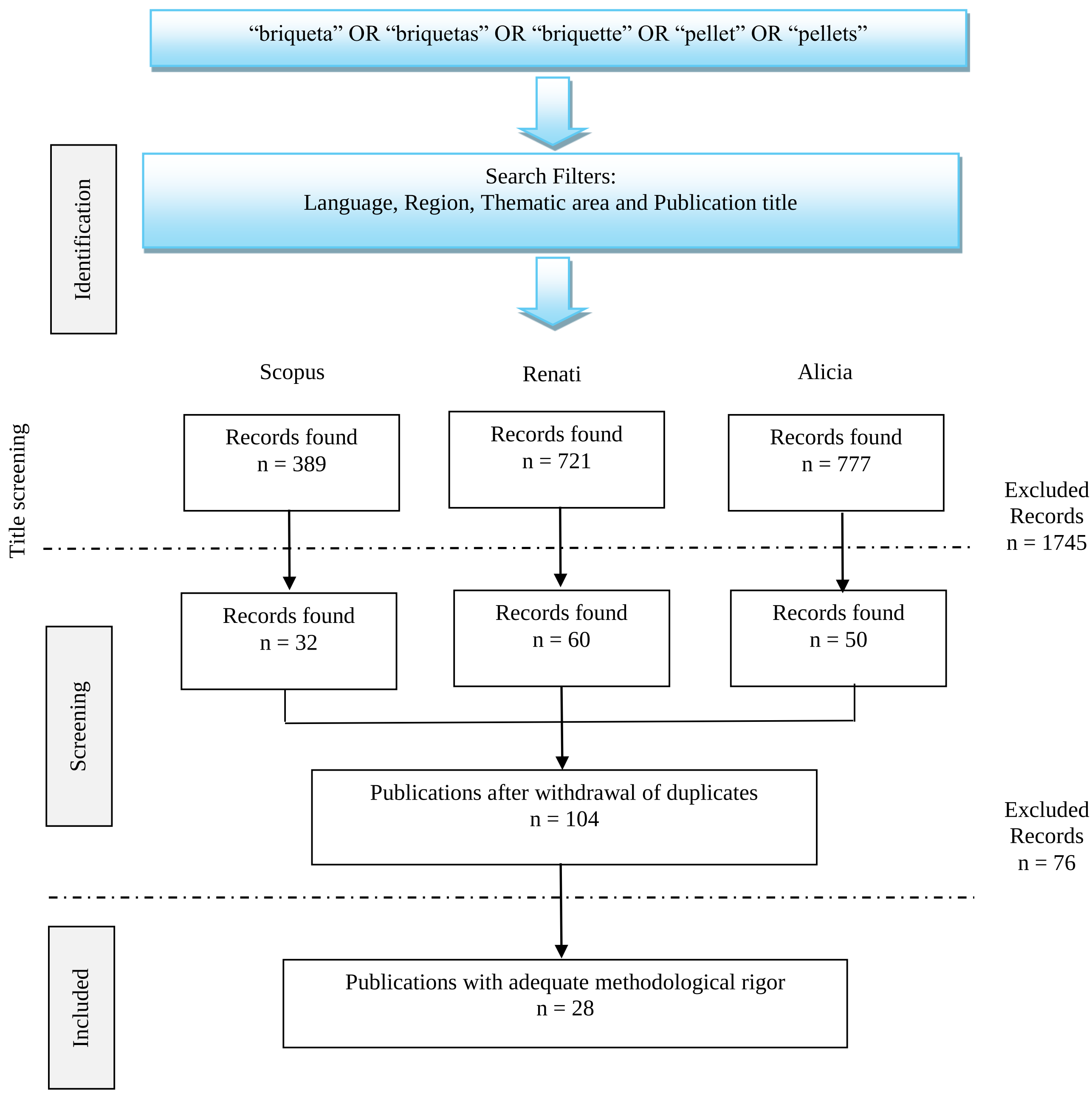

Fig. 1 Flow diagram of research selection

3. Results

Figure 2 illustrates the trends in scientific publications identified in this systematic review. The number of publications increased annually, peaking in 2022. However, the review revealed a clear imbalance in publications: only 3 focused on pellet properties, compared to 25 on briquette properties.

As previously mentioned, using biomass as a solid biofuel requires addressing its low bulk density, typically ranging from 80 to 100 kg/m³ for agricultural residues and 150 to 200 kg/m³ for woody biomass [19]. Consequently, biomass densification into briquettes, pellets, or other forms is essential. The properties and production processes of densified biofuels vary depending on whether the raw biomass is woody or non-woody. This review categorizes the existing literature by presenting studies on woody biomass-based briquettes in section 3.1 and non-woody biomass-based briquettes in section 3.2. Additionally, studies of biochar-based briquettes are summarized in section 3.3, and the limited number of studies on pellets are presented in section 3.4. In section 3.5, the properties of the densified biofuels are summarized. Finally, section 3.6 presents the most common small-scale densification technologies identified in the reviewed literature.

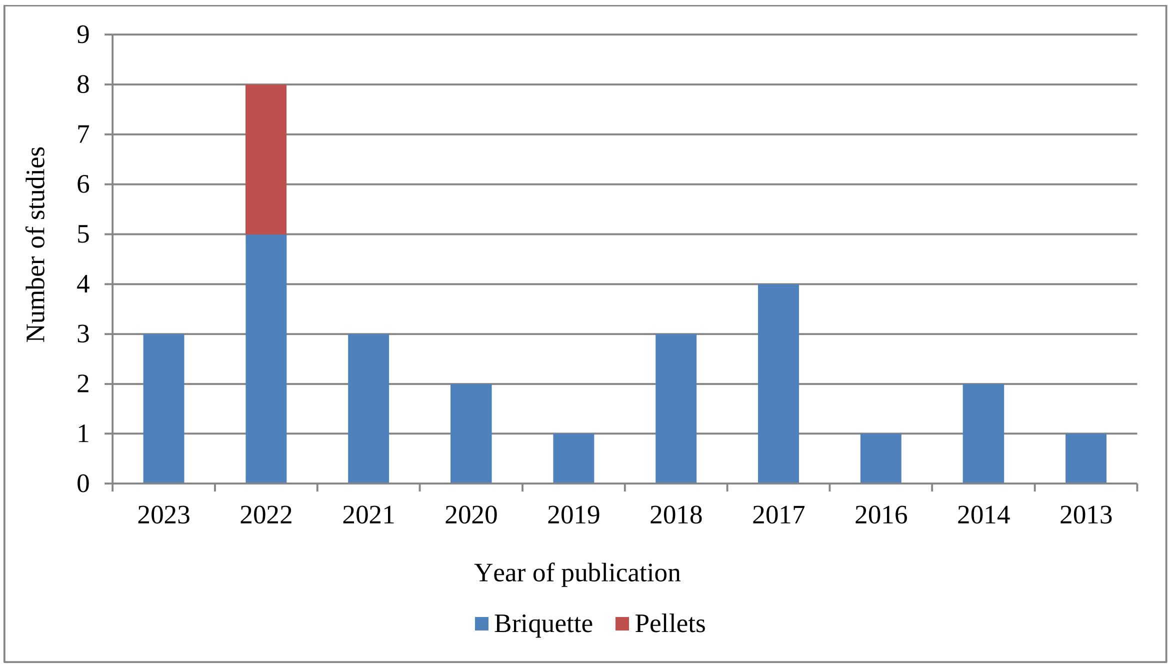

Fig. 2 Trends in scientific publications on densified biofuels in Peru

3.1. Woody Biomass-Based Briquettes

Studies on sawdust briquettes have explored diverse production methods and their impact on the resulting biofuel properties. For instance, Sánchez et al. [20] produced briquettes from Congona *Brosimum uleanum* sawdust using a hydraulic press at 5 MPa, achieving a calorific value of 19.8 MJ/kg, with a 10% moisture content, 1.3% ash content, and dimensions of 6 cm in diameter and 12 cm in length. Similarly, Valerio Requiz [21] with 30% tapioca *Manihot esculenta* starch and compacted at 2400 kg/cm², exhibited a calorific value of 19.38 MJ/kg, an 11.51% moisture content, and dimensions of 3.93 cm in diameter and 6.04 cm in length. These examples highlight the influence of both raw material and processing parameters on briquette characteristics.

Moving beyond pure sawdust, other studies have investigated diverse biomass sources. For example, Barbaran et al. [22] examined briquettes made from the bark of three Amazonian tree species: *Dipteryx micrantha*, *Ceiba pentandra*, and *Manilkara bidentata*. Using a 13.79% by weight tapioca starch binder and a compaction pressure of 1200 kg/cm², the study found species-dependent variations in length (4.5-6.43 cm), density (0.74-1.17 kg/cm³), and moisture content (4-13%). Interestingly, the calorific values of these briquettes were relatively consistent, ranging between 18.24 and 22.38 MJ/kg. Other research indicates that exceptional calorific values, exceeding 45.12 MJ/kg, are achievable with certain unconventional biomass sources. Sam Tuesta [23] reported such values for briquettes produced from *Astrocaryum sp.*, *Mauritia flexuosa*, and *Cocos nucifera*, which were bound with sugarcane molasses, compacted at 3000 kg, and featured moisture contents below 9.62%, ash contents below 16.34%, and a particle size of 1 mm.

In addition to raw material, other aspects, such as binder type and compaction parameters, also play a role. Ramos Chavez [24] presented ecological briquettes comprising 75% wood and 25% cardboard residues, bound with clay and compacted at 62.48 kg/cm² into rectangular prisms, demonstrating optimal friability for efficient combustion. These briquettes achieved calorific values between 16.74 MJ/kg and 17.99 MJ/kg, low ash content, and minimal moisture after sun-drying. Similarly, Choquecota Mendoza [25] produced pine sawdust briquettes bound with clay from the Quilca River and compacted at low pressure (up to 5 MPa), which achieved a density of 596 kg/m³, a calorific value of 17.77 MJ/kg, 9.2% moisture, and 14.8% ash content.

Finally, the use of binder-free techniques is also relevant. Huanca Ríos [26] produced briquettes from Cumala *Virola sp.* and Marupa *Simarouba amara* sawdust and chips using a compaction pressure of 1200 kg/cm², achieving a calorific value of 17.51 MJ/kg, with a diameter of 93 mm, a length of 150 mm, an 11.75% moisture content, and 1.63% ash content. Table 1 summarizes the properties of woody biomass-based briquettes.

Table 1. Summary of analyzed literature for woody-based briquette production

Main raw material	Binder	Calorific value (MJ/kg)	Moisture content	Ash content	Diameter and length (mm)	Densification technology	Compaction load (tonnes)	Source
Brosimum uleanum Mildbe	-	19.8	10%	1.3%	60 × 120	Hydraulic press	1.44	[20]
Ceiba pentrada	Manihot esculenta starch	19.38	11.51%	N/A	39.3 × 60.4	Hydraulic press	29.14	[21]
Dipteryx micrantha	Manihot esculenta starch	22.38	4%	N/A	32 × 45	Hydraulic press	9.65	[22]
Astrocaryum sp, Mauritia flexuosa and Cocos nucifera	Sugarcane molasses	45.12	9.62%	16.34%	N/A	-	3	[23]
Simarouba amara and Virola sebifera Aubl.	-	17.51	11.75%	1.63%	93 × 150	Piston press briquetting machine	81.55	[26]
Pinus Caribaea	Clay	17.77	9.2%	14.8%	-	-	-	[25]

3.2. Non-Woody Biomass-Based Briquettes

3.2.1. Rice Husk

Rice husk briquettes with a calorific value of 16.90 MJ/kg were produced using compaction and drying. These briquettes contained 80% rice husk and 20% cassava starch binder, with a humidity range of 8% to 10%, a 1000 kg/m³ density, and variable sizes depending on their intended use [27]. Briquettes made from sawdust, rice husk, and organic waste exhibit a calorific value of 16.78 MJ/kg with 8.5% moisture content, compacted using a 4-ton hydraulic press and bound with cassava starch [28]. Fuel briquettes made from 80% rice husk and 20% carob gum/resin binder exhibited a calorific value of 18.92 MJ/Kg, a moisture content of 5.32%, and an ash content of 12.28% [29].

3.2.2. Sugarcane Biomass

Composite briquettes combining wood dust and sugarcane bagasse were developed using a viscous binder paste and compacted with a mold or mechanical compactor. These briquettes achieved a calorific value of 19.69 MJ/kg and a moisture content of 9% [30]. Sugarcane leaves were processed to obtain a cylindrical briquette of 35.6 mm in diameter, 37.3 mm in height and a calorific value of 16.59 MJ/kg, using 75% (dry weight) sugarcane leaves, 15% clay, 10% corn starch, and 60% water (wet weight), compacted at 150 bar [31].

3.2.3. Olive Residues

Briquettes made from 10% olive pomace, 82% olive tree pruning, and 8% starch binder achieved a calorific value of 23.89 MJ/kg, a maximum ash content of 30%, and a moisture content of 2.5%. These were produced using low-pressure compaction with a bottle jack, resulting in briquettes measuring 5 cm high and 10 cm in diameter [32]. Similarly, olive residue briquettes (pomace, pit, and pruning) with corn starch binder, compacted using a bottle jack, had a calorific value of 24.18 MJ/kg with 9.45–10.79% moisture and 1.50–1.99% ash content, while oregano residue briquettes with corn starch binder, compacted similarly, had a calorific value of 7.34 MJ/kg [33].

3.2.4. Cacao Biomass

Optimal briquettes made from cacao, coffee, or wheat shells, bound with molasses and potato peels under a 2-ton compaction force, achieved calorific values of 41.46 MJ/kg, 41.47 MJ/kg, and 41.54 MJ/kg, respectively [34]. Cacao pod husk briquettes, bound with molasses and potato starch (21:8:8 ratio), were compacted using a hydraulic press at 2 ton for 2 minutes, yielding products with varying dimensions, a moisture content of 13.29%, ash content of 8.10%, and a calorific value of 35.54 MJ/kg [35].

3.2.5. Corn Stover

Corn stover, which includes stalks, leaves, cobs, and husks, is commonly collected as low-bulk-density bales. To enhance consistency and usability, it is often converted into densified products such as pellets, briquettes, and cubes, usually achieving a bulk density of 450–750 kg/m^3 [36]

Trapezoidal briquettes with a central hole, measuring 8 cm × 8 cm × 10 cm, have been produced from a mixture of corn husk, barley straw, sawdust, and recycled paper. These briquettes, bound with corn starch, potato starch, aloe vera gel, or a combination of these, were compacted using a c-type screw clamp. The resulting products had moisture content ranging from 9.91% to 13.38% and ash content between 9.23% and 11.51% [37]. Corncob briquettes, with an external diameter of 12 cm, an internal diameter of 2 cm, and a height of 5.5 cm, were produced using coconut oil as a binder and dried for four days. These briquettes exhibited a moisture content of 0.93%, an ash content of 5.82%, a density of 838 kg/m^3, and an ignition temperature of 103.67 °C [38].

3.2.6. Other Biomass Sources

Research has explored a variety of unconventional biomass sources for briquette production, demonstrating diverse properties and potential. Sánchez and Torpoco [39] produced cylindrical briquettes composed of 90% coffee husks and 10% cassava starch binder, measuring 6.5 cm in diameter and 7.3 cm in length. These briquettes, produced at a densification pressure of 44.96 PSI, achieved a calorific value of 19.80 MJ/kg, with 11.01% moisture content and 0.50% ash content. Similarly, Lukuy et al. [40] reported briquettes made from avocado pits, sawdust, and cassava starch as a binder, which had a calorific value of 13.36 MJ/kg, an 8.75% moisture content, and a 1.5% ash content. These studies highlight the potential of agricultural byproducts and residues.

Other studies have focused on unique biomass blends. Leon and Villareal [41] characterized highly efficient fuel briquettes from a 25%/75% blend of *Inga feuilleei* and pecan shells, achieving a calorific value of 33 MJ/kg, a low moisture content of 2.31%, and a low ash content of 2.01%. These briquettes also exhibited a high thermal efficiency of 26.68% and a burn time of 30 minutes. In another study, Palo Tejada et al. [42] produced briquettes from a mix of 80% alpaca manure, 18% *ichu* (a type of grass), and 2% lime. Bound with water and compacted into cylindrical molds (8 cm diameter, 7.5 cm height, and 2 cm internal radius), these briquettes reached a calorific value of 18.1 MJ/kg and a 9.9% moisture content after sun drying for six days. These studies demonstrate the viability of using combined biomass for enhanced fuel characteristics.

Fuel briquettes were also produced from household organic waste and recycled newspaper using a horizontal screw press. These briquettes measured 18.65 cm in length, weighed 825 g, had a volume of 16.49 cm^3, and a diameter of 10.65 cm, with a moisture content of 31.25%. However, their calorific value was not reported [43]. Table 2 summarizes the properties of the non-woody biomass-based briquettes. The table includes only data from cylindrical briquettes, allowing for comparison of similar properties.

3.3. Biochar Briquettes

Biochar, a solid product derived from thermochemical conversion processes like pyrolysis, exhibits physical and chemical properties akin to coal, positioning it as a potentially viable alternative to fossil fuels on an industrial scale [44]. Given its potential as a fuel, previous studies have explored biochar as a component in briquette production. For example, Rivas Curisinche et al. [45] produced coffee husk biochar briquettes containing 50\% biochar using a hydraulic press at 44.96 PSI, with cassava starch as a binder. These briquettes achieved a calorific value of 17.26 MJ/kg, with a moisture content of 12.5\% and a low ash content of 2.08\%. Similarly, cylindrical briquettes (5.5 cm in diameter and 3 cm in height) made from household organic waste biochar, bound with cassava starch in a 4:1 ratio, and compacted using a mechanical press demonstrated a higher calorific value of 19.87 MJ/kg, a density of 1400 kg/m^3. They produced 200 g/kg of ash during combustion [46].

3.4. Pellets

A few studies have explored the production of pellets from different biomass sources, highlighting different material combinations and performance characteristics. Melgarejo et al. [47] manufactured pellets using raw material residual biomass from harvesting broad bean *Vicia faba* and pea *Pisum sativum*, with starch from cassava and pecan *Carya illinoinensis* as binders. Their findings revealed that pellets made from broad bean residues and cassava starch exhibited the highest calorific value, at 48.26 MJ/kg, while those made from pea residues and pecan seeds demonstrated the highest compressive strength, at 0.17 kg/cm^2.

Other studies have investigated more specific biomass sources for pellet production. For instance, Barroso León et al. [48] produced pecan shell pellets with a diameter of 15 mm and lengths between 6 and 10 cm. These pellets, made using a particle size greater than 3 mm with a particle binder less than 3 mm, exhibited a calorific value of 41.79 MJ/kg, a moisture content of 51.92%, and an ash content of 2.9%. Furthermore, Santos Mudarra [49] produced pellets from castor bean residues with a moisture content of 10.05%, achieving a calorific value of 16.5 MJ/kg, a density of 1133.062 kg/m³, and a friability index of 0.96. These pellets were compacted at a pressure of 147.10 MPa. Table 3 summarizes the properties of the reported pellet production.

Table 2. Summary of analyzed literature for non-woody based briquette production

Main raw material	Binder	Calorific value (MJ/kg)	Moisture content	Ash content	Diameter and length (mm)	Densification technology	Compaction load (tonnes)	Source
Persea americana pit	Manihot esculenta starch	13.35	8.75%	1.5%	50 × 70	Single-lever briquette press	-	[40]
Oryza sativa	Manihot esculenta starch	16.90	8%	-	50 × 75	-	-	[27]
Oryza sativa	Manihot esculenta starch	16.78	8.5%	0.6%	N/A	Hydraulic press	4	[28]
Coffea arabica	Manihot esculenta starch	19.8	11.01%	0.5%	65 × 73	Hydraulic press	0.105	[39]
Coffea arabica	Manihot esculenta starch	17.26	12.5%	2.08%	65 × 46	Hydraulic press	0.105	[45]
Household organic waste	Manihot esculenta starch	19.87	12%	-	55 × 30	Manual screw press	-	[46]
Saccharum officinarum	N/A	19.69	9%	-	-	-	-	[30]
Saccharum officinarum	Zea mays Starch and clay	16.59	-	-	35.6 × 37.7	Hydraulic press	1.52	[31]
Carya illinoinensis	Zea mays starch	33	2.31%	2.01%	-	Hydraulic press	-	[41]
Olea europaea	N/A	23.89	2.5%	30%	100 × 50	Peterson briquette press	-	[32]
Olea europaea	Zea mays starch	24.18	10.79%	1.99%	-	Peterson briquette press	-	[33]
Theobroma cacao	Solanum tuberosum peel and molasses	41.46	-	7.2%	-	-	2	[34]
Theobroma cacao	Solanum tuberosum starch and molasses	35.54	13.29%	8.10%	-	Hydraulic press	2	[35]
Oryza sativa	Locust bean gum	18.92	5.32%	12.28%	-	-	-	[29]

Table 3. Summary of analyzed literature for pellet production

Main raw material	Binder	Calorific value (MJ/kg)	Moisture content	Ash content	Diameter and length (mm)	Densification technology	Compaction load (tonnes)	Source
Vicia faba	Manihot esculenta starch	48.26	9.40%	1.3%	7.5 × 50	N/A	2	[47]
Carya illinoinensis	Fine particles of Carya illinoinensis shell (<3 mm)	41.79	51.92%	2.9%	15 × 60 - 100	N/A	1	[48]
Ricinus communis	N/A	16.5	10.05%	N/A	12.3 × 7.12	Manual screw press	1.7	[49]

3.5. Densified Biofuel Properties

Figure 3 presents the frequency of raw biomass sources used in densified biofuel research in Peru, as identified through this systematic review.

The analysis reveals that woody biomass is the most frequently studied source, followed by rice (Oryza sativa) rice residues, sugarcane Saccharum officinarum, household organic waste, coffee Coffea arabica, cacao (Theobroma cacao), pecan (Carya illinoinensis), and olive (Olea europaea). Other biomass sources, including Chenopodium quinoa residues, alpaca manure, corn stover, castor bean (Ricinus communis) residues, broad bean (Vicia faba) residues, and avocado pit (Persea americana), were less frequently investigated.

The high frequency of studies focused on woody biomass reflects its relative availability and suitability for briquette production. The reviewed literature highlights the use of diverse wood species, including Congona (Brosimum uleanum), Ceiba (Ceiba pentandra), Cumala (Virola sp.), Marupa (Simarouba amara), and pine (Pinus Caribaea), as well as the bark of Dipteryx micrantha, Ceiba pentandra, and Manilkara bidentata. As shown in Table 1, woody biomass briquettes have been extensively studied under varying production conditions and different densification technologies. They include diverse binder sources but typically show values between 16 and 20 MJ/kg. Using a wide range of wood species further underscores the potential of woody biomass as a promising and available resource for densified biofuel production in Peru.

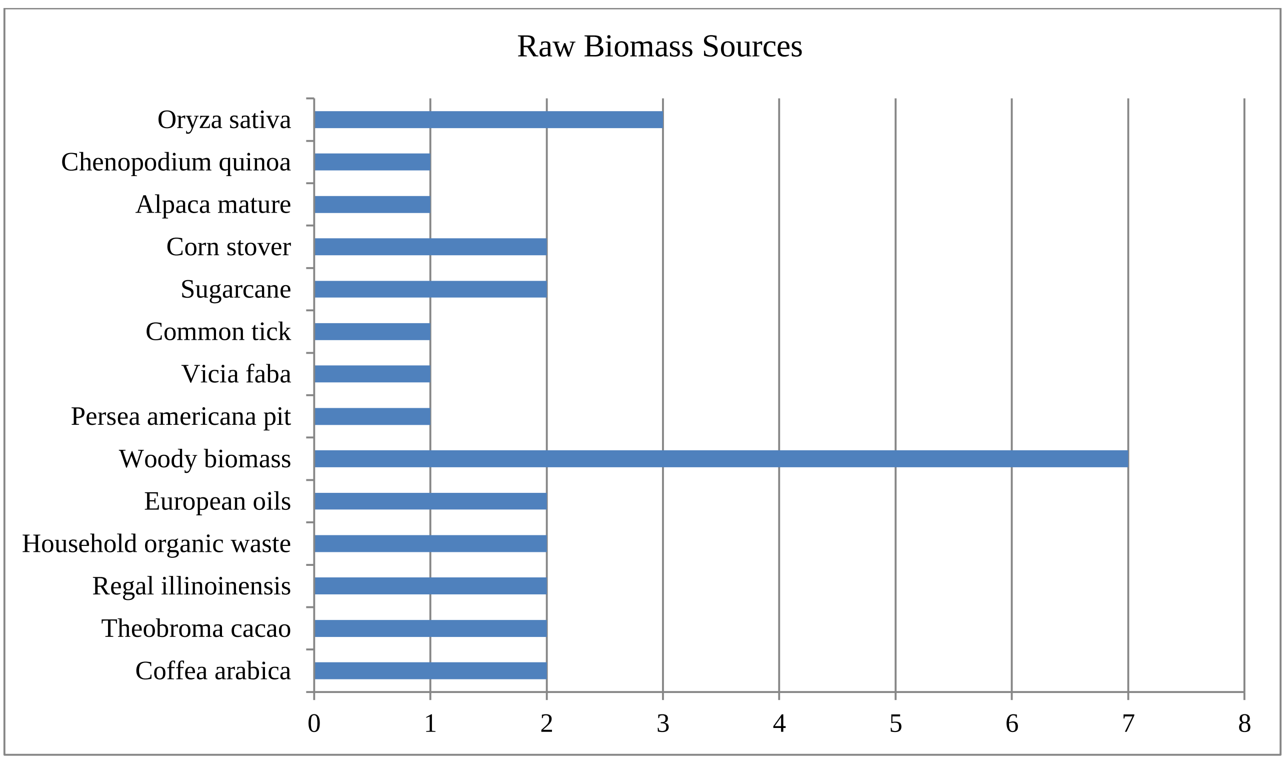

Fig. 3 Most common raw biomass sources in Peru according to the revised literature

Figure 4 illustrates the calorific value (MJ/kg) of various densified biofuels, including woody biomass briquettes, rice husk briquettes, cacao biomass briquettes, other biomass briquettes and pellets, based on the conducted systematic review.

Woody biomass briquettes consistently exhibit high calorific values, with several studies reporting values above 19 MJ/kg. For example, Sánchez et al. (2014) [20] reported a calorific value of 19.8 MJ/kg for Congona (*Brosimum uleanum*) sawdust briquettes produced using a hydraulic press at 5 MPa. Similarly, Valerio Requiz (2021) [21] found a calorific value of 19.38 MJ/kg for *Ceiba pentandra* sawdust briquettes. Furthermore, exceptional calorific values exceeding 45.12 MJ/kg have been documented for briquettes from unconventional woody biomass sources. Sam Tuesta (2020) [23] reported such values for briquettes made from *Astrocaryum sp.*, *Mauritia flexuosa*, and *Cocos nucifera*.

While less frequently studied, pellets display significant calorific values depending on the raw materials and production methods. Melgarejo et al. (2022) [47] manufactured pellets using residual biomass from the harvesting of broad bean (*Vicia faba*) and pea (*Pisum sativum*), with cassava starch and pecan (*Carya illinoinensis*) as binders. Their results revealed that pellets from broad bean residues and cassava starch achieved the highest calorific value, at 48.26 MJ/kg. Additionally, Barroso León et al. (2022) [48] produced pecan shell pellets with a calorific value of 41.79 MJ/kg. Santos Mudarra (2022) [49] reported a calorific value of 16.5 MJ/kg for castor bean residue pellets.

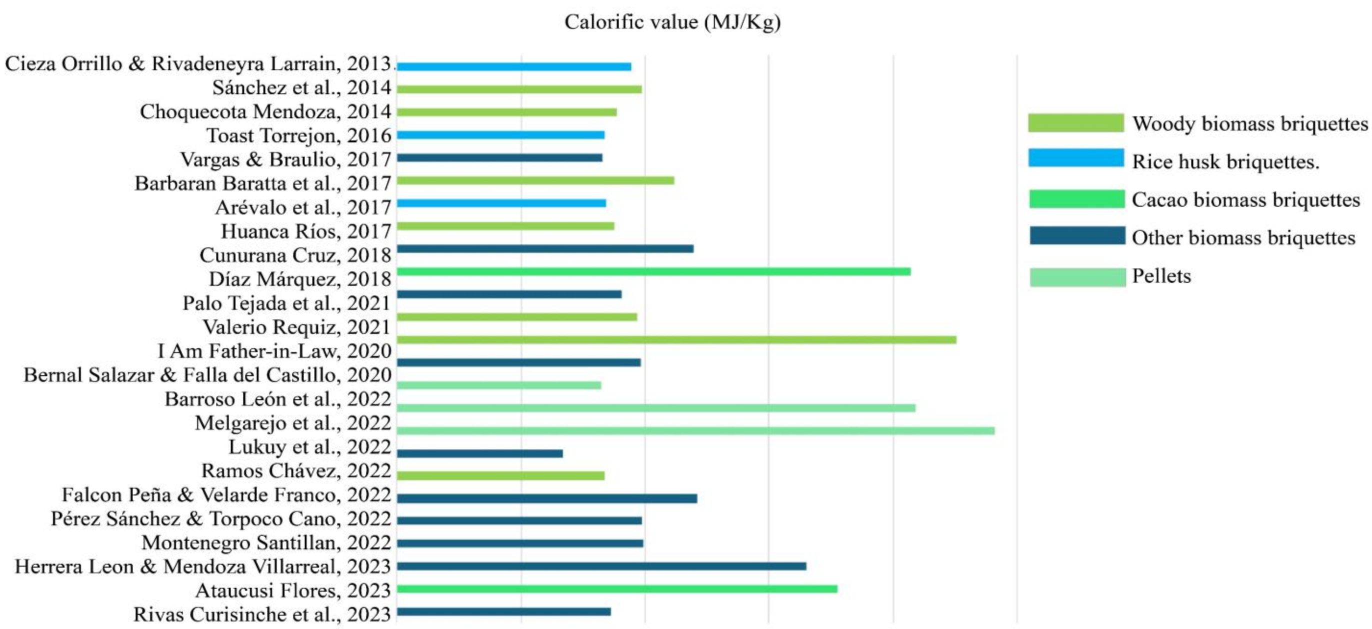

Fig. 4 Reported ranges of the calorific value for different types of densified biofuels in the reviewed literature

3.6. Small-Scale Densification Technologies

3.6.1. Single-Lever Briquette Press

Given the substantial investment and energy demands of high-pressure briquetting presses, low-pressure alternatives, such as manual, single-lever wooden presses operating at pressures below 5 MPa, present a more economically and energetically feasible option [50].

Lukuy et al. [40] developed a wooden briquette press featuring a pusher lever, a vertical rail, and a support platform Figure 5(a). Their design shares similarities with the single-lever press described in [51], which includes a wooden frame, pusher lever, vertical rails, a removal jig, a plunger, and a tilted support platform to facilitate water drainage Figure 5(b). Both designs utilize PVC for the mold, mold base plate, and drainage tube, incorporating holes for water removal.

(a) (b)

Fig. 5 Single-lever briquette press. (a) Designed by Lukuy et al. [40], and (b) Design featuring an inclined support platform [51].

3.6.2. Peterson Briquette Press

A Peterson briquette press typically consists of an entirely wooden frame [52] or metallic sheets combined with a wood frame [53], a bottle jack, and a draining system. For instance, Cunurana Cruz [32] developed a Peterson press with a wood frame to produce briquettes from olive biomass. Similarly, a Peterson press was used in another study to create briquettes from olive biomass [33]. Figure 6(a) illustrates a Peterson briquette press with an entirely wooden frame, while Figure 6(b) shows the same press during the briquetting process.

(a) (b)

Fig. 6 Peterson briquette press, (a) Peterson press structure [52], and (b) Peterson press briquetting process.

3.6.3. Manual Screw Press

A manual screw press consists of a lead screw, a press head mounted on a metallic frame, and a mold [54]. This manual crew press has been used to fabricate biochar briquettes in [46], as shown in Figure 7(a), and for pelleting of castor bean biomass [49], as shown in Figure 7(b).

(a) (b)

Fig. 7 Manual screw press, (a) Briquetting of biochar [46], and (b) Pelleting of castor bean biomass [49].

4. Discussions

The increasing production and use of densified biofuels in Latin America offer a significant opportunity to support and expand Emission Trading Schemes (ETS) and energy decarbonization programs. An ETS is a cap-and-trade, market-based approach designed to internalize the social cost of carbon [55]. While several nations are progressing-Mexico launched a pilot ETS in 2020, and Chile and Colombia are developing national schemes [15] - Peru lacks specific policies for densified biofuels. Although Peru has a general framework like the Law for the Promotion of the Biofuels Market (Law N° 28054), it has primarily focused on liquid biofuels and has not effectively incentivized the production and use of solid densified forms. This policy gap is notable, given that the country's significant biomass potential aligns with regional efforts towards sustainable energy and CO_2 emission reductions [16, 17].

This study highlights unique opportunities and challenges for Peru in the bioenergy sector. Unlike Brazil's mature, industrial-scale biofuel industries (focused on sugarcane ethanol) and Argentina's (soy-based biodiesel), Peru's sector is nascent and characterized by small-scale, decentralized production. The key opportunity lies in leveraging its abundant and diverse agricultural and forestry residues (e.g., from coffee husks, sugarcane bagasse, and sustainable Amazonian wood waste), which could foster rural development and energy independence. However, unique challenges persist, including logistical complexities in transporting biomass from remote Andean or Amazonian regions, the high degree of informality in the agricultural sector, and the need for technological solutions adapted to local conditions rather than imported industrial models.

A critical aspect for the sustainable development of this sector is its environmental impact. Densified biofuels are often considered carbon-neutral, as the CO_2 released during combustion is theoretically offset by the carbon sequestered during biomass growth. However, a comprehensive environmental assessment must also consider potential negative impacts, such as emissions from processing and transportation, unsustainable water use, and the risk of indirect land-use change or biodiversity loss if dedicated energy crops displace food crops or natural ecosystems. The fact that regional research has predominantly focused on thermo-mechanical properties [15], a trend confirmed by our review's findings on calorific value, moisture, and ash content, underscores a critical research gap. Future studies must therefore prioritize Life Cycle Assessments (LCA) to quantify the net environmental footprint of Peruvian biofuels. Furthermore, we suggest further research into the socio-economic impacts on rural communities, the optimization of supply chains across Peru's complex geography, and techno-economic analyses to assess the feasibility of scaling up production.

The conclusions of this study should be interpreted in light of its limitations, which affect the generalizability of the findings. First, the review is geographically constrained to publications on Peru. Second, the analysis is based on a relatively small corpus of 28 articles, which may not fully capture the diversity of regional activities or emerging trends despite a rigorous selection process. Finally, our finding that small-scale densification technologies (e.g., wooden briquette and manual screw presses) were commonly employed in Peru highlights accessible production methods. However, it restricts the applicability of our conclusions to the larger, industrial-scale operations everyday in more developed bioenergy sectors. These limitations highlight the need for more extensive and diverse research to build a robust evidence base for policymaking in Peru.

5. Conclusion

This systematic review explored the landscape of densified biofuel production in Peru, encompassing a bibliometric analysis and a sustainability assessment of pellets and briquettes. The review of publications from 2013 to 2023 revealed an increasing research trend in this field. While most studies focused on the production and energy feasibility of briquettes, particularly those made with woody biomass, a notable lack of research was observed regarding the production of pellets.

Among the different types of briquettes, woody biomass-based briquettes were the most extensively studied, achieving calorific values ranging from 17.51 to 22.38 MJ/kg. Commonly utilized woody species included *Brosimum uleanum Mildbe.*, *Ceiba pentandra*, *Dipteryx micrantha*, *Simarouba amara*, *Virola sebifera Aubl.*, and *Pinus caribaea*. However, briquettes derived from unconventional biomass sources, such *as Astrocaryum sp.*, *Mauritia flexuosa*, and *Cocos nucifera*, achieved an exceptional calorific value of 45.12 MJ/kg. Rice husk was the second most studied material for briquettes, with reported calorific values from 16.78 to 18.92 MJ/kg. Although less frequently studied, pellets exhibited the highest calorific values of all the densified biofuels analyzed in this review. Specifically, Vicia faba and Carya illinoinensis pellets reached 48.26 MJ/kg and 41.79 MJ/kg, respectively.

The review of production methods revealed that cassava starch and corn starch are the most common binders, while manual screw presses were frequently used for both briquette and pellet production. The reported compaction load varied widely depending on the fuel type and biomass sources: ranging from 1 to 2 tonnes for pellets; from 1.44 to 81.55 tonnes for woody biomass-based briquettes; and from 0.105 to 4 tonnes for non-woody biomass-based briquettes.

While pellets exhibit superior calorific values compared to most briquettes, indicating a greater energy density, the diversity in materials and production methods observed for briquettes suggests a significant potential for further optimization. In contrast, more research on pellets is urgently needed. This study identified the main production characteristics and gaps in the knowledge of densified biofuels in Peru.

Acknowledgments

The authors would like to thank Continental University for its valuable support in promoting scientific development in the country, contributing to progress toward the Fourth Industrial Revolution.

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