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Review

Insights into Properties of Biomass Energy Pellets Made from Mixtures of Woody and Non-Woody Biomass: A Meta-Analysis

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Abstract: There is a widespread global shift toward renewable energy sources, where the emphasis is on enhancing the utilization of renewable energy due to the rising costs associated with fossil fuels. In this light, biomass pellets made from woody and non-woody biomass and blends have gained increased attention. Extensive research has been conducted globally to enhance the quality of biomass pellets and to explore the potential to combine woody biomass with other non-woody forms of biomass in biomass pellet production. The heterogeneity of the raw materials used and resulting properties of the biomass pellets have led to the establishment of internationally recognized benchmarks such as the International Organization for Standardization (ISO) 17225 standard to regulate pellet quality. In this article, the key mechanical, physical, chemical, and energy properties of pellets made of different non-woody herbaceous biomass are investigated, and the available test values for such properties of the pellets were meta-analyzed. A comparison of the properties of these pellets with the relevant standards was also performed. A meta-analysis of studies on biomass pellet production was conducted via a comprehensive Systematic Literature Review (SLR). The SLR focuses on determining and analyzing the average values for the key physical properties of biomass pellets using woody biomass as a component in concert with other biomass materials. In addition, the optimal range of mixtures of woody and non-woody biomass was reviewed to produce biomass pellets with potential acceptance in the marketplace. The majority of studies included in the SLR concentrate on pellets made from a mixture of biomass materials. The results show that the average values for wood/non-wood mixtures such as pellet diameter, pellet length, moisture content, ash content, fine particle content, gross calorific value, and bulk density were found to adhere to the ISO standards. However, the average mechanical durability fell short of meeting the requirements of the standards. Additional comparisons were nitrogen, sulfur, volatile matter, and fixed carbon content. The findings in this meta-analysis could be useful in directing future research focused on producing high-quality and efficient biomass pellets derived from biomass blends and mixtures.

Keywords: pellets; mixed biomass; standards; moisture; density; durability; calorific value

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1. Introduction

1.1. Biomass as a Renewable Energy Source

The adoption of renewable energy sources is rapidly gaining momentum worldwide due to the growing global demand for energy [1–3]. There is a significant decrease in global concern about and dependency on fossil fuel energy sources, attributed to various factors such as fluctuations in energy demand, oil price shocks, disruptions in energy supply chains, hampered energy investments, energy price hikes, and energy security challenges [4,5]. Moreover, the urgency to address climate change and pursue low-carbon energy transitions has become a top priority in the energy sector [6]. Consequently, numerous countries have implemented policies to integrate environmentally friendly energy sources into their energy portfolios [7]. Notably, in October 2023, the European Union officially approved an updated Renewable Energy Directive aimed at increasing the share of renewable energy in Europe from 32% to 42.5% by 2030, with the ultimate goal of achieving a 45% share of renewables [8]. While specific targets for individual countries have not been established, each Member State will contribute to this collective objective. Concurrently, renewable resources such as solar, wind, geothermal, biogas, and biomass are gaining substantial recognition as viable options for sustainable and eco-friendly energy [9].

Within this realm of renewable energy, biomass has emerged as a pivotal contender over the last few decades. Its ascendancy is attributed to its renewable nature, environmental cleanliness, robust technical viability, economic feasibility, and widespread availability [10–14]. Moreover, biomass holds a distinct appeal as a renewable reservoir readily transformable into three distinct fuel states—gas, liquid, and solid [15–21].

Wood possesses the distinct advantage of negligible sulfur content, distinct from coal and liquid fuels, thus mitigating the emission of sulfur dioxide into the atmosphere [22]. Recent scientific inquiries have substantiated biomass as a key energy source with the potential to supplant fossil fuels [23]. Within this context, biomass emerges as a promising remedy to the challenges posed by fossil fuels, including coal and liquid fossil fuels, which are implicated in critical environmental concerns such as climate change, global warming, and their deleterious impact on human well-being [24]. Biomass is important in addressing such predicaments associated with fossil fuels [25].

According to the Statistical Report of Bioenergy Landscape 2020 [26], biomass-derived energy holds the second position in global bioenergy consumption, following nuclear energy, with a substantial market share of 63.11% (123,592 kilotons of oil equivalent (ktoe)), followed by hydro energy at 16.46% (32,242 ktoe) and wind energy at 11.11% (21,768 ktoe) [27,28].

The importance of bioenergy reaches far beyond developed nations and plays a pivotal role in developing nations. Recent studies have shed light on its impressive ability to deliver energy in various forms that cater to people's needs, encompassing liquid and gaseous fuels, heat, and electricity. Therefore, bioenergy plays a significant role in reducing poverty in developing countries while simultaneously tackling the restoration of unproductive and degraded lands [29,30]. This restoration process yields multiple benefits, such as increased biodiversity, enhanced soil fertility, and improved water retention [31–33]. Bioenergy remains the primary source of energy in several countries and regions, including Bhutan (86%), Nepal (97%), Asia (16%), East Sahelian Africa (81%), and Africa (39%). In these areas, bioenergy is predominantly utilized for cooking and heating purposes, wherein firewood serves as the main source [31,34]. Particularly, Southeast Asia is rapidly emerging as a vibrant market for the development of biomass as an energy source [35]. Notably, countries such as Malaysia, Thailand, and Indonesia, known for their significant agricultural residues comprising rice, sugarcane, palm oil, coconut, and rubber, are among the foremost producers. Noteworthy crop residues include rice husk, sugarcane bagasse, oil palm residues, and wood residues [36]. The trajectory of bioenergy is witnessing novel trends and growing markets across the globe, with projections indicating that bioenergy will meet 30% of the world's energy demand by 2050 [37,38].

While various forms of biomass, including wood, energy crops, agricultural residues, industrial wastes, and municipal solid waste, are available [39], the utilization of raw biomass is accompanied by certain inefficiencies. Factors such as irregular shapes, low bulk density, and elevated moisture content contribute to challenges in handling, transportation, and storage [40–47]. To tackle these issues, intensive research and implementation of biomass conversion technologies have transpired over the past decade [48–52].

Densification of biomass has emerged as a prominent conversion technology, achievable using distinct processes: pelletization, briquetting, extrusion, and tumbling [53]. This introduction of densification technologies has paved the way for the energy market entry of densified biomass products such as chipped wood, wooden pellets, and biomass briquettes. Moreover, the research underscores the consistent global consumption of firewood and charcoal, along with a twofold increase in the use of wood chips and wood pellets for power generation and residential heating over the past decade. This upward trajectory is projected to persist in years to come [12,13,37,54–56].

1.2. Biomass Pellet Market Dynamics

Biomass pellets, whether with or without additives, are compacted milled biomass typically cylindrical in shape, spanning 5 to 40 mm in standard market length [57]. The surging popularity of wood pellets in heating markets has triggered novel market dynamics and supply chains. Building and industrial heating and cooling in the European Union constitute 50% of its annual energy consumption [58], with 80% of central heating systems in Germany adopting biomass combustion technologies [59]. Similarly, growing demand for wood pellets as a heat source are observed in both the European Union and Asian countries [60].

In the Asia Pacific region, boasting 76% of the global coal generation capacity and 94% of the new coal plant pipeline [61], wood pellets are positioned as potential coal replacements in power generation. Via processes like torrefaction, hydrothermal carbonization, and steam explosion, wood pellets have gained thermal enhancements to mimic coal properties, advancing their suitability as a fuel [12,62–64]. Given the high concentration of coal power plants in the Asia Pacific region, their adoption of biomass pellets has risen, leading to exponential growth in wood pellet imports to South Korea, Japan, and China in recent years. Notably, South Korea's imports surged to 2.4 million tons in 2017, a 20-fold increase from 2012 [65]. Similarly, Japan's 2017 imports exceeded 0.5 million tons, marking a sevenfold rise since 2012 [65,66]. China, with its large population and energy source constraints, has established a substantial potential market. Though ample literature is lacking to substantiate the attainment of the 15-million-kilowatt goal set in its 2016 five-year plan, China stands as the primary producer of bioelectricity, witnessing a 4.5-fold rise in production since 2011 [67].

Approximately half of global pellet consumption serves power generation plants that have transitioned from coal to pellets or engage in co-firing with coal. The other half is predominantly allocated to household heat generation via pellet stoves, boilers, and for industrial steam demand [68–72]. Amidst this landscape, firewood, paraffin, electricity, liquid gas, and natural gas stand as principal competitors to wood pellets in energy generation. However, only firewood surpasses pellets economically; other energy sources falter in terms of toxic emissions, expensive handling, storage, and transportation when compared to biomass pellets [73].

Numerous sustainable indicators and multi-criteria decision analysis research conducted in Germany underscore wood pellets' superior quality and efficiency for private households compared to alternative biomass-to-energy pathways [59,74,75]. The low density of unprocessed biomass such as wood chips (180–220 kg/m^3) poses significant handling and transport challenges, unlike pellets, which offer higher density (around 600 kg/m^3) and energy content per unit volume, thereby reducing costs in transportation, storage, handling, and use [68,76]. Unlike raw biomass, biomass pellets align more closely with liquid fuels in terms of their properties [73,76].

1.3. Quality Assurance of Biomass Pellets

Biomass pellets must adhere to standardized properties to optimize their utility. Designing boilers, stoves, or pellet burners aligned with these properties ensures effective deployment, catering to diverse scales of demand, from domestic appliances to large-scale power plants [68]. The primary parameters within pellet standards encompass physical attributes such as dimensions, mechanical durability, fine particle content, bulk and unit densities, additives, chemical composition, including sulfur, nitrogen, chlorine, and heavy metals, and energy properties such as moisture and ash content, net calorific value, and energy density [41,77]. These parameters are tied to raw materials, quality management, and manufacturing processes [78].

During 2000–2006, the European Committee for Standardization (CEN) under committee TC 335 established general technical specifications (TS) and testing methods for solid biofuels, culminating in the prEN14961 series by 2014 [79,80]. To align standards globally due to escalating biomass energy production and trade, these specifications transitioned to the International Organization for Standardization (ISO) via the Technical Committee: ISO TC 238 of Solid Biofuels [81]. The ISO released the EN ISO 17225 series in 2014 (ISO 17225-2:2014 [82], ISO 17225-6:2014 [83]), encompassing standards for wood pellets, chips, firewood, and non-woody briquettes, replacing EN 14961 [81,84].

EN ISO 17225-2 [82] for graded wood pellets sets limits for various applications, while EN ISO 17225-6 [83] focuses on non-woody pellets, including blends and mixtures (Table 1). Both standards underwent minor updates in 2020 republished in 2021 [85,86]. Graded wood pellets encompass property classes A1, A2, A3, I1, I2, and I3, with distinct quality characteristics for different applications [85]. Non-woody pellets, derived from diverse biomasses, bear higher ash, chlorine, nitrogen, and sulfur contents, warranting tailored combustion systems and corrosion mitigation due to their unique characteristics [84].

Table 1. Specification of graded woody and non-woody pellets.

Parameter	Unit	EN ISO 17225-2						EN ISO 17225-6	
Utility	-	Commercial and Residential Applications			Industrial Use			Industrial Use	
		A1	A2	A3	I1	I2	I3	A	B
Diameter (D)	Mm	6 ± 1	6 ± 1	6 ± 1	6 ± 1	6 ± 1	6 ± 1	6–25	6–25
Length (L)	Mm	$3.15 \leq L \leq 40$	$3.15 \leq L \leq 40$	$3.15 \leq L \leq 40$	$3.15 \leq L \leq 40$	$3.15 \leq L \leq 40$	$3.15 \leq L \leq 40$	$3.15 \leq L \leq 40$	$3.15 \leq L \leq 40$
Moisture content (MC)	%	≤10	≤10	≤10	≤10	≤10	≤10	≤12	≤15
Ash content (A)	%	≤0.7	≤1.2	≤2	≤1	≤1.5	≤3	≤6	≤10
Mechanical durability (Du)	%	≥98	≥97.5	≥96.5	$97.5 \leq Du \leq 99.0$	$97.0 \leq Du \leq 99.0$	$96.5 \leq Du \leq 99.0$	≥97.5	≥96
Fines (F)	%	≤1	≤1	≤1	≤4	≤5	≤6	≤2	≤3
Net calorific value (NCV)	MJ/kg	≥16.5	≥16.5	≥16.5	≥16.5	≥16.5	≥16.5	≥14.5	≥14.5
Bulk density (BD)	kg/m^3	$600 \leq BD \leq 750$	$600 \leq BD \leq 750$	$600 \leq BD \leq 750$	600≤	600≤	600≤	600≤	600≤
N	%	≤0.3	≤0.5	≤1	≤0.3	≤0.3	≤0.6	≤1.5	≤2.0
S	%	≤0.04	≤0.04	≤0.05	≤0.05	≤0.05	≤0.05	≤0.2	≤0.3
Cl	%	≤0.02	≤0.02	≤0.03	≤0.03	≤0.05	≤0.1	≤0.1	≤0.3
As	mg/kg	≤1	≤1	≤1	≤2	≤2	≤2	≤1	-
Cd	mg/kg	≤0.5	≤0.5	≤0.5	≤1	≤1	≤1	≤0.5	-
Cr	mg/kg	≤10	≤10	≤10	≤15	≤15	≤15	≤50	-
Cu	mg/kg	≤10	≤10	≤10	≤20	≤20	≤20	≤20	-
Pb	mg/kg	≤10	≤10	≤10	≤10	≤10	≤10	≤10	-
Hg	mg/kg	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	-
Ni	mg/kg	≤10	≤10	≤10	≤10	≤10	≤10	≤10	-

In this article, the key mechanical, physical, chemical, and energy properties of pellets made of different non-woody herbaceous biomass are investigated, and the available test values for such properties of the pellets are meta-analyzed. A comparison of the properties of these pellets with the relevant standards is also performed.

This study aims to conduct a comprehensive analysis of recent studies that have been conducted on pellets produced from various non-woody herbaceous biomass sources. The research will include a thorough comparison of the finest pellets from the reviewed studies against globally recognized standards. Furthermore, this investigation will seek to identify the most suitable types of biomass for efficient pellet production. By examining the quality differentiation associated with different biomass types and blending ratios, this study will provide valuable insights into the optimal combination of biomass materials for pellet production. In addition to that, this review aims to discuss the permissible limits or property ranges of the different standards that align with the desired pellet characteristics. This will enable the identification of biomass-bended pellet compositions that are compatible or incompatible with the specified quality standards. Following these objectives, this study seeks to contribute to the advancement of knowledge in the field of non-woody herbaceous biomass pellet production and guide industry professionals in making informed decisions regarding biomass selection and blending ratios to achieve high-quality pellet products.

2. Materials and Methods

2.1. Systematic Literature Review

The bibliographical search employed Boolean operators and a symbolic logic system developed around conceptual relationships and core keywords relevant to the study. This systematic approach allows for a comprehensive analysis of pertinent studies within a subject area. This methodology has been widely used in various scientific domains for presenting research data and conducting reviews [87–89]. Searches were conducted across the Scopus, Google Scholar, and DOAJ databases, utilizing a Boolean equation developed from keywords and phrases identified during preliminary literature surveys prior to the SLR. Publications spanning 2000 to 2021 within the "Biomass and Bioenergy" domain were considered and only English-language publications were included for analysis.

2.2. Data Extraction

Data extraction was performed with adherence to a standardized protocol within the framework of the SLR. After the selection of the studies, they were listed according to the title, author(s), and the published year. To manage, annotate, and categorize the findings, Zotero version 5.0.96.3 was employed, with duplicates excluded based on title and author congruence. Since the test results of the pellet quality parameters needed to be supplemented with standard deviation for use in the meta-analysis, articles without full-paper access were excluded from the final compilation. Subsequently, the refinement of article selection was achieved via meticulous scrutiny of each title and abstract. The exclusion criteria encompassed:

1. Studies published in languages other than English.
2. Investigations centered on biofuel liquid products (e.g., biodiesel, bio-oil).
3. Research focused on solid materials such as soil manure and compost, excluding pellets and briquettes.
4. Research inquiries into activated carbon, biochar, and similar substances.
5. Exploration of biogas production from solid waste materials originating from digestion processes.
6. Analysis of waste incineration practices.

After the exclusions, the final selection of suitable studies for meta-analysis was carried out by reading each study. Important and useful data were listed in a Microsoft Excel spreadsheet for easy reference.

2.3. Statistical Analysis

The meta-analysis was conducted for studies on pellets made from non-woody biomass blends and non-woody/woody biomass blends. In cases where test results for various raw materials and combinations were presented within a single study, the following procedure was adhered to:

- For biomass blended pellets produced using the same raw materials but different combinations, the quality parameters of the most optimal pellet (chosen based on the author's recommendations) were selected for the analysis.
- For blended biomass pellets manufactured using diverse raw materials and combinations, the quality parameters of all pellet types were chosen for analysis.
- For pellets produced using different raw materials but the same combinations, quality parameters of all pellet types were selected for analysis.

Following this, meta-analysis was executed using the statistical software R Studio (Version 2021.09.1+372 "Ghost Orchid" Release for Windows, Mozilla/5.0).

A flowchart of the review process followed in this study is depicted in Figure 1. The initial search yielded 1002 potentially relevant hits. Out of these, 719 studies were excluded during the first round, and an additional 97 articles were removed based on the criteria outlined at the data extraction stage. From the remaining 186 articles concerning biomass pellet production, the final data extraction was performed.

From the 186 selected studies, a set of 19 research studies containing test results for pellet quality parameters was extracted for meta-analysis. Although the remaining 167 studies were excluded from the meta-analysis, they were utilized as literature sources to gather relevant information and factual data for composing the SLR. To conduct the meta-analysis, parameters such as the number of test cycles (n), the mean of the test results (mean), and the standard deviation of the results (SD) were required. Studies lacking n, mean, and SD were excluded from the meta-analysis. The meta-analyzed results were presented in forest plots, and a comparison of each parameter with pellet standards was performed.

Both commercial pelleting machines and single-unit pelletizers [90] have been used to produce the tested pellets and obtain the test results that were meta-analyzed in this article. Although different test methods have been used, the final units of the tested results were consistent with the ISO 17225 standard series. The popular standard methods that have been employed include the International Organization for Standardization (ISO) standards, American Society for Testing and Materials (ASTM) standards, German Institute for Standardization (DIN) standards, European Nations (EN) standards, Brazilian National standards (NBR), the National Renewable Energy Laboratory Standard Scenarios (NREL), and technical specifications like those of the Environmental Protection Agency (EPA) (Table 2).

The properties of the pellets manufactured using 100% non-woody biomass materials and woody and non-woody biomass blends selected were listed to identify the special features and to compare them with ISO 17225-6 standard [83] categories A and B. The structural properties of the pellets such as diameter (D) and length (L); energy properties such as moisture content (MC), ash content (A), gross calorific value (GCV), volatile matter content (VM), and fixed carbon content (FC); mechanical properties such as bulk density (BD), mechanical durability (Du), fine particle content (F), and hardness; and chemical properties like nitrogen (N) and sulfur content (S) were analyzed. The main purpose of this was to identify the unique properties of pellets produced using single biomass and to develop a comparison of these property values with pellets that are manufactured using biomass blends. Some test values without sufficient data on the test method or the process were excluded from the study (chlorine content).

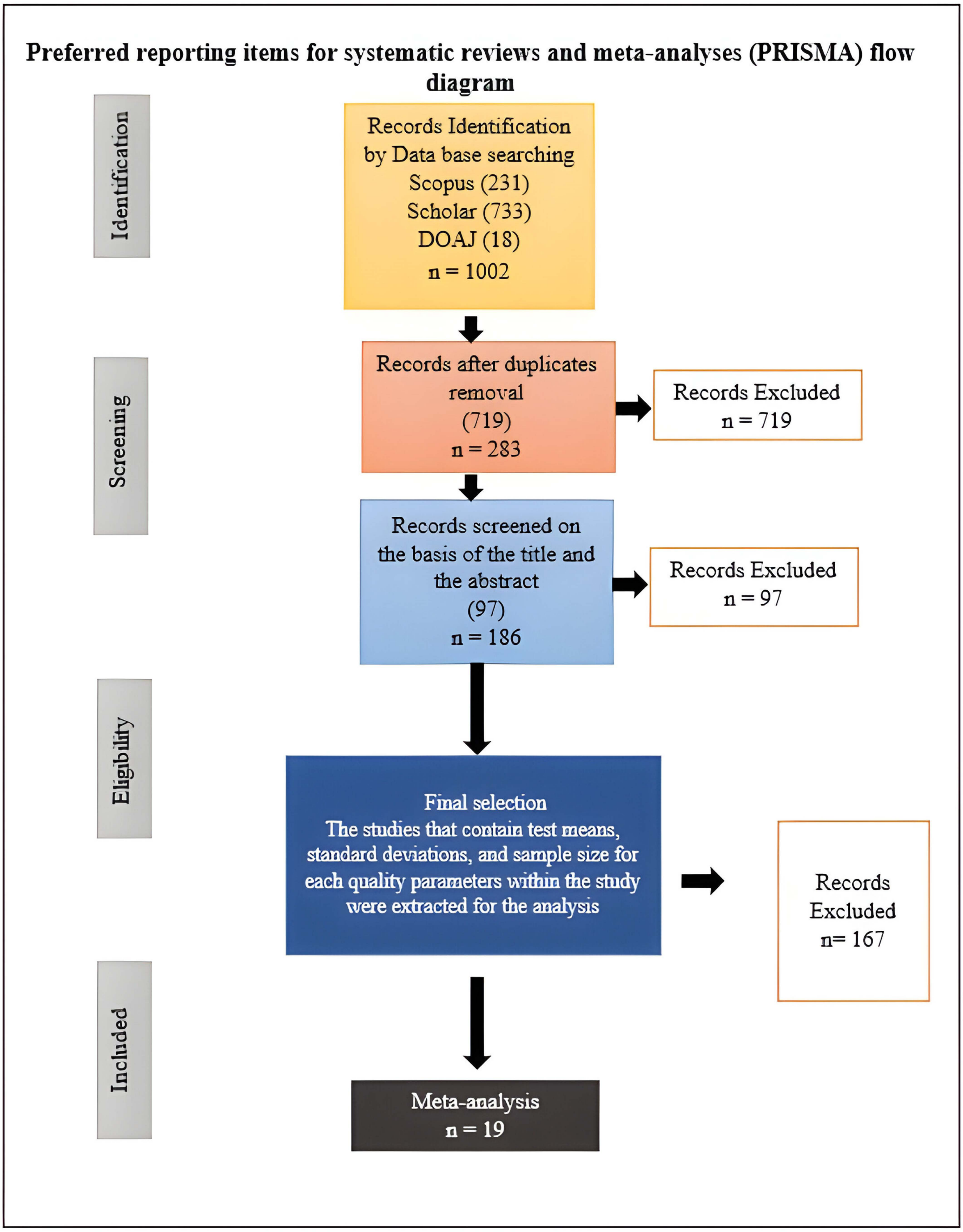

Figure 1. Selection process of the analyzed studies.

Table 2. Different standards used in different studies to test the quality parameters of the pellets.

Test Parameter	Standard Followed for Testing	References
Pellet dimensions	DIN EN 16127	[91,92]
	EN 16127	[92–95]
	EN 17829 (2015)	[96]
	ASTM standard E711-87	[97]
	Directly from vernier caliper	[13,90,98–104]

Table 2. *Cont.*

Test Parameter	Standard Followed for Testing	References
Moisture content	PROY-NOM-211-SSA1-2002 standard	[104]
	DIN EN 14774-1	[92,102]
	EN ISO 18134	[13,96]
	EN 14774-1	[93,94]
	ASTM D1762	[103]
	UNE-EN 14774-3	[99]
	D1762, ISO 1822	[100]
	NBR 7993	[98]
	Oven-drying method (105 °C for 24 h)	[90,91,101]
Ash content	ASTM D3174-04, 2004	[103,105]
	ASTM D 1762-84	[95,100,102,106]
	DIN EN 14775	[91–94]
	EN ISO 18122	[13,96]
	NBR 8112	[98]
	NREL/TP-510-42622	[90]
	ONORM M7135	[107]
	UNE-EN 14775	[99]
Mechanical durability	DIN EN 15210-1	[93–95,98,102,103,106]
	EN 17831-1:2015	[13,96]
	ASABE standards (ASABE, 2007)	[101]
	ASTM E1641-04	[90]
Bulk density	DIN EN 15103	[92–95,98,100,102,104,106]
	BS EN ISO 17828 (2015)	[13,91,96,99]
	SS 187120	[107]
	ASTM E1641-04	[90]
	X-ray densitometry method	[103]
N and S content	DIN EN 15104	[92,94]
	ISO 16948 (2015)	[13,96]
	ASTM D5291	[90]
	ASTM E778/08	[100]
	Using CHNS (O) analyzers	[91,101]
	Using elemental analyzers	[95,98,103,105,106]
Volatile matter content	ASTM D1762-84	[92,95,100,102,103,106]
	ASTM D3175-07, 2007	[90,97]
	EN 15148	[93,99]
	DIN EN 51720	[13]
	EN ISO 18123	[13]
	NBR 8112	[98]
Gross calorific value	Bomb calorimeter method	All

3. Results and Discussion

3.1. Pellets Analyzed

A summary of the 19 studies from different geographic regions of the world is presented in Table 3. Most of the selected studies were conducted in the European region, where there is a higher demand for pellets. The summary provides insights into pellets produced from biomass materials and the properties of the biomass types employed for production, as detailed in Table 3. However, among the selected studies, some report the properties of pellets produced and tested from both 100% single biomass and biomass blends. Mechanical pellet testing processes were employed across all studies. Some studies [13,90,92–95,98,100,101,104,106] also examined and reported the pellet die pressure and temperature during the pelletizing process, with these values also documented in Table 3.

Table 3. Summary and the properties of pellets in selected studies. NA—not available.

Property of the Pellet		Physical Properties		Mechanical Properties				Energy Properties					Chemical Properties	
		D	L	Du	Fines	BD	Hardness	MC	Ash	CV	VM	FC	N	S
Unit		mm	mm	%	%	kg/m^3	%	%	%	MJ/kg	%	%	%	%
1. Pellet Standards														
EN ISO 17225-6 category A		6 to 25	3.15≤ L ≤ 40	≥97.5	≤2	600≤	NA	≤12	≤6	≥14.5	NA	NA	≤1.5	≤0.20
EN ISO 17225-6 category B		6 to 25	3.15 ≤ L ≤40	≥96	≤3	600≤	NA	≤15	≤10	≥14.5	NA	NA	≤2.0	≤0.30
2. Pellets produced from both 100% biomass and biomass blends														
Reference: Rezania et al., 2016 [97] Focal region: MALAYSIA														
Production parameters: RM M: 10–15%, RM PS: 0.85 mm, Die P: NA, Die T: NA														
Biomass pellets	100% Water Hyacinth	NA	NA	NA	NA	NA	NA	9.90 (0.00)	**6.90 (0.11)**	14.58 (0.05)	66.27 (0.10)	26.83 (0.00)	NA	NA
Blended biomass pellets (selected for meta-analysis)	25% Water Hyacinth + 75% Empty Fruit Bunches	NA	NA	NA	NA	NA	NA	9.30 (0.03)	3.73 (0.54)	NA	80.3 (1.02)	15.97 (3)	NA	NA
Reference: Scatolino et al., 2018b [102] Focal region: BRAZIL														
Production parameters: RM M: 9–10%, RM PS: 3–4 mm, Die P: NA, Die T: NA														
Biomass pellets	100% Soybean Waste	6.47 (0.13)	17.13 (0.65)	47.49 (1.09)	3.32 (0.81)	686.00 (0.00)	3.87 (2.00)	9.03 (0.50)	26.72 (0.74)	16.70 (0.13)	62.47 (0.71)	10.81 (0.03)	NA	NA
	100% Sugarcane Bagasse	6.14 (0.06)	18.46 (1.35)	**96.64 (0.27)**	0.18 (0.03)	698.00 (0.00)	39.46 (7.33)	5.57 (0.16)	5.58 (0.44)	17.40 (0.08)	80.56 (1.98)	13.87 (1.77)	NA	NA
Blended biomass pellets (selected for meta-analysis)	50% Sawdust + 50% Soybean Waste	6.17 (0.13)	15.60 (1.70)	67.42 (3.39)	1.53 (0.52)	610	6.13 (2.58)	6.87 (0.12)	14.03 (1.4)	17.92 (0.09)	71.13 (0.26)	14.84 (1.15)	NA	NA
	50% Sugarcane Bagasse + 50% Soybean Wastes	6.13 (0.11)	15.93 (1.72)	67.01 (3.6)	2.50 (0.64)	634	7.75 (3.83)	6.48 (0.17)	15.02 (0.71)	17.25 (0.12)	69.47 (0.60)	15.48 (0.26)	NA	NA
Reference: Garcia et al., 2019 [100] Focal region: BRAZIL														
Production parameters: RM M: 15%, RM PS: 4 mm, Die P: NA, Die T: 90 °C														
Biomass pellets	100% Elephant Grass	NA	NA	89.82 (1.40)	NA	509.80 (8.20)	NA	NA	**6.80 (0.30)**	18.51 (0.26)	79.09 (3.48)	14.11 (1.10)	**1.51 (0.08)**	0.07 (0.01)
	100% Sugarcane Bagasse	NA	NA	87.54 (3.10)	NA	579.90 (30.60)	NA	NA	4.78 (0.06)	18.52 (0.18)	79.61 (1.60)	15.62 (1.34)	1.21 (0.07)	0.08 (0.01)
	100% Sorghum	NA	NA	93.59 (1.10)	NA	607.70 (34.50)	NA	NA	3.42 (0.12)	19.34 (0.22)	78.47 (2.34)	18.10 (1.20)	**1.68 (0.52)**	0.08 (0.01)
Blended biomass pellets (selected for meta-analysis)	95% Sawdust + 5% Charcoal of Eucalyptus spp.	NA	NA	92.63 (2.7)	NA	667.6 (30.1)	NA	NA	0.48 (0.07)	20.42 (0.14)	78.35 (2.25)	21.18 (0.92)	0.88 (0.12)	0.07 (0.06)

Table 3. *Cont.*

Property of the Pellet		Physical Properties		Mechanical Properties				Energy Properties					Chemical Properties	
		D	**L**	**Du**	**Fines**	**BD**	**Hardness**	**MC**	**Ash**	**CV**	**VM**	**FC**	**N**	**S**
Unit		**mm**	**mm**	**%**	**%**	**kg/m^3**	**%**	**%**	**%**	**MJ/kg**	**%**	**%**	**%**	**%**
Reference: da Silva et al., 2020 [93] Focal region: BRAZIL														
Production parameters: RM M: 12–16%, RM PS: 3–5 mm, Die P: 29.42 MPa, Die T: 80–95 °C														
Biomass pellets	100% Elephant Grass	6.20 (0.05)	17.07 (1.35)	**96.58 (0.19)**	**2.36 (0.42)**	654.10 (3.69)	NA	8.83 (0.36)	**6.48 (0.11)**	14.84 (0.10)	81.20 (0.26)	11.75 (0.26)	NA	NA
	100% Sugarcane Bagasse	6.18 (0.50)	12.87 (1.48)	92.22 (0.48)	44.00 (1.69)	574.74 (4.82)	NA	9.85 (0.14)	2.40 (0.01)	15.20 (0.23)	84.27 (0.56)	13.33 (0.50)	NA	NA
Biomass blended pellets (selected for meta-analysis)	50% Elephant Grass + 50% Sawdust	6.14 (0.04)	17.85 (1.16)	98.66 (0.77)	**2.69 (0.23)**	690.09 (3.2)	NA	8.12 (0.12)	2.89 (0.01)	15.74 (0.06)	86.24 (0.85)	10.87 (0.85)	NA	NA
	50% Elephant Grass + 50% Sugarcane Bagasse	6.13 (0.04)	15.01 (1.45)	**96.18 (0.38)**	**2.55 (0.21)**	653.51 (1.38)	NA	8.96 (0.05)	4.8 (0.01)	15.09 (0.10)	83.31 (1.28)	11.89 (1.42)	NA	NA
Reference: Carrillo-Parra et al., 2020 [99] Focal region: MEXICO														
Production parameters: RM M: 15%, RM PS: 3 mm, Die P: NA, Die T: NA														
Biomass pellets	100% Oil Palm Residue	NA	NA	NA	NA	540.00 (170.00)	NA	6.45 (0.26)	0.54 (0.07)	21.89 (0.16)	79.40 (1.90)	20.05 (1.83)	NA	NA
Blended biomass pellets (selected for meta-analysis)	40% Oil Palm Residue + 60% Sawdust	NA	NA	NA	NA	660 (10)	NA	6.76 (0.89)	0.44 (0.11)	20.75 (0.06)	87.32 (1.92)	12.23 (1.81)	NA	NA
	20% Oil Palm Residue + 80% Sawdust	NA	NA	NA	NA	680 (10)	NA	5.84 (0.19)	0.53 (0.07)	19.70 (0.13)	85.68 (1.63)	13.79 (1.57)	NA	NA
Reference: de Souza et al., 2020 [92] Focal region: BRAZIL														
Production parameters: RM M: 12%, RM PS: 3 mm, Die P: 29.42 MPa, Die T: 80–95 °C														
Biomass pellets	100% Coffee Husk	6.12 (0.02)	18.43 (1.17)	**97.09 (0.30)**	0.17 (0.07)	687.48 (4.16)	29.76 (3.11)	9.50 (0.26)	**9.69 (0.03)**	15.76 (0.19)	73.15 (0.19)	NA	3.18 (0.03)	0.19 (0.04)
	100% Coffee Parchment	6.15 (0.02)	14.01 (0.73)	93.77 (2.96)	0.46 (0.16)	632.56 (0.73)	25.84 (4.21)	8.64 (0.18)	2.55 (0.03)	16.96 (0.09)	85.24 (0.52)	NA	**1.85 (0.05)**	0.05 (0.01)
	100% Coffee Silver Skin	6.11 (0.03)	21.02 (2.85)	**97.10 (2.16)**	0.10 (0.21)	644.36 (6.69)	18.32 (2.67)	8.84 (0.21)	**9.90 (0.03)**	16.26 (0.04)	75.95 (0.61)	NA	3.29 (0.04)	0.18 (0.02)
Blended biomass pellets (selected for meta-analysis)	40% Sawdust + 30% Parchment + 30% Silver Skin	6.17 (0.02)	13.85 (0.83)	**93.28 (1.57)**	0.22 (0.07)	634.26 (4.97)	24.28 (4.20)	9.79 (0.30)	4.00 (0.11)	17.08 (0.14)	84.38 (0.20)	NA	2.45 (0.05)	0.13 (0.02)
	40% Sawdust + 30% Parchment + 30% Coffee Husk	6.13 (0.08)	14.43 (0.99)	**95.33 (1.19)**	0.19 (0.05)	690.79 (5.47)	29.56 (8.01)	8.88 (0.07)	**6.28 (0.17)**	16.51 (0.21)	82.37 (0.30)	NA	**1.99 (0.05)**	0.08 (0.02)

Table 3. *Cont.*

Property of the Pellet		Physical Properties		Mechanical Properties				Energy Properties					Chemical Properties	
		D	**L**	**Du**	**Fines**	**BD**	**Hardness**	**MC**	**Ash**	**CV**	**VM**	**FC**	**N**	**S**
Unit		**mm**	**mm**	**%**	**%**	**kg/m^3**	**%**	**%**	**%**	**MJ/kg**	**%**	**%**	**%**	**%**
Reference: Szyszlak-Bargłowicz et al., 2021 [13] Focal region: POLAND														
Production parameters: RM M: 12%, RM PS: 0.5–1.0 mm, Die P: NA, Die T: 85 °C														
Biomass pellets	100% Miscanthus	NA	NA	91.40 (1.00)	NA	567.30 (6.70)	NA	7.20 (0.05)	2.36 (0.14)	16.31 (0.02)	73.61 (0.29)	16.40 (0.23)	0.24 (0.00)	0.000 (0.00)
	100% Copra Meal	NA	NA	87.2 (0.00)	NA	255.10 (0.50)	NA	5.43 (0.02)	5.46 (0.04)	18.38 (0.05)	75.62 (0.15)	13.49 (0.18)	3.15 (0.02)	0.13 (0.00)
Blended biomass pellets (selected for meta-analysis)	90% Miscanthus + 10% Copra	NA	NA	**97.20 (0.60)**	NA	514.90 (3.4)	NA	6.76 (0.03)	2.70 (0.04)	17.80 (0.05)	74.93 (0.43)	15.94 (0.37)	0.37 (0.01)	0.01 (0.00)
	70% Miscanthus + 30% Copra	NA	NA	95.10 (0.00)	NA	417.40 (3.2)	NA	6.41 (0.02)	3.09 (0.54)	17.92 (0.03)	74.56 (0.43)	15.94 (0.31)	0.55 (0.02)	0.02 (0.00)
Reference: Harun and Afzal, 2015 [90] Focal region: CANADA														
Production parameters: RM M: 10%, RM PS: 0.1–0.6 mm, Die P: 159 MPa (5 s holding time), Die T: 80 °C														
Biomass pellets	100% Reed Canary Grass	NA	NA	18.61 (0.02)	NA	NA	NA	6.40 (0.00)	5.34 (0.45)	NA	NA	NA	0.17 (0.00)	0.04 (0.01)
	100% Switchgrass	NA	NA	18.20 (0.17)	NA	NA	NA	7.0 (0.00)	3.61 (0.44)	NA	NA	NA	0.12 (0.00)	0.03 (0.00)
	100% Timothy Hay	NA	NA	17.58 (0.06)	NA	NA	NA	6.90 (0.00)	4.06 (0.37)	NA	NA	NA	0.18 (0.00)	0.04 (0.01)
Biomass blended pellet (selected for Meta-analysis)	50% Spruce Sawdust and 50% RCG	NA	NA	NA	NA	NA	NA	7.2	2.07 (0.21)	18.56 (0.04)	NA	NA	0.04 (0.00)	0.02 (0.00)
	50% Spruce Sawdust and 50% Timothy Hay	NA	NA	NA	NA	NA	NA	7.3	1.51 (0.18)	18.37 (0.06)	NA	NA	0.04 (0.00)	0.02 (0.00)
	50% Spruce Sawdust and 50% Switchgrass	NA	NA	NA	NA	NA	NA	7.7	1.53 (0.5)	18.46 (0.14)	NA	NA	0.03 (0.00)	0.01 (0.00)
	50% Pine Sawdust + 50% RCG	NA	NA	NA	NA	NA	NA	7.5	1.54 (0.51)	19.00 (0.16)	NA	NA	0.04 (0.00)	0.02 (0.00)
	50% Pine Sawdust + 50% Timothy Hay	NA	NA	NA	NA	NA	NA	7.6	1.62 (0.05)	18.68 (0.1)	NA	NA	0.04 (0.00)	0.02 (0.00)
	50% Pine Sawdust + 50% Switchgrass	NA	NA	NA	NA	NA	NA	7.5	1.55 (0.4)	18.44 (0.08)	NA	NA	0.03 (0.00)	0.01 (0.00)

Table 3. *Cont.*

Property of the Pellet		Physical Properties		Mechanical Properties				Energy Properties					Chemical Properties	
		D	L	Du	Fines	BD	Hardness	MC	Ash	CV	VM	FC	N	S
Unit		mm	mm	%	%	kg/m^3	%	%	%	MJ/kg	%	%	%	%
3. Pellets produced only from 100% biomass materials														
Reference: Tenorio et al., 2016 [103] Focal region: COSTA RICA														
Production parameters: RM M: 5%, RM PS: ≤0.5 mm, Die P: NA, Die T: NA														
Biomass pellets	100% Oil Palm Empty Fruit Bunches	6.09 (2.01)	22.94 (9.59)	92.76 (0.72)	NA	575.00 (1.53)	NA	9.05 (6.87)	5.75 (2.69)	14.18 (0.097)	71.70 (0.13)	NA	NA	NA
	100% Oil Palm Fruit Mesocarp	6.12 (4.08)	17.34 (26.68)	92.82 (1.38)	NA	595.80 (1.62)	NA	9.2 (3.06)	**6.24 (0.88)**	15.83 (0.06)	72.41 (0.78)	NA	NA	NA
Reference: Almeida et al., 2017 [98] Focal region: BRAZIL														
Production parameters: RM M: Initially, 50% and after drying MC was not mentioned, RM PS: 5 mm, Die P: NA, Die T: 80 °C														
Biomass pellets	100% Sugarcane Bagasse	9.70 (0.10)	22.70 (4.94)	NA	NA	726.32 (0.62)	NA	5.49 (0.04)	**8.70 (0.34)**	NA	77.27 (2.24)	14.03 (0.84)	0.28 (0.05)	0.02 (0.03)
Reference: Pradhan et al., 2018a [101] Focal region: INDIA														
Production parameters: RM M: 10%, RM PS: 6 mm, Die P: NA, Die T: 80–90 °C														
Biomass pellets	100% Garden Waste	14.70 (0.20)	39.20 (5.0)	97.70 (0.00)	5.90 (0.00)	NA	24.5 (0.00)	4.50 (1.00)	NA	NA	NA	NA	NA	NA
Reference: Azócar et al., 2019 [106] Focal region: CHILE														
Production parameters: RM M: 15 ± 2%, RM PS: 0.1–1.2 mm, Die P: NA, Die T: 70 °C														
Biomass pellets	Wheat Straw	6.48 (0.16)	22.07 (9.23)	**97.23 (0.39)**	0.33 (0.02)	469.00 (8.00)	NA	9.57 (0.60)	2.64 (0.60)	15.43 (0.17)	NA	NA	0.33 (0.02)	0.00 (0.00)
Pretreated biomass pellets	Torrefied Wheat Straw (Brown Pellets)	6.28 (0.11)	25.38 (9.98)	**96.23 (0.39)**	**0.26 (0.06)**	568.00 (4.00)	NA	7.12 (0.00)	3.19 (0.00)	16.01 (0.09)	NA	NA	0.45 (0.05)	0.01 (0.00)
Reference: Trejo-Zamudio et al., 2021 [104] Focal region: MEXICO														
Production parameters: RM M: 20%, RM PS: 8 mm, Die P: NA, Die T: 95–105 °C														
Biomass pellets	100% Bean Crop Residues	8.13 (0.01)	18.50 (0.16)	NA	NA	607.38 (7.69)	NA	11.67 (0.72)	5.32 (0.00)	16.09 (1.98)	NA	NA	NA	NA

Table 3. *Cont.*

Property of the Pellet		Physical Properties		Mechanical Properties				Energy Properties					Chemical Properties	
		D	**L**	**Du**	**Fines**	**BD**	**Hardness**	**MC**	**Ash**	**CV**	**VM**	**FC**	**N**	**S**
Unit		**mm**	**mm**	**%**	**%**	**kg/m^3**	**%**	**%**	**%**	**MJ/kg**	**%**	**%**	**%**	**%**
Reference: (Acampora et al., 2021) [91] Focal region: ITALY														
Production parameters: RM M: 10–20%, RM PS: 6 mm, Die P: NA, Die T: NA														
Biomass pellets	100% Hazelnut	6.20 (0.12)	10.47 (2.67)	98.00 (0.5)	NA	581.00 (3.00)	NA	NA	3.10 (0.60)	NA	NA	NA	0.77 (0.21)	0.00 (0.00)
	100% Olive Tree Pruning Waste	6.20 (0.10)	16.66 (1.82)	98.30 (0.60)	NA	562.00 (6.00)	NA	NA	2.50 (0.10)	NA	NA	NA	1.24 (0.36)	0.00 (0.00)
Reference: Pegoretti Leite de Souza et al., 2021 [94] Focal region: CHILE														
Production parameters: RM M: 5–7%, RM PS: 4 mm, Die P: NA, Die T: 80–100 °C														
Biomass pellets	100% Miscanthus	NA	NA	**96.86 (0.07)**	0.19 (0.01)	615.00 (1.5)	NA	7.42 (0.10)	2.94 (0.07)	16.22 (0.02)	NA	NA	NA	NA
Biomass pellets	100% Miscanthus	NA	NA	**96.86 (0.07)**	0.19 (0.01)	615.00 (1.5)	NA	7.42 (0.10)	2.94 (0.07)	16.22 (0.02)	NA	NA	NA	NA
Reference: Senila et al., 2020 [96] Focal region: ROMANIA														
Production parameters: RM M: 12%, RM PS: 5 mm, Die P: NA, Die T: NA														
Biomass pellets	Vineyard Waste (VW)	20.90 (4.50)	10.10 (0.04)	97.80 (2.20)	1.25 (0.07)	657.65 (4.30)	NA	10.30 (0.40)	NA	17.35 (1.20)	NA	NA	1.23 (0.07)	0.02 (0.10)
4. Pellets produced from biomass blends														
Reference: Chavalparit et al., 2013 [105] Focal region: THAILAND														
Production parameters: RM M: 20%, RM PS: 2 mm, Die P: NA, Die T: NA														
Blended biomass pellets (selected for meta-analysis)	55% Oil Palm Frond + 45% Crude Glycerin	NA	NA	NA	NA	994 (8.4)	NA	4.35 (0.07)	11.9 (0.1)	20.4	2.38 (2.6)	2.38 (2.6)	NA	81.3 (2.7)
Reference: Amirta et al., 2018 [107] Focal region: INDONESIA														
Production 17.2: RM M: 12%, RM PS: Dust, Die P: NA, Die T: NA														
Blended biomass pellet (selected for meta-analysis)	70% Sawdust + 20% Tapioca + 20% Glycerol	7.7 (0.03)	3.03 (0.26)	NA	NA	730 (20)	NA	7.42 (3.37)	4.3 (0.81)	NA	89.5 (3.03)	6.2 (3.84)	NA	NA

Table 3. *Cont.*

Property of the Pellet		Physical Properties		Mechanical Properties				Energy Properties					Chemical Properties	
		D	L	Du	Fines	BD	Hardness	MC	Ash	CV	VM	FC	N	S
Unit		mm	mm	%	%	kg/m^3	%	%	%	MJ/kg	%	%	%	%
Reference: (Santana et al., 2021) [95] Focal region: BRAZIL														
Production parameters: RM M: 7–11%, RM PS: 5 mm, Die P: NA, Die T: 80–95 °C														
Blended biomass pellet (selected for meta-analysis)	65% Soybean Waste + 35% Cotton Waste (65SyB + 35CW)	6.34 (0.09)	18.75 (1.10)	92.59 (0.46)	0.36 (0.03)	NA	NA	9.88 (0.29)	NA	15.59 (0.04)	NA	NA	4.29 (0.22)	0.25 (0.01)
	65% Soybean Waste + 35% Sorghum Waste (65SyW + 35SoW)	6.39 (0.09)	18.83 (1.34)	87.20 (2.28)	0.30 (0.19)	NA	NA	4.46 (0.11)	NA	14.79 (0.49)	NA	NA	3.47 (0.15)	0.16 (0.03)
	65% Soybean Waste + 35% Pine Needles (65SyW + 35PN)	6.42 (0.10)	17.36 (0.86)	76.78 (3.37)	0.76 (0.22)	NA	NA	6.89 (0.26)	NA	15.90 (0.14)	NA	NA	3.54 (0.10)	0.16 (0.01)
	65% Rice Powder + 35% Sawdust (65RP + 35SD)	6.40 (0.21)	18.14 (1.25)	94.28 (0.30)	0.16 (0.10)	NA	NA	7.50 (0.08)	NA	17.15 (0.11)	NA	NA	3.16 (0.16)	0.17 (0.00)
	65% Rice Powder + 35% Charcoal Fines (65RP + 35CF)	6.28 (0.08)	18.95 (1.38)	97.75 (0.14)	0.17 (0.07)	NA	NA	10.34 (1.40)	NA	20.14 (0.22)	NA	NA	2.88 (0.03)	0.12 (0.01)

NOTE: Standard deviations are shown in brackets, D: diameter of the pellets, L: length of the pellets, MC: moisture content, Ash: ash content, Du: mechanical durability, Fines: fine particle content, BD: bulk density, CV: calorific value (ISO standards NCV and analyzed studies GCV) and, N: nitrogen content, S: sulfur content, VM: volatile matter content, FC: fixed carbon content, RM M: moisture content of the raw materials, RM PS: particle size of the raw materials, Die P: pellet die pressure, Die T: pellet die temperature.

When considering blended biomass pellets (non-woody and woody biomass blended pellets), the properties of 100% non-woody pellets produced in the aforementioned 19 studies were collected. Out of these 19 studies, 8 contained test results for both 100% non-woody biomass pellets and blended biomass pellets, another 8 studies contained test results for 100% non-woody biomass pellets, and an additional 3 studies contained test results exclusively for blended biomass pellets. The selection of blended biomass pellets for meta-analysis followed the method outlined in the statistical analysis section, and the chosen blended biomass pellet types are listed in Table 3 to facilitate a fair comparison with pellets produced from 100% non-woody biomass materials. In certain studies, pre-heating of the pellet die prior to the pellet production process was noted [98,103]. The rationale behind this pellet die heating is discussed in the literature, where an increase in biomass feedstock temperature reduces the friction in the press channel of the pellet mill [53] and decreases the energy required for the pelleting process [108], leading to decreased friction with a higher die temperature [53]. Nonetheless, the pelletizing temperature varied within the analyzed studies, ranging from 70 °C to 105 °C. The pressure levels to which biomass is subjected during pelletization influence product density and durability [53]. Thus, the available pressure levels applied during pellet production are also documented in Table 3. Most studies applied the same pressure levels [92,93], although higher pressure values have also been observed [90].

Table 3 presents the properties of biomass pellets produced using single biomass materials as well as biomass blends. Repetition of the same biomass materials across different studies has been observed. The properties not compliant with ISO 17225-6 standard category A are highlighted in bold in Table 3, and those failing to meet both categories (A and B) are highlighted in gray. While the other parameters fall within the ISO 17225-6 standard range, ash content, fine particle content, net calorific value, bulk density, and mechanical durability exhibit values slightly above the standards. Notably, the nitrogen content in pellets derived from coffee industry residues surpasses the permitted levels (Table 3).

Another intriguing observation pertains to pellets produced using the same raw materials across different studies, demonstrating varying pellet properties. For instance, the literature [93,98,100,102] has discussed the properties of pellets produced from sugarcane bagasse (SB). Despite utilizing the same biomass material, properties such as the ash content, fine particle content, mechanical durability, and bulk density exhibit considerable variability between studies. Similar patterns can be discerned in other studies, wherein authors attribute the variations in biomass properties to differences in sourcing regions. Some pellet production studies involve raw material heating processing or steam explosion before pellet production [98,109,110].

The literature [106] also describes the properties of pellets derived from torrefied wheat straw (Table 2). It is clear that the torrefaction process has resulted in an improvement in as well as a decrease in certain pellet parameters. Torrefaction serves as a pretreatment for upgrading woody biomass primarily for energy production [64,111]. This thermochemical treatment subjects biomass to heat within a reaction temperature range of 200 to 300 °C, employing an inert medium like nitrogen for a specified period, often ranging from seconds to an hour, depending on the particle size (PS). The research indicates that torrefaction techniques can enhance the material properties of raw straw, including a higher heating value (HHV) or gross calorific value (GCV), hydrophobicity, grinding ability, and an improved mass yield and energy density ratio [63,106,112].

Conventional torrefaction conditions and elevated temperatures result in torrefied biomass with an elevated ash content and substantial mass loss [63,113]. This phenomenon is also evident in the torrefied pellets discussed by [106], where the ash content of the pellets increased post-torrefaction (Table 3). The inherent binding properties of lignocellulosic biomass can be fortified via structural modifications of the cellulose–hemicellulose–lignin matrix using torrefaction methods [63]. However, excessive torrefaction and over-modification can amplify the compression and compaction characteristics of the raw materials, leading to increased energy consumption during pelleting due to the heightened friction in the press channel. In certain scenarios, this can also result in reduced pellet density [62,112].

In summary (Table 4), the literature indicates a significant correlation between the pelletization pressure, temperature, bulk density, and mechanical durability values of the resultant products [41,53,114]. The quality of blended biomass pellets improves as the percentage of woody materials in the blend increases. This suggests that incorporating a higher percentage of woody materials enhances the quality of the pellets [90,92,99].

Table 4. Property variation of the Du and BD of the pellets produced in the same conditions in different studies.

Main Biomass Material	Author and the Published Year	MC of the Biomass (%)	PS of Biomass (mm)	Pelletizing Pressure (MPa)	Pelletizing Temperature (°C)	Du of the Pellets (%)	BD of the Pellets (kg/m^3)
Elephant Grass (EG)	da Silva et al., 2020 [93]	12–16	3–5	29.42	80–95	96.58	654.10
	Garcia et al., 2019 [100]	9–10	3–4	29.42	80–95	89.82	509.80
Miscanthus (M)	Pegoretti Leite de Souza et al., 2021 [94]	5–7	4	NA	80–100	96.86	615.00
	Szyszlak-Bargłowicz et al., 2021 [13]	12	0.5–1.0	NA	85	91.40	567.30
Sugarcane Bagasse (SB)	da Silva et al., 2020 [93]	12–16	3–5	29.42	80–95	92.22	574.74
	Scatolino et al., 2018a [102]	15	4	NA	90	96.64	698.00
	Garcia et al., 2019 [100]	9–10	3–4	29.42	80–95	87.54	579.90

3.2. Pellet Quality Parameters

This section presents forest plot diagrams illustrating the meta-analyzed pellet properties, each compared with the standard parameters. Additionally, the findings from the reviewed literature are incorporated.

3.2.1. Pellet Dimensions

Dimensions are crucial parameters for any solid fuel as they influence feeding and furnace technologies, impacting the fuel conveyance and combustion behavior. The pellet diameter is determined by selecting a die with appropriately sized die holes. The meta-analysis revealed a diameter of approximately 6 mm, with minimal variations. Notably, the EN ISO 17225 standard series specifies a maximum pellet length of 40 mm, a significant consideration for pneumatic feeding systems. Overly lengthy pellets can obstruct the feeding system, potentially causing system standstills [80].

In the meta-analysis, the mean pellet diameter was found to be 6.37 mm, with a corresponding mean length of 15.65 mm (Figures 2 and 3). These mean values comply with the stipulated diameter and length requirements outlined in the pellet standards for both domestic and industrial purposes. An intriguing observation is that the pellet diameters manifest higher values than the die holes from which they are produced. The existing literature posits several possible reasons for this phenomenon. Scatolino et al., 2017 [102] proposes that the change in pellet size may be attributed to water filling the voids within the pellets, disrupting the bonds formed during the pelletization process. Additionally, this could be the result of particle rearrangement upon the release of compression force, compounded by the varying moisture content of the raw materials [102,115]. Furthermore, the literature suggests that pellets with smaller diameters exhibit a more uniform combustion rate compared to larger diameter pellets, attributed to the greater exposed surface area, facilitating efficient combustion [101].

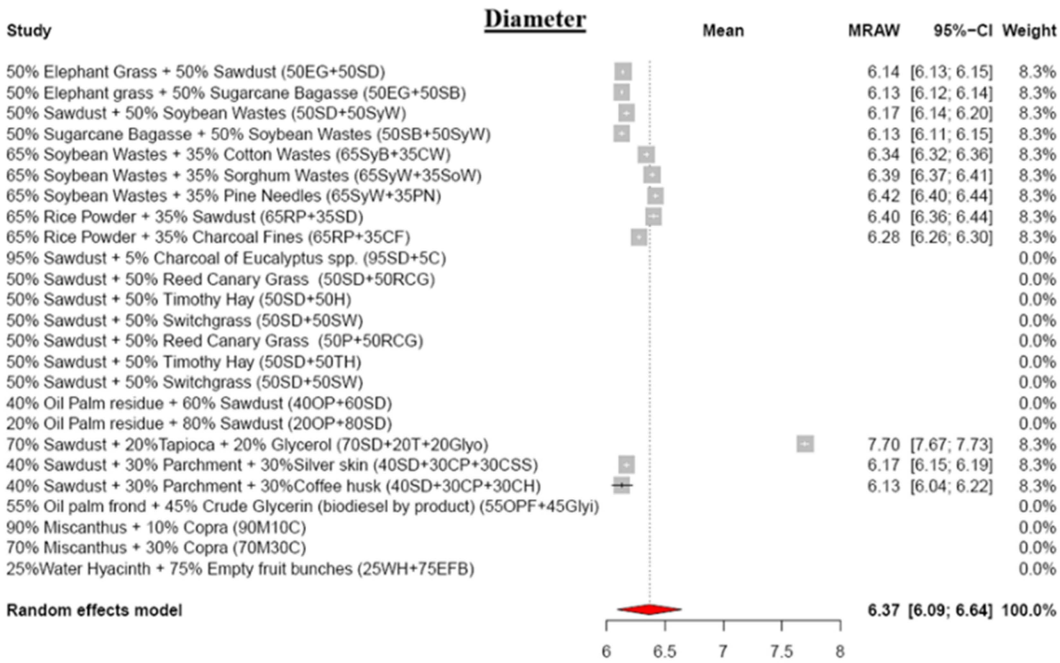

Figure 2. Average pellet diameter.

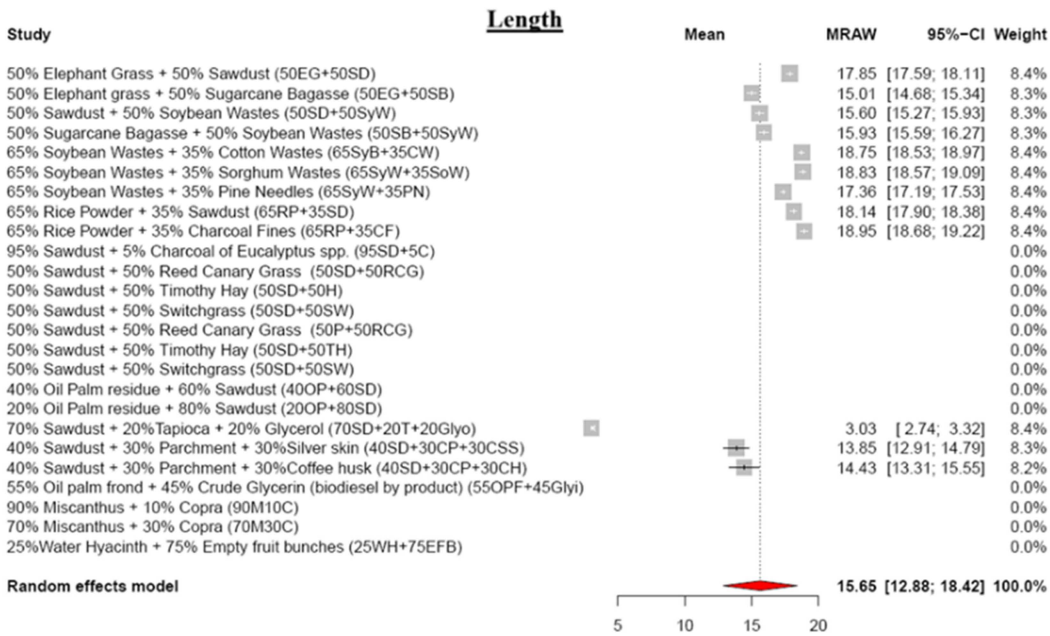

Figure 3. Average pellet length.

European standards mandate that pellet length should not exceed four times the die diameter, promoting uniformity to facilitate smooth material flow during combustion or gasification processes [115]. The length-to-diameter ratio, termed the aspect ratio, is pivotal for pellet durability, which is called "green strength," especially in pneumatic feeding processes [41,116,117] and the production of blockage-free pellet mills [101,118]. Additionally, the aspect ratio serves as a metric for compression during palletization [111]. An increased pelletizing pressure lengthens the pellet, while a larger pellet diameter reduces the pelletizing pressure. The aspect ratio directly influences pellet durability, with a higher ratio enhancing the durability, possibly due to enhanced particle bonding and lower hygroscopicity [76,95].

Notably, pellets comprising multiple biomass materials tend to have smaller diameters [93,102], a trend evident in this analysis. This reduction in diametric variation in mixed pellets is beneficial for the efficient design of pellet burners and feeders [102,119].

3.2.2. Moisture Content (MC)

Moisture influences the binding properties, density, storage conditions, and combustion characteristics of the pellets [93,120–122]. The MC is expressed as a percentage of the total weight of wood pellets for energy, and the ISO 17225-6 standard delineates two distinct MC limits: 12% for category A (Table 3) and 15% for category B (Table 3) for industrial non-woody biomass pellets. Moisture acts as a binding agent, strengthening biomass pellets via inter-particle van der Waals' forces and/or hydrogen bonding [41,120]. However, excessive moisture can impede particle compaction and thereby reduce the pellet quality [99,108]. Moreover, a higher moisture content necessitates elevated energy consumption during the drying process, a significant cost factor in pellet production [98].

Insufficient moisture content in raw materials poses challenges during pelletization by elevating the friction forces in compression zones, resulting in increased electricity consumption and repair costs for pelleting machines [102]. Determining an exact moisture content (MC) range for ideal biomass pellets is complex, as it varies based on the granulometry, raw material properties, and process conditions [95,123,124]. Post-pelletization, the pellet moisture decreases by approximately 1 to 6% compared to the fed biomass's MC [117,125]. In addition, torrefaction can also lead to a reduction in the moisture content of the produced pellets [106]. Maintaining lower MC values is essential to prevent incomplete biomass burning and fly ash formation [97,99,103]. Optimal MC ranges are 8–12% for 100% woody pellets and up to 15% for non-woody pellets to achieve an efficient burner performance [82,126].

The meta-analysis reveals lower moisture content (MC) values in blended biomass pellets, averaging 7.48% (Figure 4). The final MC depends on the raw material types and their blending ratios in the pellet production. For instance, a blend of 65% soybean waste and 35% cotton waste yields pellets with a 9.88% MC, whereas substituting cotton waste with sorghum waste reduces the MC to 4.46% [95]. MC exhibits a positive correlation with sawdust content but a negative relationship with herbaceous biomass materials [90,100,102], showcasing its intricate dynamics in blended biomass pellets. Notably, the MC significantly influences calorific value, combustion behavior, and efficiency, and fosters mold growth [116,126].

3.2.3. Ash Content

The ash content in wood pellets serves as a vital parameter, especially for heating applications, providing manufacturers and quality checkers with a rapid initial quality assessment [107,127]. This metric is representative of the non-combustible residue left at the end of the combustion cycle, originating from the inorganic elements present in the biomass. Elevated ash levels directly impact the combustion efficiency [93,125,128], resulting in increased maintenance costs for burner systems like boilers, furnaces, stoves, and gasifiers [129–132]. Notably, biomass with a high ash content can erode the pellet die, affecting pellet-binding mechanisms [122].

While the standards permit biomass pellet ash content up to 10%, an extensive proportion of the literature emphasizes that the ash levels should ideally stay within 4% for agro-residues in biomass briquetting and pelleting [133,134]. This range ensures enhanced combustion efficiency [97,135]. Notably, pellets derived from biomass blends exhibit a lower ash content and higher calorific values compared to single biomass pellets [93].

Another important fact is that the ash content of the torrefied wheat straw pellet is higher than the non-torrefied wheat straw pellet. Although torrefied pellets remained within the standard range, these kinds of increments in ash content are quite common scenarios with other torrefied biomass pellets as well [136–139]. It has been identified that the ash content gradually increases with the increasing severity of torrefaction [137]. The literature suggests that the high alkali metal contents (Na, K, Ca, Mg, Si, Cl, and S) [139,140] and the loss of organic matter during torrefaction are the reasons for the increased ash content of the torrefied biomass pellets [137].

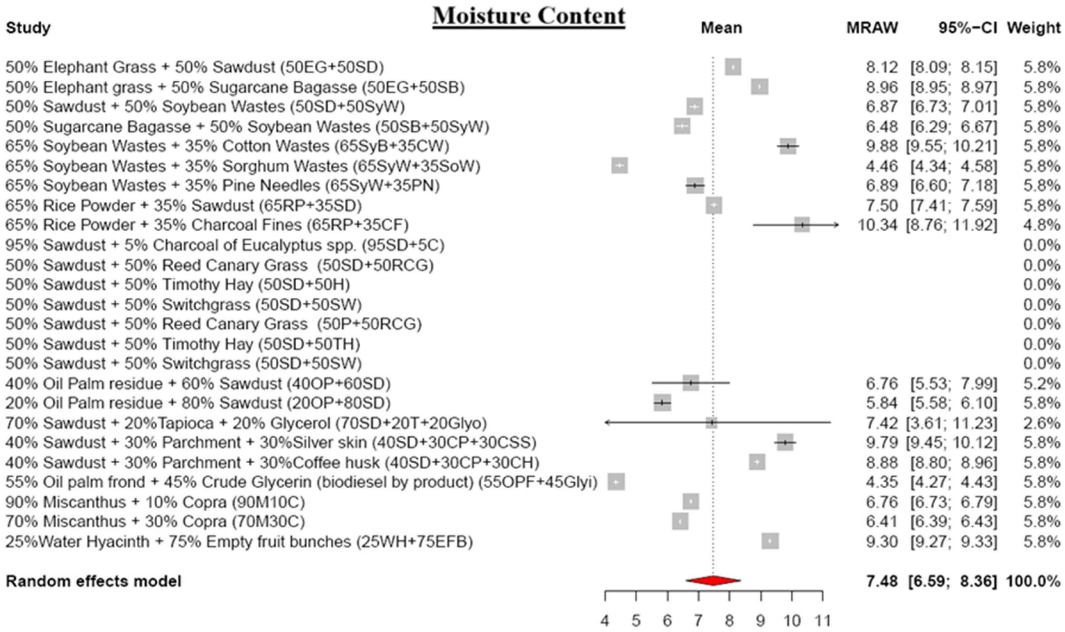

Figure 4. Mean moisture content of the pellets. The arrow can be seen when the range of the final results goes beyond the range of the graph.

The majority of the analyzed pellets fall within the specified ash content limits for industrial-scale non-woody pellets (Figure 5). However, pellets containing soybean waste demonstrate significantly higher ash levels, attributed by the authors to potential soil contamination during storage [102].

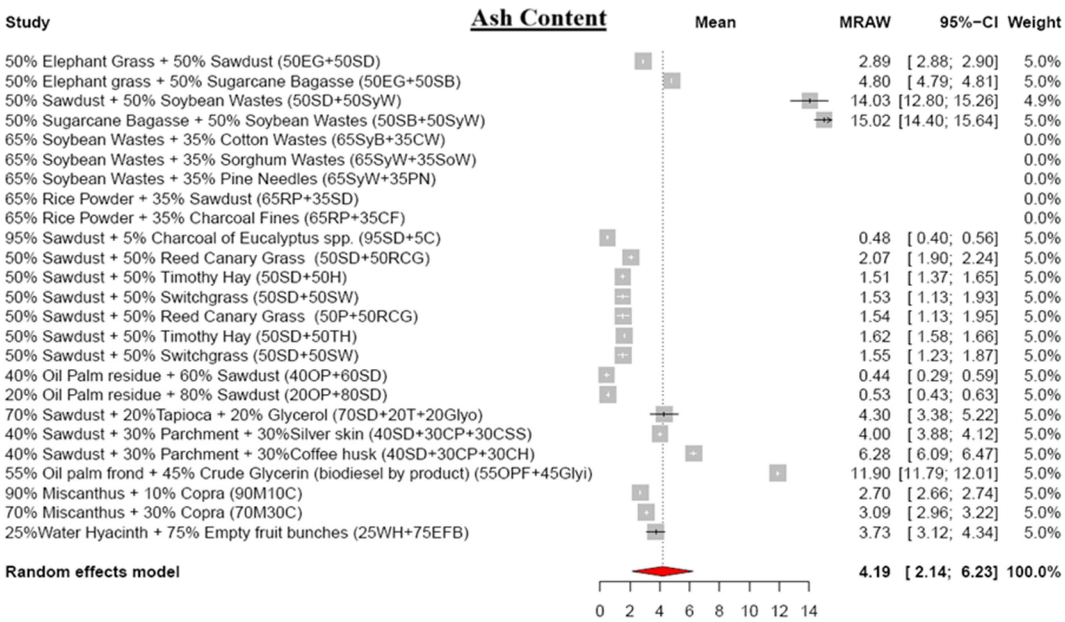

Figure 5. Mean and permissible range of ash content of the pellets. The arrow can be seen when the range of the final results goes beyond the range of the graph.

With the exception of soybean blended pellets (ash content: 14.03%, 15.02%) and oil palm residue blended pellets (ash content: 11.90%), all analyzed studies remained within the prescribed maximum limits for industrial-scale non-woody biomass standards (Figure 5). Notably, pellets derived from a mix of sawdust and waste from the coffee industry surpassed the upper limit of ISO 17225-6 category A, potentially due to soil contamination. However, a significant portion of the analyzed blended pellets adhered to both the upper and lower standards compared to pellets produced from single biomass materials.

3.2.4. Mechanical Durability

Durability, a measure of a pellet's resistance to abrasion, is an important parameter in ensuring smooth fuel-feeding systems and reducing dust emissions during handling. Pellets with low durability can lead to storage and transportation challenges, along with health and environmental concerns, due to the susceptibility to disintegration caused by moisture adsorption, falls, or friction [105]. In light of the meta-analysis results and existing literature, maintaining the mechanical durability of both single and blended pellets is of paramount importance. For instance, single biomass pellets produced from soybean waste exhibited a low mechanical durability value of 18% (Table 3). However, when combined with sawdust, this value significantly improved to 67.42%. A similar trend is observed in pellets made from other non-woody biomass materials [102,141].

Most of the analyzed pellets exhibit mechanical durability values well within the ISO 17225-6 standards, with an extracted mean value of 89.03% (Figure 6). The literature has studied what causes reduced mechanical durability values. Recent research shows that pellet durability depends on several important factors. These factors include the material used (such as starch, protein, fiber, fat, lignin, extractives, moisture content, and particle size and distribution) [76,93,95,99,142], the processes used before pellet formation (such as steam conditioning, preheating, and adding binders) [41,114,143–145], and the equipment used for pellet formation (such as forming pressure, pellet mill, and roll press variables) [76,111,146]. These factors can affect the strength and durability of the pellets. Additionally, how the pellets are treated after production, such as via cooling, drying, or storage in high humidity conditions, can also affect their strength and durability [41,147].

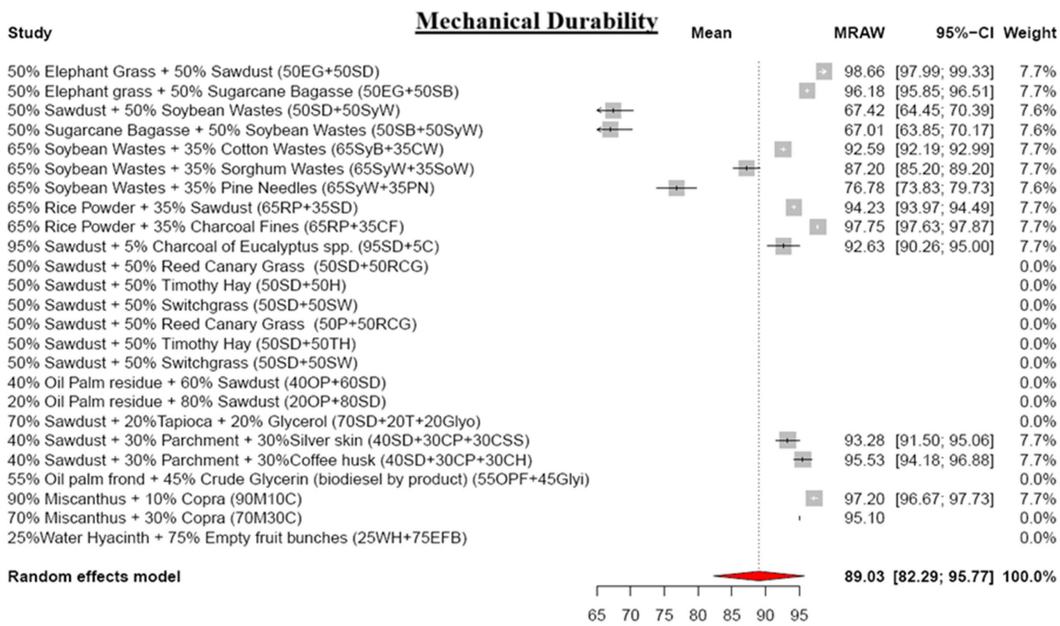

Figure 6. Mean and permissible range of mechanical durability of pellets. The arrow can be seen when the range of the final results goes beyond the range of the graph.

Woody biomass, distinguished by its higher cellulose content than non-woody (agricultural) biomass, accounts for the diminished mechanical durability of pellets produced from agricultural residues, challenging the commercial viability of these solid biofuels [148]. To bolster mechanical stability, contemporary research suggests increasing the proportion of sawdust over non-woody biomass in biomass blends [76,90,115,149].

According to Lavergne et al. (2021) [150], moisture plays a dual role in enhancing particle bonding while also reducing the friction within the die due to its lubricating properties. However, excessive moisture levels can result in the formation of a layer that is too large to effectively hold the particles together [41]. Once an optimal moisture content is achieved, the moisture content enhances not only the durability but also the physical characteristics and overall product quality. Studies have indicated that a higher moisture content diminishes pellet durability [151]. It is recommended that the moisture content falls within the range of 10–15% for optimal results [152].

Furthermore, the size of the particles has a direct effect on the mechanical strength of the biomass pellets. Studies have shown that using smaller particles improves the density, leading to higher yield stress and ultimately resulting in stronger pellets compared to those produced with larger particles [153–155]. It is generally recommended to use particles with a diameter below 5 mm for optimal pellet quality [53,102]. While it is beneficial to have a wide range of particle sizes for improved pellet quality, an excessive amount of fine particles (less than 0.5 mm in diameter) in the raw material negatively influences friction and the overall quality of the pellets [53,156].

Researchers have revealed how the equipment parameters affect the strength and durability of the pellets. Increasing the length of the press channel creates more friction between the biomass particles and the channel walls. This also increases the amount of time for which the material is exposed to heat and pressure [157]. The temperature of the die during pelletizing is mainly influenced by friction [153,157–161]. The die temperature, along with the composition of the feedstock and moisture content, affects the softening of the natural binding agents in the biomass (such as lignin and mono sugars). This leads to the enhancement of the pellet strength and durability and is therefore a major factor in pellet quality [162]. It has been observed that using small die holes with a high die width (a higher L/D ratio) can improve the pellet durability [111,114,146]. However, excessively long die lengths increase friction without providing any additional improvement in pellet durability.

Torrefaction is a common pre-production technique that directly affects the quality of the pellets. Despite its benefits in improving pellet density by reducing the moisture content, enhancing the grinding properties, and altering the chemical compositions [144], it has been observed that torrefied materials have diminished durability properties [136,138,163]. This finding is supported by the analyzed data, as demonstrated by the significantly lower mechanical durability values in torrefied wheat straw pellets compared to non-torrefied pellets (Table 3).

The research and analysis conducted indicated that freezing pellets during storage or transport only has a slight impact on their mechanical durability. If the pellets have a high initial mechanical durability in normal conditions, freezing and subsequent defrosting do not significantly affect their mechanical durability. However, if the pellets have low quality and low initial mechanical durability, their mechanical durability may further decrease if they were previously frozen. Therefore, companies and consumers involved in pellet storage need to consider their mechanical durability index. To minimize the risk of deterioration, it is recommended to prevent freezing pellets by storing them at temperatures above 0 degrees Celsius. However, proper storage practices play a crucial role in achieving a high mechanical durability index (DU > 97.5%) [147].

3.2.5. Fine Particle Content

Excessive fines in pellets can pose challenges during combustion due to the risk of elevated temperatures caused by the rapid burn rate of fine particles compared to pellets [164]. Notably, bagged pellets generally contain fewer fines compared to those delivered in bulk, while pellets stored in silos may exhibit a higher fine particle content upon delivery [165]. The amount of fine particles in pellets is determined by both the ISO

17225-2 and ISO 17225-6 standards. Interestingly, ISO 17225-2 allows for a fine particle content of up to 6% in woody pellets, while ISO 17225-6 requires the fine particle content to be below 3% for biomass pellets. It is important to note that the reasons for this difference in the maximum limits are not documented. However, one possible explanation is that many agricultural biomass materials are more explosive and pose a higher risk of ignition compared to woody biomass. This is due to their lower ignition temperature and lower ignition energy. Another reason could be the mechanical durability (Du) limit, where very good-quality pellets must have a Du higher than 97.5%. This limit helps restrict the presence of loose particles to 3%.

In the meta-analysis of the studied pellets, the fine particle content values consistently fell below the ISO 17225-6 standards, yielding an average value of 1.03%. While soybean waste pellets and sugarcane bagasse pellets individually exhibited higher fine particle content values (3.32% and 44.00%, respectively), the blending of these materials resulted in a lower fine particle content of 2.50%. This observation suggests that the incorporation of multiple biomass materials into pellet production tends to reduce the fine particle content in comparison to pellets derived from a single biomass source (Figure 7).

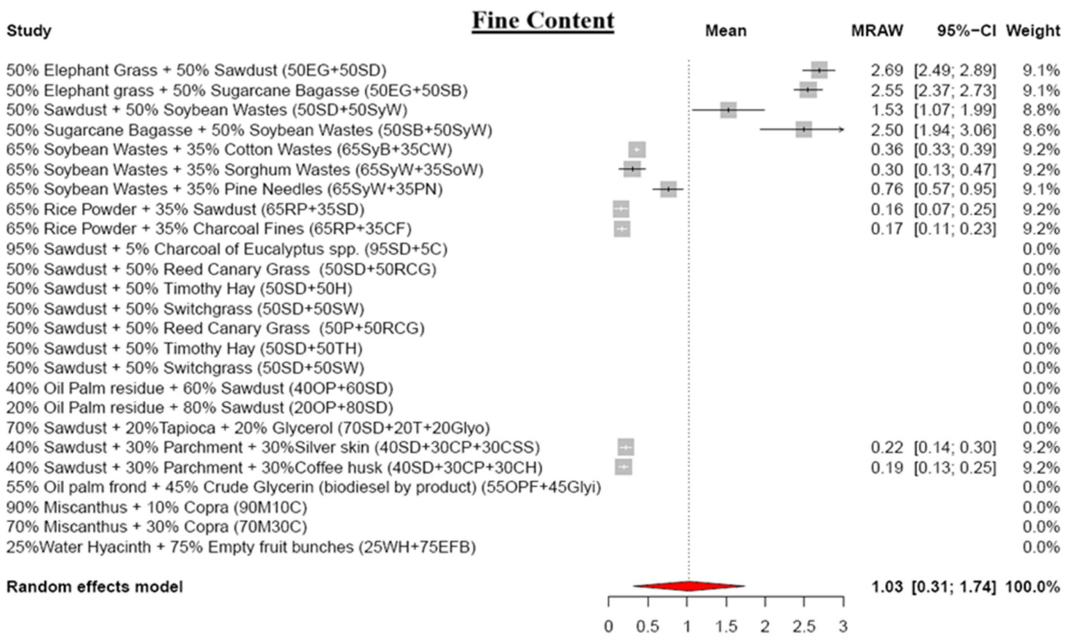

Figure 7. Mean and permissible range of fine particle content of pellets. The arrow can be seen when the range of the final results goes beyond the range of the graph.

3.2.6. Calorific Value

The calorific value of wood pellets is intrinsically tied to the type of raw materials utilized, influenced by the presence of organic components like lignin, cellulose, starch, protein, and fat, which vary across plant species and plant parts. The gross calorific value (GCV) measures the heat generated by burning a unit volume, whereas the net calorific value (NCV) takes into consideration the gross calorific value minus the latent heat in the water caused by hydrogen combustion above an atmospheric temperature. For domestic use, pellets require higher standards of calorific value compared to their industrial counterparts (Table 3).

Recent literature findings underscore the pivotal role of carbon and hydrogen content in boosting pellets' GCV, while ash (A), oxygen, moisture content (MC), and nitrogen content tend to have adverse effects. Blended pellets, incorporating a mix of biomass materials, consistently exhibit an enhanced GCV compared to single biomass pellets. This observation aligns with the previous literature, advocating the blending of agricultural residues with wood as a promising approach to energy production.

The thermal pretreatment process of biomass, such as torrefaction, has been proven to enhance the combustibility of biomass [166–168]. Consequently, biomass retains the majority of its energy components after undergoing torrefaction, resulting in a torrefied product that has a higher calorific value and increased energy density [122,139]. This process is also consistent with the study conducted by Azócar et al. in 2019 [106], which examined pellets made from torrefied wheat straw (Table 3).

Even though the standards provide a permissible limit for the NCV, some studies have examined both the NCV and GCV [92,93,95,102], while others have only examined the GCV/HHV values of the developed pellets [97,99,100,107]. Therefore, the GCV values were used for the meta-analysis, as stated in all the studies.

To address the misinterpretation that may arise when comparing the meta-analyzed values with the permissible limits of the standards, an assumption was made based on studies that present both the GCV and NCV values.

The difference between the GCV and NCV values was calculated for each study [92,93,95,102], and an average value of 2.55 MJ/kg was obtained. It was assumed that this difference represents the calorific value of the water vapor resulting from the combustion of hydrogen and the vaporization of the original water, which is then condensed into a liquid state.

The GCV of the pellets that were analyzed ranged from 17.03 MJ/kg to 18.54 MJ/kg, with an average of 17.79 MJ/kg. Based on the above assumption, the NCV can be calculated as 15.24 MJ/kg, which is higher than the lowest NCV of 14.5 MJ/kg mentioned in the ISO standard (Table 3). Therefore, it can be concluded that the meta-analysis results of the NCV suggest that biomass blends are a favorable source for industrial usage in terms of the NCV (Figure 8).

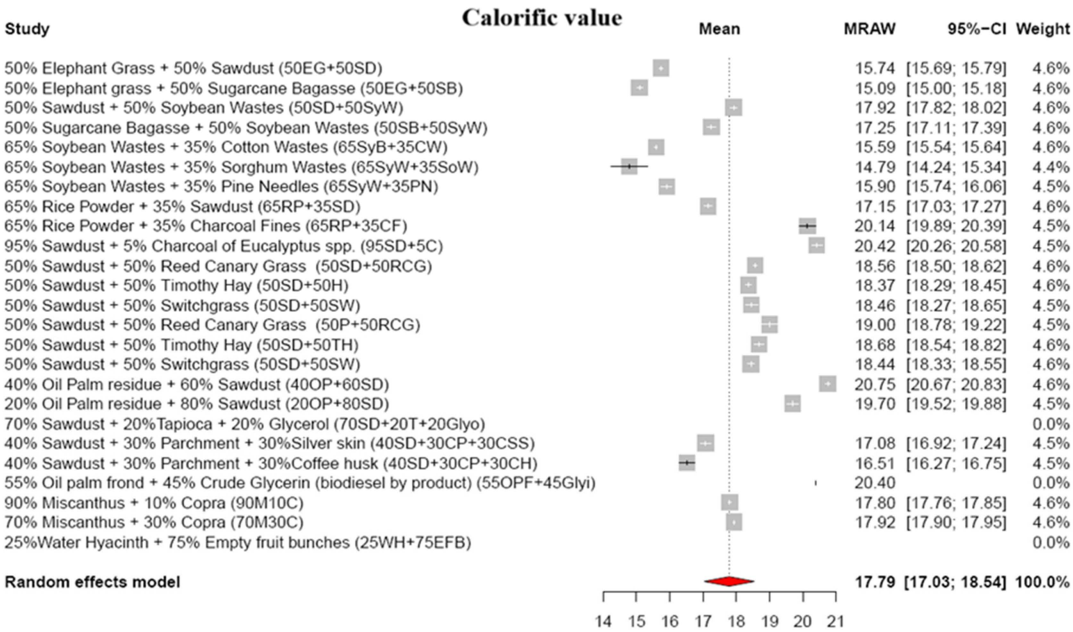

Figure 8. Mean and permissible range of gross calorific value of pellets.

When the sawdust percentage increases in the biomass blends, an increment in the GCV can be seen [102,161]. In other words, the heating value of a material is linearly related to its lignin content [169]. Further, Serrano et al., 2011 [125] described that pellets produced from mixtures of herbaceous and woody materials with a low ash content and high lignin content will help to improve the heating value of the pellets produced [93].

3.2.7. Bulk Density

The bulk density of pellets is determined by the particle density and overall bulk porosity. Elevating the pellet bulk density not only heightens the energy density within the compressed pellets but also streamlines transport and storage, simplifying logistics. The ISO standards for pellets mandate a minimum bulk density of 600 kg/m^3. Concurrently, blended biomass pellets, typically comprising various lignocellulosic materials, consistently exhibit elevated bulk density values. This phenomenon is notably associated with the chemical composition of biomass mixtures, specifically the presence of cellulose, hemicellulose, lignin, and extracts. An increase in cellulose and lignin content augments the bulk density, as both these components serve as natural binders. The analyzed blended biomass pellets, with a few exceptions, demonstrate higher bulk density values than their single biomass counterparts. Most of the studied bulk density values fall within the range of 600–700 kg/m^3, with a mean bulk density of 666.52 kg/m^3 extracted from the meta-analysis (Figure 9).

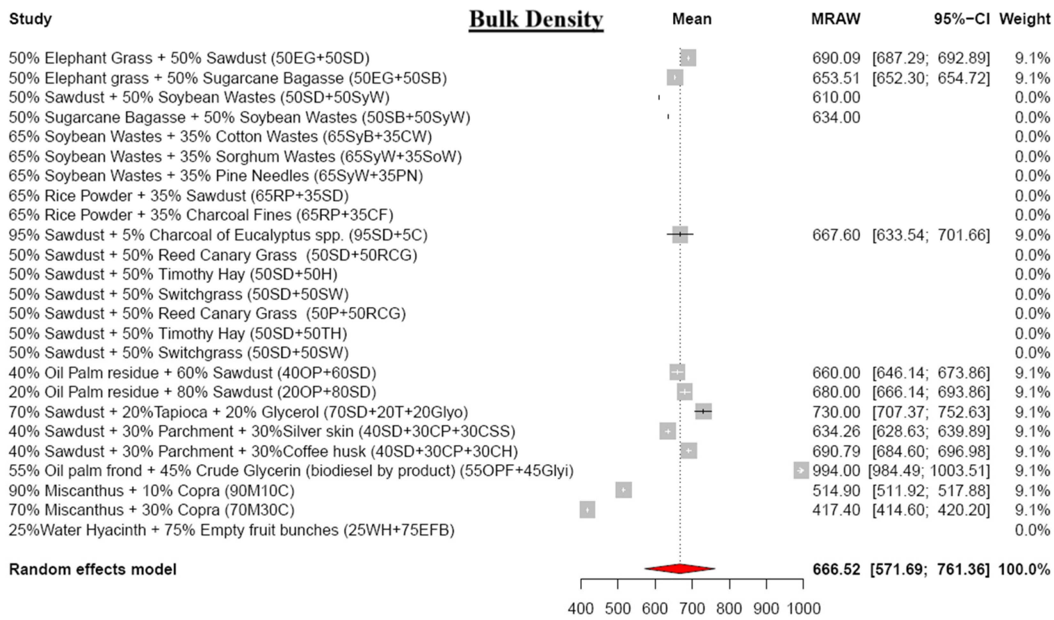

Figure 9. Mean and permissible range of bulk density of pellets.

3.2.8. Elemental Analysis of Pellets

The ISO 17225 standard series focuses on various elements present in biomass pellets, including nitrogen (N), sulfur (S), chlorine (Cl), and heavy metals such as arsenic (As), cadmium (Cd), and chromium (Cr), among others. Nevertheless, the ISO 17225-6 standards establish notably elevated permissible thresholds for nitrogen, sulfur, and chlorine, surpassing the ISO 17225-2 guidelines. According to the literature, it is possible to strategically control these elemental contents by carefully selecting biomass materials and their mixing compositions [92,100].

Nitrogen

Nitrogen is permitted at 1.5% in ISO 17225-6 category A, while category B allows for 2.0%. Although the meta-analysis reveals a mean nitrogen content of 1.49%, most analyzed studies report nitrogen levels exceeding these standards (Figure 10). Notably, agricultural residues like sugarcane bagasse, sorghum, coffee residues, soybean residues, and elephant grass naturally contain an elevated nitrogen content. Such disparities in nitrogen levels can be attributed to the use of fertilizers during crop growth. The nitrogen content of residual biomasses from coffee production, specifically stem bark and leaves, was reported to be 2.13% and 3.54%, respectively. In conclusion, the intrinsic properties of the biomass significantly influence the pellet quality, with blended biomass pellets generally exhibiting a lower nitrogen content than their single biomass counterparts.

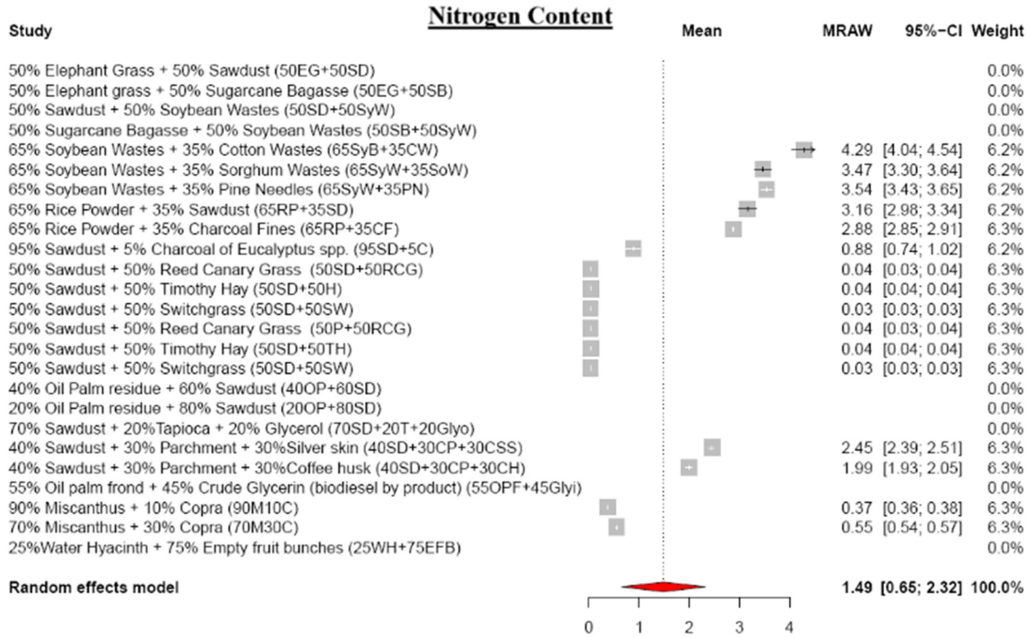

Figure 10. Mean and permissible range of nitrogen. The arrow can be seen when the range of the final results goes beyond the range of the graph.

Sulfur

In the ISO 17225-6 standards, the allowable sulfur content for non-woody biomass pellets stands at 0.20% for category A and 0.30% for category B. While these limits may appear relatively low, they are essential for mitigating sulfur emissions during biomass combustion, in accordance with stringent emission policies. All the examined blended biomass pellets conform to the prescribed standards (Figure 11). Notably, only pellets derived from soybean waste and cotton waste (65SyB and 35CW) exhibited sulfur content levels surpassing those of ISO 17225-6 category A, with a mean sulfur content of 0.08%. This pattern of adhering to the standard sulfur limits holds for both blended biomass and single biomass pellets.

Chlorine

In compliance with the ISO 17225-6 standards, the allowable chlorine content in biomass pellets is significantly restricted (0.1% in category A and 0.3% in category B). It is noteworthy that although biomass generally exhibits lower nitrogen, sulfur, and chlorine contents, these elements can lead to combustion chamber corrosion and the emission of greenhouse gases, akin to the effects of ash and fines [42,170,171]. In specific agricultural biomasses, reed canary grass and switchgrass demonstrated elevated silicon levels, while timothy hay displayed a heightened potassium content. However, when reed canary grass was blended with woody biomass, the silicon content decreased by nearly half compared to the individual reed canary grass [96]. Alkaline minerals such as calcium, phosphorous, chloride, and potassium, although not significantly impacting pelletization, can result in severe issues like corrosion, slagging, and fouling within thermal systems during combustion formation [100,161,172–174].

However, the test parameters for chloride could not be found in the analyzed literature. This could be due to the calculation of ash and fine particle contents separately. Nevertheless, these findings indicate that biomass residues can be harnessed in pellet production with further research and development [96].

3.2.9. Volatile Matter Content

The volatile matter content in biomass significantly impacts its reactivity, contributing to increased frictional heat. Biomass solid fuel, possessing a higher volatile matter content, exhibits a swifter combustion rate during devolatilization, rendering it easier to ignite and burn effectively [97]. Research by Kataki and Konwer, 2002 [175] reinforces that pellets with over 30% volatile matter yield greater heat and facilitate quicker and more efficient combustion. It is noteworthy that agro-pellets display a variable volatile matter content, ranging from 9.40% to 89.31% [99] and 79.58% to 85.11% [176]. The analysis of these studies reveals a mean volatile matter content of 80.55%, aligning closely with the reported ranges of 76.99% to 84.11% (Figure 12). Similar to other properties, blended biomass pellets exhibit a higher volatile matter content compared to the raw biomass before compaction [93].

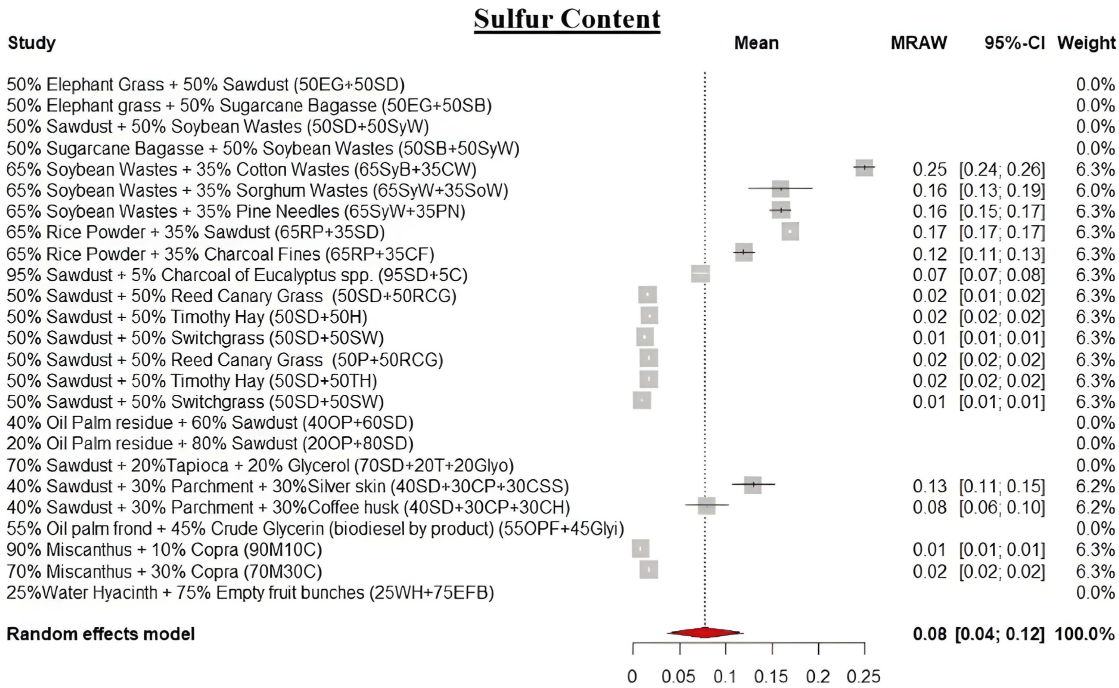

Figure 11. Mean and permissible range of sulfur.

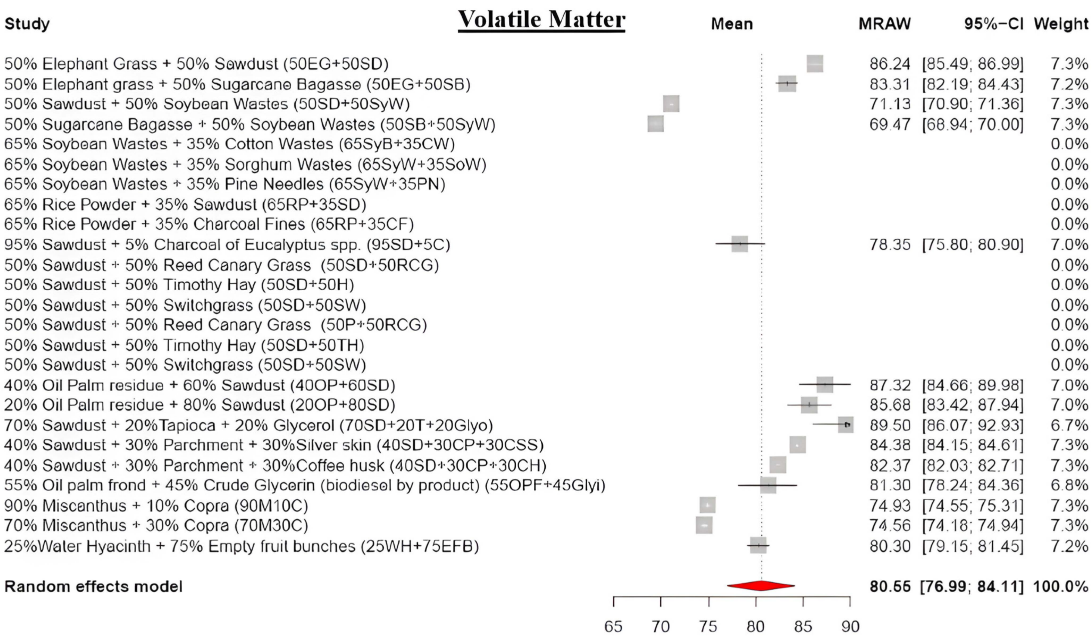

Figure 12. Mean and permissible range of volatile matter. The arrow can be seen when the range of the final results goes beyond the range of the graph.

3.2.10. Fixed Carbon

The inherent low fixed carbon content of biomass renders it an exceptional and highly reactive fuel. This attribute facilitates rapid combustion, as biomass with a low carbon content tends to burn more swiftly [97,135]. One study [93] substantiates this observation by noting a reduction in fixed carbon content following the pelletizing process. The meta-analysis conducted on various samples yielded a mean fixed carbon content value of 12.98% (Figure 13).

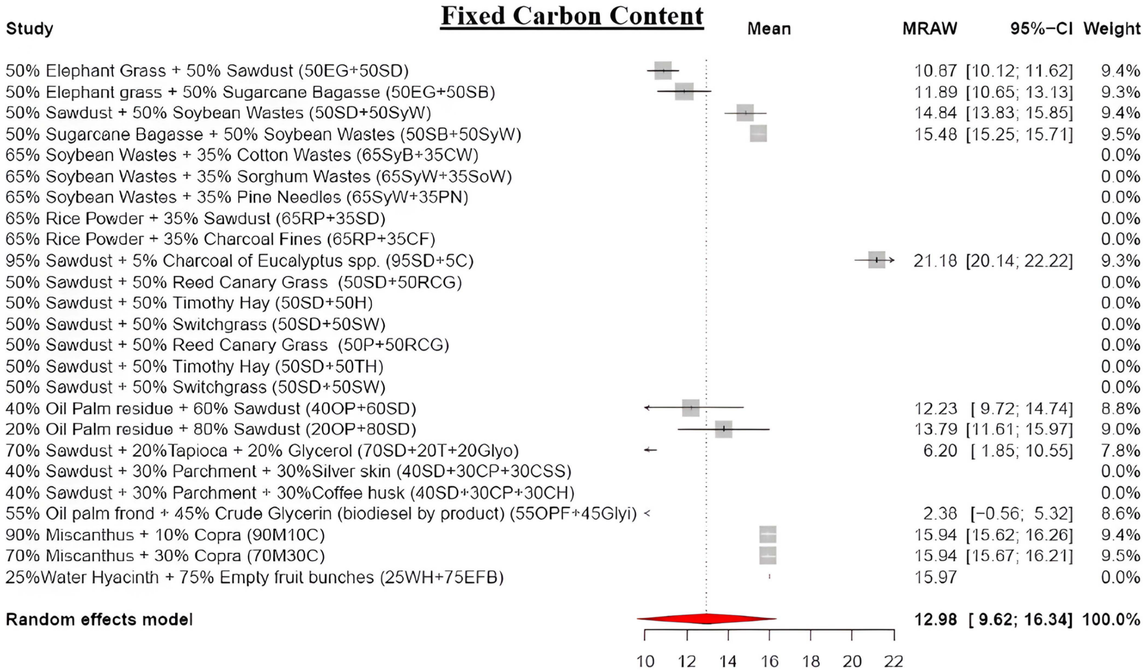

Figure 13. Mean and permissible range of fixed carbon content. The arrow can be seen when the range of the final results goes beyond the range of the graph.

4. Conclusions

The findings of this study suggest that combining non-woody biomass (such as agricultural residues) with sawdust can provide a viable and environmentally friendly method for generating energy. Additionally, the study indicates that using a blend of non-woody and woody biomass in pellet production results in higher-quality pellets.

Furthermore, various agricultural residues such as palm oil industry waste, sugarcane industry waste, rice industry waste, soybean industry waste, and other environmentally generated materials like water hyacinth can be explored as raw materials for biomass pellet production. This approach has the potential to provide a lasting solution for waste management and promote the development of rural livelihoods, notably in developing nations.

Challenges persist in processing lignocellulosic biomass waste materials, specifically in optimizing the compositions of various biomass types. If these issues can be addressed via continued research and development, biomass pellets derived from unconventional materials have the potential to compete with wood pellets as a sustainable heat generation source. Notably, studies have identified nitrogen and ash content as the most restrictive parameters for achieving high-quality pellets.

After examining the researched studies and evaluating the parameters, it becomes clear that pellets made from a mixture of woody and non-woody materials are considered to be of intermediate quality between 100% woody and non-woody biomass pellets. They boast higher heating values, mechanical durability, hardness, and reduced fine particle and ash contents in comparison to pellets derived from single non-woody biomass materials. Blended biomass pellets are also known to possess a heightened ability to release more energy per unit volume during the combustion process, resulting in reduced particle emissions, CO emissions, and minimized slag formation. These superior quality parameters are guaranteed since the mixed pellets contain a portion of woody biomass that possesses higher-quality parameters.

However, certain gaps still exist within this field. The temperature and pressure applied during the pelletization process are essential factors that require further exploration. Although the present analysis does not provide substantial evidence for the relationship between pelletizing temperature and pressure and their involvement in mechanical durability and bulk density, it is clear that elevated pelletizing temperatures lead to lower pressure requirements.

In summary, the meta-analysis results provide mean values for various parameters including diameter (6.37 mm), length (15.65 mm), moisture content (7.48%), ash content (4.19%), fine particle content (1.03%), gross calorific value (17.79 MJ/kg), bulk density (666.52 kg/m^3), nitrogen content (1.49%), sulfur content (0.08%), volatile matter content (80.55%), and fixed carbon content (12.98%). All these mean values align with the requirements of both EN ISO 17225-6 standard categories A and B. However, mechanical durability is the exception, showing a lower value than the standards dictate (89.03%). This deviation is attributed to the lower mechanical durability values of pellets produced from non-woody biomass mixtures.

Based on the findings of the examined research, it is advisable to consider the utilization of a composition range of 0–50% non-woody biomass (varying according to the specific material type) in conjunction with woody biomass to produce mixed pellets. This process should be conducted at a pelleting temperature exceeding 80 °C, alongside a pelleting pressure of approximately 29.42, as it yields superior quality parameters.

Moreover, the study highlights that the bulk density and mechanical durability values are generally lower in blended biomass pellets, which can vary by the raw material types and blending compositions.

Consequently, conducting thorough test runs and adhering to quality standards is crucial when introducing any new biomass or agricultural residues as raw ingredients into pellet production. Potential methods for enhancing product quality and efficiency include machinery modification, steam explosion, torrefaction, and other processes. The successful development of these waste-to-energy products stands to positively impact global energy needs and industrial sustainability.

In light of the current analysis, it is recommended to:

- Optimize biomass compositions: Selecting the right blend of woody and non-woody materials and their proportions ensures high-quality biomass pellets.
- Machinery and process modifications: Innovative processes such as steam explosion and torrefaction shall be considered to improve the pellet quality.
- Encourage agricultural residue utilization: Exploring the use of agricultural residue as raw materials can contribute to effective waste management and the development of sustainable energy solutions.
- Prioritize research into compositional effects: Further investigation into the influence of pelletizing temperature and pressure on pellet properties is warranted.
- Manage elemental content: Careful selection of biomass materials and blending compositions can effectively manage the nitrogen and ash content, resulting in higher-quality pellets.
- Consider woody materials: To enhance the pellet quality, incorporating a higher percentage of woody materials into biomass blends is recommended.

This meta-analysis analysis provides valuable insights into the improvement of biomass pellet quality and sustainability, which holds great promise in addressing global energy challenges.

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