

Review

A Systematic Review of Mechanical Pretreatment Techniques of Wood Biomass for Bioenergy

Giorgia Di Domenico ¹, Elisa Cioccolo ¹, Leonardo Bianchini ¹, Rachele Venanzi ¹, Andrea Colantoni ¹, Rodolfo Picchio ^{1,*}, Luca Cozzolino ² and Valerio Di Stefano ³

¹ Department of Agriculture and Forest Sciences (DAFNE), University of Tuscia, 01100 Viterbo, Italy; giorgia.didomenico@unitus.it (G.D.D.); elisa.cioccolo@unitus.it (E.C.); l.bianchini@unitus.it (L.B.); venanzi@unitus.it (R.V.); colantoni@unitus.it (A.C.)

² Research Centre for Engineering and Agro-Food Processing, Council for Agricultural Research and Economics (CREA), 00015 Rome, Italy; luca.cozzolino@crea.gov.it

³ Research Centre for Forestry and Wood, Council for Agricultural Research and Economics (CREA), 00166 Rome, Italy; valerio.distefano@crea.gov.it

* Correspondence: r.picchio@unitus.it

Abstract

Lignocellulosic biomass is an exciting renewable resource for producing sustainable biofuels, thanks to its abundance and low environmental impact. However, its intricate structure makes it tough for enzymes to break it down effectively. Only efficient pretreatment methods can solve these problems. Among these, mechanical pretreatment methods are particularly good for industry because they are easy to use, do not require chemicals, and make it easier to achieve biomass. This systematic review adhered to the PRISMA protocols and used text analysis with VOSviewer to examine 33 academic articles published between 2005 and 2025. It highlighted two main types of mechanical pretreatment: size reduction (which includes grinding, crushing, and shredding) and densification (like pelletizing and briquetting). The results show that mechanical pretreatment can significantly boost biofuel yields by increasing surface area, lowering crystallinity, and allowing better enzyme penetration. Energy consumption remains a major hurdle for the overall sustainability of biomass conversion processes. This research provides a comprehensive review of current mechanical techniques, detailing their operational settings and performance metrics while also offering suggestions for optimizing biomass conversion processes. By promoting the use of mechanical pretreatment in biofuel production systems, the findings align with the principles of a circular economy and contribute to the development of greener energy sources.

Keywords: lignocellulosic biomass; mechanical pretreatment; energy potential; biofuel



Academic Editors: Byong-Hun Jeon and Albert Ratner

Received: 29 April 2025

Revised: 28 May 2025

Accepted: 18 June 2025

Published: 24 June 2025

Citation: Di Domenico, G.; Cioccolo, E.; Bianchini, L.; Venanzi, R.; Colantoni, A.; Picchio, R.; Cozzolino, L.; Di Stefano, V. A Systematic Review of Mechanical Pretreatment

Techniques of Wood Biomass for Bioenergy. *Energies* **2025**, *18*, 3294. <https://doi.org/10.3390/en18133294>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Lignocellulosic biomass is a renewable raw material consisting mainly of polysaccharides (cellulose and hemicellulose) and an aromatic polymer (lignin) [1]. This biomass includes agricultural residues (such as straw and corn stover), forest residues (branches, bark, and sawdust), dedicated energy crops (such as miscanthus), and waste from the wood industry. It represents a promising resource due to its abundance, sustainability, and potential for conversion into advanced biofuels. The reuse of lignocellulosic biomass, and in general of all agricultural and forestry waste, is one of the objectives of the main international and European policies such as Agenda 2030 (SDG 12) and the European

Green Deal to combat climate change and to encourage sustainable production in a circular economy perspective [2].

According to recent statistics, globally the annual production of lignocellulosic biomass is about 181.5 billion tons, of which only 8.2 billion tons of lignocellulosic biomass is used in different application areas [3,4]. However, its complex structure, characterized by high cellulose crystallinity and the presence of lignin, hampers the efficiency of biochemical conversion, and it is therefore necessary to apply appropriate pretreatment to improve its accessibility to enzymes and microorganisms used in transformation processes. Pretreatment thus emerges as an essential prerequisite for improving the digestibility of cellulose by removing hemicelluloses and/or lignin or reorganizing them in the cell wall, thereby increasing the accessibility of cellulose “Huang” [5]. In some cases, legislation itself requires the mandatory pretreatment of the good mass in order to improve the quality of the new product and its efficiency in new uses.

The different types of pretreatments are distinguished by the processing techniques adopted to improve the structure of the biomass, favoring its degradability and optimizing the efficiency of subsequent conversion steps. In addition to delignification, defragmentation and partial biomass depolymerization are two additional useful steps in the overall pretreatment process [6].

Traditional pretreatments include physical, chemical, and biological methods [7]. However, combinations of these approaches can further optimize the yield of biomass conversion, with physical–chemical methods being among the most promising [8].

Physical pretreatments, in addition to the mechanical ones that we will explore below, include techniques that can modify fundamental biomass properties, such as porosity and particle moisture, often employed to improve the yield of enzymatic hydrolysis [9] and to optimize subsequent steps of conversion [10]. These include ultrasonic treatment, which uses high-energy ultrasonic vibrations to alter the crystal structure of the lignocellulose, facilitating its breakdown [11]; extrusion, a mechanical process that subjects the biomass to high temperatures and pressures, improving its degradability [12,13]; and microwave exposure, which uses radiation to break down the lignocellulosic structure and release intracellular cellulose [14].

Chemical pretreatments employ organic or inorganic compounds to degrade the biomass structure by interacting with the intra- and interpolymer bonds of the primary organic components [15]. The effectiveness of these treatments depends on the characteristics of the reagents used and the severity of pretreatment [16]. For example, acid pretreatment effectively degrades hemicellulose and cellulose [17], while alkaline and oxidative pretreatment increase the surface area of the biomass, improving its biodegradability [18].

While physical pretreatments aim to reduce biomass size through mechanical means, chemical pretreatments use distinct chemicals and solvents to minimize lignin content through reactions [19]. In biological treatment, neither external energy input nor additional chemical supplementation is required; these, in fact, deal with microorganisms producing enzymes to degrade the lignocellulosic structure, significantly changing the chemical and physical structure of the biomass [20]. It is clear, therefore, that the correct pre-treatment of biomass, in addition to being necessary in some specific cases, guarantees a better quality of the product and a greater reuse in different economic and productive contexts [21].

This review aims to systematically analyze the main mechanical pretreatments applied to lignocellulosic biomass, examining their mechanisms, effects on biomass structure, and their role in improving conversion to biofuels. In fact, mechanical pretreatments are essential to modify the biomass from a physical point of view, making it more suitable for subsequent processing, transport, and storage and because these represent a significant part of the energy costs of the biomass–biofuel supply chain: analyzing them helps to

understand the trade-off between energy spent on pretreatment and energy produced [22]. This article offers a structured, data-driven overview of global research on the mechanical pretreatment of lignocellulosic biomass for biofuel production, providing valuable insight into the field's evolution, key contributors, and thematic trends. Through bibliometric analysis, it consolidates fragmented knowledge across disciplines such as bioenergy, agricultural engineering, and materials science, fostering interdisciplinary dialogue. By highlighting underrepresented regions and research gaps, it encourages more inclusive and context-sensitive approaches—particularly in countries rich in biomass but lacking access to adapted technologies. The focus on mechanical pretreatment aligns with global efforts to enhance the economic viability of second-generation biofuels. Overall, the study supports strategic decision-making in research funding, technology development, and sustainability policy while also serving as a foundation for future meta-analyses and long-term assessments of how research aligns with climate and bioeconomy goals.

Mechanical Pretreatment

In general, mechanical pretreatment is considered more appropriate for industrial applications than alternative methods (e.g., thermal, chemical, and biological) [23]. The mechanical method is the simplest and most direct pretreatment method, which can increase the specific surface area of the raw material, destroy the crystallization zone, and reduce the crystallinity of cellulose [24]. These physicochemical modifications are crucial: the reduction in crystallinity makes cellulose more accessible to enzymes, while the increased specific surface area provides more reaction sites. Furthermore, the disruption of the complex lignocellulosic structure facilitates the release of sugars, improving the efficiency of enzymatic hydrolysis and, consequently, the production of biogas or bioethanol. In addition, the absence of chemicals in mechanical pretreatment makes it ecologically beneficial, avoiding the formation of toxic byproducts. On the other hand, this process requires high energy consumption [25], which can significantly affect the overall operating costs [19]. According to Ortega et al. [26], the cost of the pretreatment stage is responsible for about one-third of the total cost of biofuel production. In addition, cellulose in lignocellulosic biomass is easily recrystallized, and lignin/hemicellulose cannot be degraded after physical milling, which remains an obstacle for enzymatic hydrolysis [27] with a direct impact on the efficiency of energy conversion processes. These pretreatments can be classified according to the crushing mechanism used and the particle size obtained, which in turn influences the efficiency of subsequent treatments. We can distinguish two main subgroups of mechanical pretreatments: the first is concerned with reducing biomass size, while the second focuses on increasing surface density (Figure 1).

In the first subgroup, grinding is the most common technique [28], but there are several mechanical methods that lead to variable size reduction of biomass with different effects on its structure. These methods include cutting, fragmenting biomass using sharp tools, and generating particles of variable size. The length of the particles depends on the characteristics of the material and the configuration of the blades. Similarly, shearing employs a lateral shearing force between two moving flat surfaces, generating particles with more irregular shapes. The difference between these two methods lies at the point of fiber breakage: in cutting, fracture occurs more uniformly along the fiber, while in shearing, breakage occurs along lines of structural weakness, producing fewer regular particles. Both methods require the use of specific tools, such as brush and crimper for cutting [29] and rotary shears, knife mills, and vane testers for shearing [30]. Crushing, on the other hand, is distinguished by its use of compression between solid surfaces, reducing the size of the biomass into smaller, irregular particles, with a significant impact on the bulk density and fibrous structure of the material. Unlike shearing methods, which separate fibers, crushing

crushes and reduces them, improving density and increasing responsiveness to subsequent treatments. The tools used here are mainly biomass crushers [31]. Crushing pretreatments combined with techniques such as alkali-mechanical treatment has been shown to improve carbon yield (CH) and reduce costs [32].

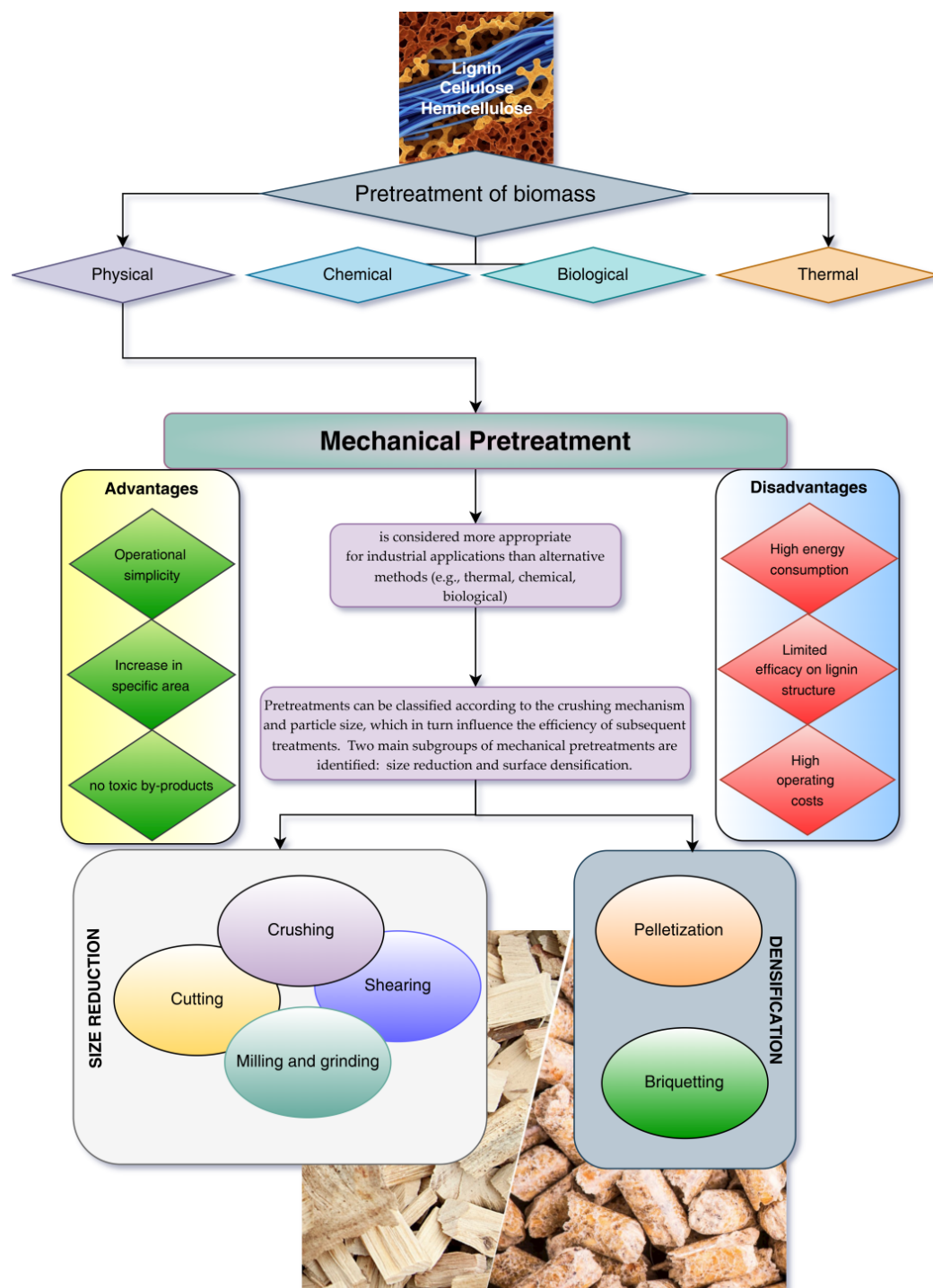


Figure 1. Mechanical pretreatment flowchart.

Other methods such as tearing and breaking separate the biomass into smaller particles, increasing the specific surface area available for chemical reactions, thus improving efficiency in energy conversion processes [33]. These processes are carried out by tools such as ball mill, roll mill, and screw extruder [28].

Milling is the most effective method for size reduction of biomass, producing particles smaller than 1 mm and significantly increasing the reactivity of the material [34]. During this process, the material undergoes intense mechanical stress, which changes the physicochemical characteristics of the biomass, further improving its reactivity for subsequent steps. The particles obtained by grinding (0.2–2 mm) are smaller than those produced by milling (10–30 mm), with a significant increase in surface area for chemical reactions. Tools used for these processes include disk mills, wet disk mills, hammer mills, tumbler ball mills, planetary ball mills, vibrational ball mills, roller mills, rod mills, and jet mills [34,35].

The second subgroup of pretreatments includes mechanical pretreatments which are not limited to reducing the size of the biomass but aim to increase its density. Indeed, densification or compaction leads to a significant increase in the bulk density of biomass, which can increase from about 40–200 kg/m³ to values between 600 and 800 kg/m³ [36]. This increase in density not only facilitates transport and storage, reducing costs, but also helps to improve energy efficiency in subsequent conversion processes [37]. Biomass densification consists of three basic steps: particle reorganization, plastic and elastic deformation of the particles, and mechanical interlocking [38]. Each step contributes to giving the densified biomass the desired characteristics in terms of strength, stability, and ability to be used in energy conversion processes. In addition, densification improves several biomass properties, including density, hardness, water and impact resistance, durability, and calorific value [39].

There are several methods of densification, but the most widely used are pressure agglomeration, which involves mechanical compression of the biomass [40], and drum agglomeration, in which binding agents are used to facilitate the joining of the particles [41]. Among the main pressure agglomeration methods, pelletization and briquetting are the most common techniques to prepare biomass for thermochemical conversion processes [19], generally using pellet mills and briquette presses. These methods make the biomass more compact and uniform, improving the efficiency of energy conversion. However, the quality of the densified material and its calorific value depend on several factors including particle size, moisture content, and chemical composition of the biomass [42].

There are different strategies to reduce the energy costs of the pretreatment of lignocellulosic biomass, which represents a good part of the total energy costs. First of all, cutting-edge machinery with low energy consumption or powered by renewable energy sources could be used. From this perspective, making the company self-sufficient from an energy point of view with systems aimed at self-consumption, which guarantees energy independence from third-party sources, could be a valid solution to reduce the costs of pretreatments. It would be interesting and useful to create a “closed”-type energy system where the energy produced by the biomass is partially used for mechanical pretreatments. Furthermore, but no less important, is the use of digitalized control systems in the pretreatment phases, which are capable of optimizing the use of the energy resource, both from the perspective of agriculture 4.0 and in contributing to reducing such expenses. It is clear, however, that the energy costs, even if reduced thanks to the techniques mentioned here, will always have to be supported by a company interested in the mechanical pretreatments of biomass.

From the perspective of physical and energy properties, pelleting produces biomass with a density of up to 700 kg/m³ and an energy density of 9.8–14.0 GJ/m³ [43]. Briquettes, though like pellets in shape, have a larger size (about 32 mm in diameter and 25 mm in thickness) and a lower density of about 350 kg/m³, with an energy density of 6.4 GJ/m³ [43]. A significant advantage of pellets over briquettes lies in their ability to combine, in large-scale operations, simplified bulk handling with high production density. This results in a densified product that offers both good energy yield and improved logistics in terms

of transportation and storage [44]. In addition, the pellets have a consistent and uniform quality, making them particularly suitable for large-scale industrial applications.

The densification or compaction of ground agricultural biomass into pellets is an essential process for biofuel production [36].

2. Materials and Methods

To truly understand the current state of research, we undertook a comprehensive review of mechanical pretreatments for lignocellulosic biomass aimed at biofuel production. This area has recently received considerable attention, driven by the growing need for environmentally friendly energy alternatives and the promise of plant biomass as a reusable resource. When we started our search for keywords with phrases like (biomass OR biofuel OR mechanical pre-treatment), we were flooded with a vast number of articles. This flow of text accentuates the variety of the topic and underlines the need for a structured method to screen information. We chose a text mining strategy to make the literature easier to manage. Using VOSviewer (<http://www.vosviewer.com>), a robust tool for bibliometric analysis, we sought to improve our understanding of the main research domains in the literature concerning lignocellulosic biomass and its mechanical pretreatment techniques. Using VOSviewer, we were able to see how different words and ideas are connected, which helped us pinpoint what is popular at this time and what needs more study. Considering 'all keywords' as a unit of analysis and using 'totalization' as a counting method, we created an initial list of the most frequently cited terms in the literature (cf. Figure 2).

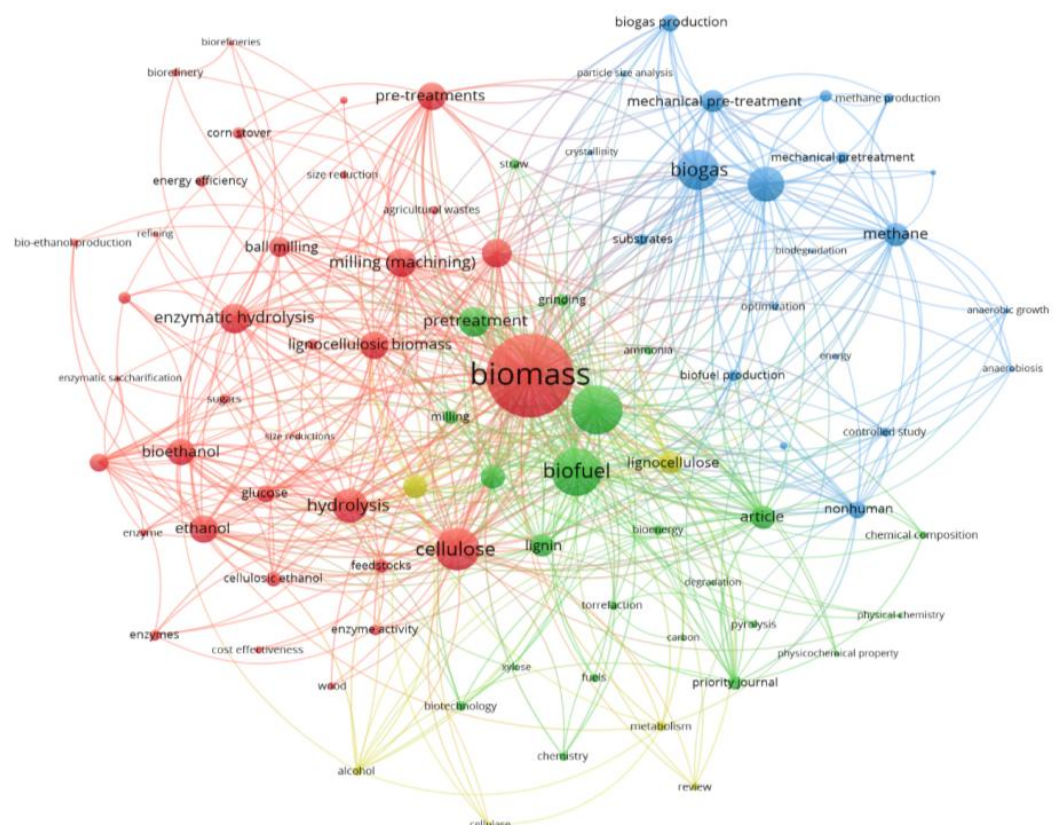


Figure 2. VOSviewer image presenting a bibliometric network visualization focused on the research field of lignocellulosic biomass and its mechanical pretreatment techniques. The nodes (circles) represent keywords used in the literature. The size of each node indicates the frequency of that keyword's appearance: larger nodes correspond to more commonly used terms. The colors distinguish clusters of keywords that tend to co-occur, revealing thematic groupings.

After pinpointing the relevant keywords with VOSviewer, we broke our methodology down into two key parts that are closely linked: a systematic literature search strategy and a detailed literature review. This two-pronged approach not only strengthened our findings but also enabled a deeper and more comprehensive exploration of the research question we are tackling. The first part of our methodology focused on the systematic literature search strategy. We gathered scientific articles from trusted databases like Scopus and Web of Science, which helps ensure that our sources are both credible and high quality. Our search utilized a thorough mix of terms, specifically: (“lignocellulosic biomass” OR “biomass”) AND (“pretreatment” OR “pre-treatment”) AND (“biofuel” OR “bioethanol” OR “biogas”) AND (“mechanical pretreatment” OR “size reduction” OR “milling” OR “grinding” OR “crushing” OR “pressing” OR “shredding” OR “chipping” OR “densification”). This careful method aimed to find original research articles published between 2005 and 2025, focusing on the fields of “title”, “keywords”, and “abstract.” To make sure the literature was relevant and accessible, we primarily conducted our search in English and favored open-access publications, which help spread knowledge more widely. In our pursuit of high-quality information, we decided to exclude non-original works like book chapters, conference proceedings, theses, and encyclopedias, concentrating only on peer-reviewed journal articles that directly contribute to the field. The second part involved a thorough analysis of the literature, following the PRISMA statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) as detailed by Tricco et al. [45].

The PRISMA framework includes a detailed flow-chart that graphically represents the systematic process of screening, selecting, and including articles in the review, providing transparency and replicability in our methodology (Figure 1).

The screening process of the articles was conducted in three distinct phases: (a) title screening, (b) abstract assessment, and (c) eligibility determination following a full-text evaluation. Throughout this rigorous process, we meticulously recorded the number of records considered at each stage, ensuring that our review is grounded in a robust and comprehensive dataset.

3. Results

In order to find pertinent research publications on the subject of mechanical pretreatments of lignocellulosic biomass for the production of biofuel, a thorough and organized literature search was carried out utilizing two of the most well-known scientific databases, Scopus and Web of Science (WoS). To capture both historical and current developments in the subject, the search was conducted between 2005 and 2025.

3.1. Initial Search Results and Data Collection

Boolean operators and targeted keywords were used in the search strategy to optimize the retrieval of pertinent papers. Consequently, a total of 170 publications were found by the first search, including 39 articles from Web of Science and 131 articles from Scopus (Figure 3).

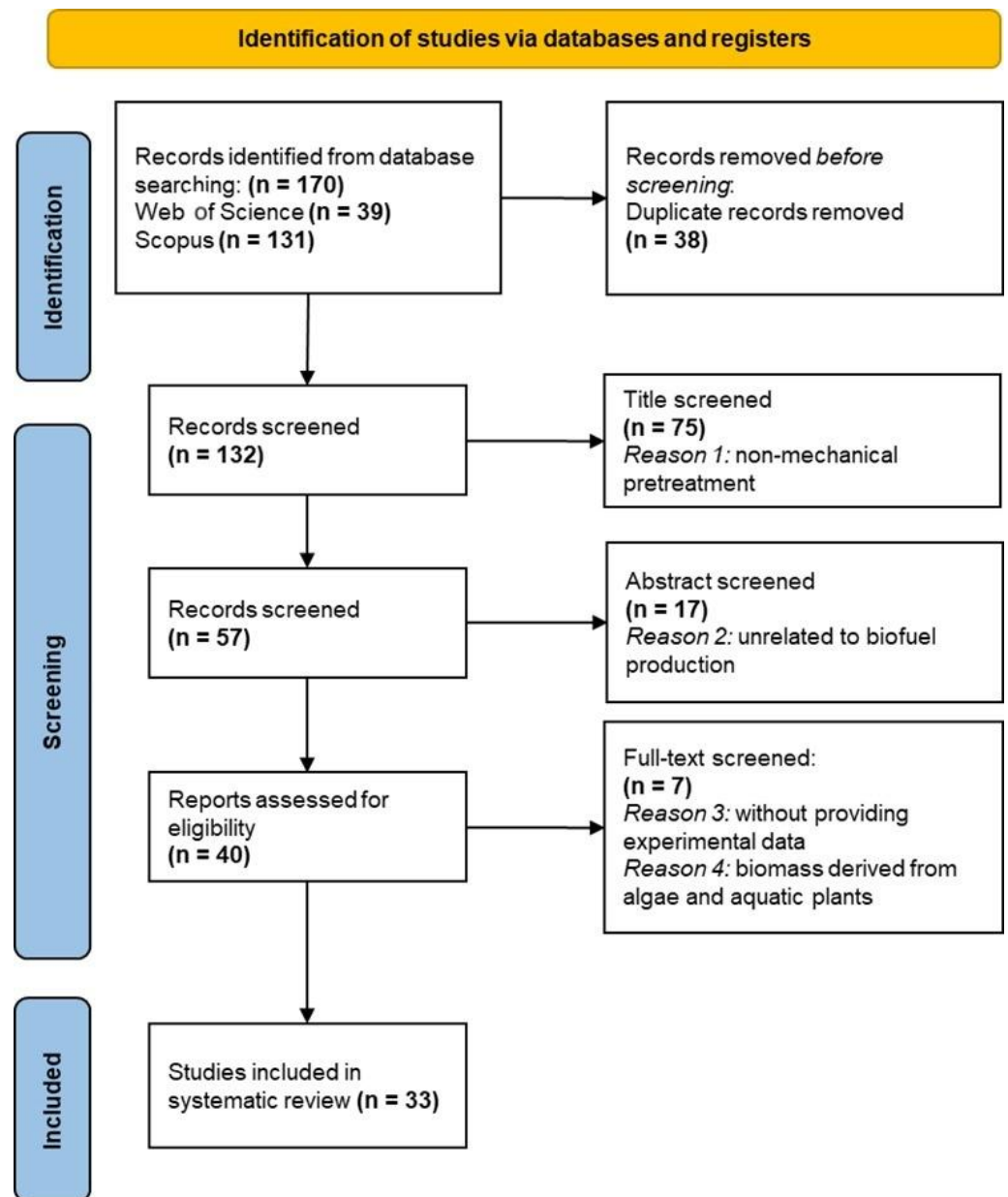


Figure 3. PRISMA flowchart: identification of studies and selection of articles included in the review.

3.2. Duplicate Removal and Preliminary Screening

Once the articles were collected, an essential duplicate removal step was performed to eliminate overlapping records retrieved from both databases. This process identified 38 duplicate entries, which were subsequently removed, leaving 132 unique articles. The next step involved a preliminary screening of titles and abstracts to determine the suitability of each study for inclusion in the review. The primary criteria for exclusion were as follows:

- Studies that focused on non-mechanical pretreatment methods, such as chemical, enzymatic, or thermochemical approaches (such as Song et al. [20]).
- Research unrelated to biofuel production, such as those exploring lignocellulosic biomass for applications in materials science, pharmaceuticals, or composite production (such as Patel et al. [46]).
- Papers discussing the characterization of biomass derived from algae and aquatic plants (such as Hütter et al. [47]).

3.3. Refinement of the Dataset and Final Selection

Ninety-two publications were eliminated after this thorough screening process because they did not fit the study's specified target. The methodology, experimental design, and results of the remaining 40 papers were examined in further detail during a secondary examination. At this stage, 7 additional articles were excluded because they lacked experimental validation, had insufficient data on mechanical pretreatment techniques, or provided only theoretical models without practical implementation.

After this multi-stage selection process, a final set of 33 articles was chosen for an in-depth review and analysis. These selected studies represent the most relevant and high-quality research on mechanical pretreatment techniques, their efficiency, energy consumption, and impact on lignocellulosic biomass conversion into biofuels.

3.4. Manual Screening and Validation

Every screening stage was carried out manually by reviewing each article's title, abstract, and, if required, complete text in order to guarantee the precision and dependability of the selection process. Figure 2, which depicts the screening and filtering procedure used to reduce the literature to the most pertinent and significant research, provides a visual representation of the whole selection approach, including exclusion criteria and the incremental dataset refinement.

3.5. Analysis of Results

The line chart (Figure 4) illustrates the number of publications per year from 2014 to 2024, showing significant fluctuations in research output. Notably, there are no recorded publications between 2005 and 2013, or in 2025. The mechanical pretreatment of lignocellulosic biomass as a distinct and focused research topic likely gained momentum only in the last decade. Before 2013, related studies may have existed but were not categorized under the exact same keywords or were focused more broadly on biofuels or chemical pretreatments. Additionally, around 2010–2013, many countries (especially the U.S. and EU members) scaled up investments in second-generation biofuels in response to climate policies. This period marks a shift toward lignocellulosic biomass and cost-efficient pretreatment methods, prompting a spike in publications.

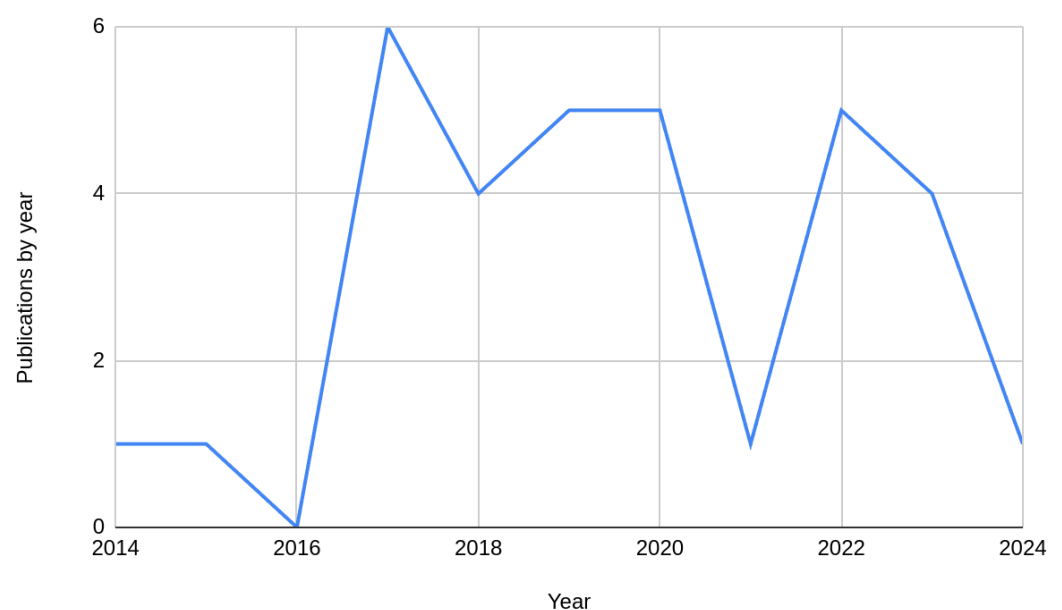


Figure 4. Number of publications per year from 2014 to 2024.

The data start in 2014 with one publication, followed by a brief decline in 2016. From 2017 onward, the research output increases, reaching a peak of six publications. This surge may indicate a particularly productive period, possibly due to increased funding, collaboration, or new research initiatives. However, after 2019, the number of publications begins to decline, dropping to just one in 2021—the lowest after 2016. This sharp drop could be due to external factors such as changes in academic priorities, shifts in funding, or global events disrupting research activities.

In 2022, there is a noticeable rebound, as the number of publications increases to five once more. Even with this comeback, the trend loses steam in 2023 and 2024 as publishing numbers start to decline. Furthermore, the lack of publications between 2005 and 2013 implies that either no research was conducted during that time or no published work was produced as a result of it. Likewise, the dearth of publications in 2025 might suggest that either no fresh data have been gathered or that ongoing research has not yet produced published results. All things considered, the graph shows a dynamic trend in research production, with both high and low productivity periods impacted by a number of variables, including financing cycles, institutional agendas, and external circumstances that have an impact on academic activity.

Finally, we studied the total number of articles published per country and the subjects of interest of the reviews analysed. The results show that most publications come from authors affiliated with institutions in the U.S. (24.24%), followed by Spain (12.12%), South Korea (9.09%), and Denmark and Thailand (6%) (Figure 5). The strong research output from the United States in the field of mechanical pretreatment of lignocellulosic biomass for biofuel production can be attributed to several strategic factors. First, the U.S. has vast agricultural and forestry resources, generating large volumes of lignocellulosic residues such as corn stover, wheat straw, and wood chips, which are ideal feedstocks for second-generation biofuels. Second, national energy policies and programs—such as the U.S. Department of Energy’s Bioenergy Technologies Office (BETO)—have long promoted biofuels to reduce dependence on fossil fuels, enhance energy security, and lower greenhouse gas emissions.

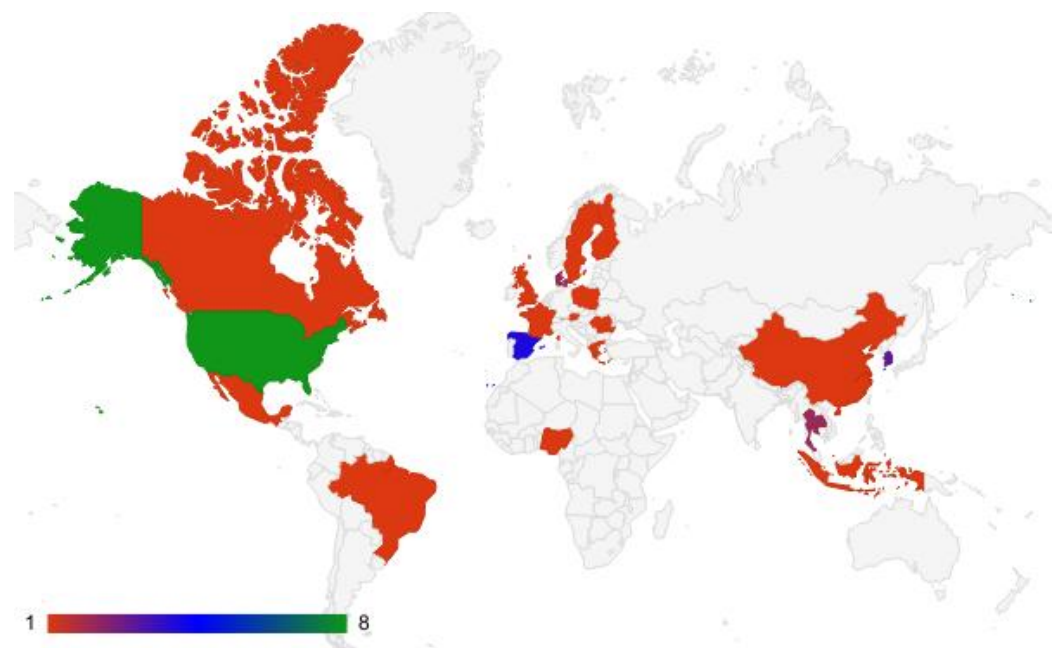


Figure 5. Number of publications per country.

The following bar chart presents the distribution of articles according to the number of citations they have garnered (see Figure 6). On the *x*-axis, we see various citation ranges, while the *y*-axis indicates the number of articles within each range.

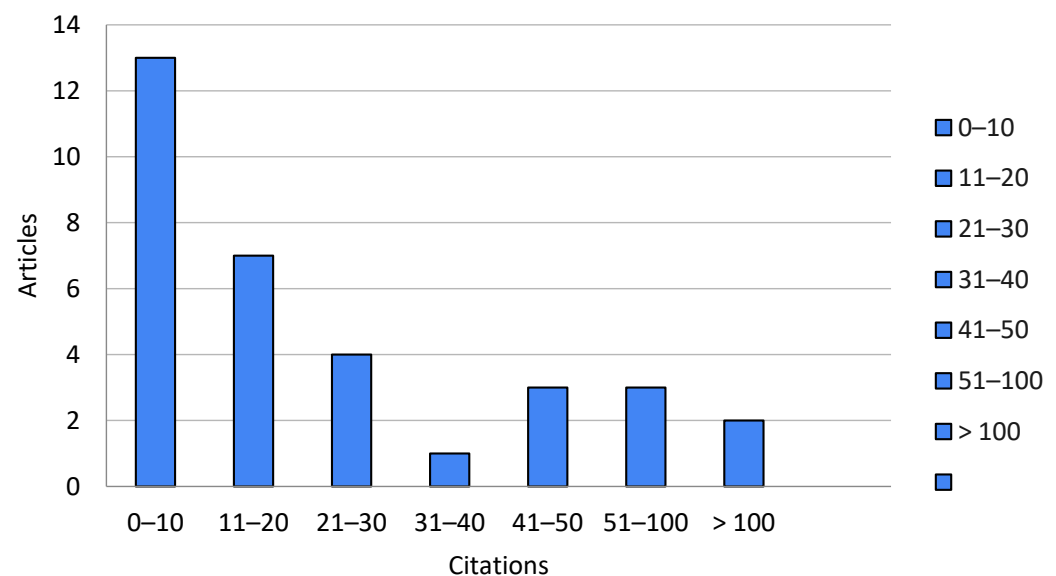


Figure 6. Number of citations.

According to the figure, the most common group of articles comprises 0 to 10 citations, with roughly 13 articles falling into this category. The second most prevalent range, with around 7 articles, consists of those having 11 to 20 citations. As the number of citations increases, there is a distinct drop in the number of articles within each following category. The fewest articles are found in the 21–30 and 31–40 citation ranges, indicating that only a small percentage of publications are cited in these regions. On the other hand, the number of articles in the 41–50 and 51–100 categories has somewhat increased, suggesting that some works do achieve a reasonable level of recognition. Finally, although they are very uncommon, articles with more than 100 citations are included in the dataset. This finding implies that while a small number of publications achieve significant citation counts, they only make up a small percentage of all the articles that were analyzed.

The distribution of publication types is depicted in the chart, which makes a clear distinction between review papers and articles. The data indicate that articles make up a significant 87.9% of all publications, highlighting a clear preference for sharing original research findings rather than review papers (see Figure 7). Generally speaking, articles are primary research contributions that include fieldwork, experimental studies, and data-driven analyses. The overwhelming number of papers in this dataset indicates that creating new information, carrying out creative experiments, and presenting unique discoveries are the main goals of research. On the other hand, 12.1% of all the publications are review papers. Reviews are essential for examining trends, identifying research gaps, and synthesizing current knowledge, even though they are less frequent. Their existence draws attention to a significant attempt to compile and assess the state of the field. Overall, the distribution shows that fresh empirical discoveries account for most of the research output, with a lesser but still important percentage going toward analyzing and contextualizing the body of the previous literature.

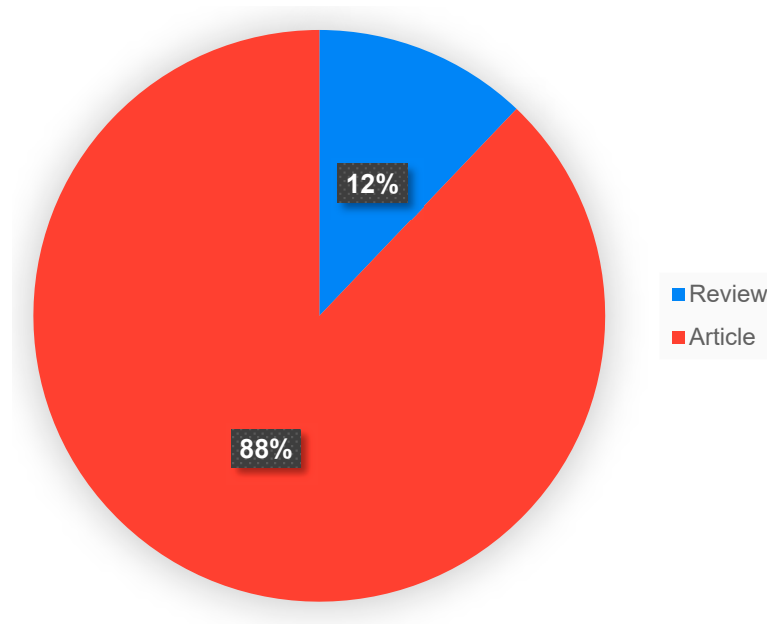


Figure 7. Publication types.

4. Discussion

4.1. Size Reduction

Milling after a fermentation phase significantly enhances the breakdown of weakened and partially digested plant cell walls, thereby exposing more cellulose fibers to microbial action. A variety of research efforts have focused on strategies aimed at reducing biomass recalcitrance and improving anaerobic digestion, particularly through mechanical treatments like milling. For example, Ortega et al. [26] reported that mechanical maceration increased biogas yields. In particular, the most advantageous phase for milling is after the initial acid fermentation phase (anaerobic) or at the end of alcoholic fermentation. In fact, in this period the microorganisms partially degrade the most accessible components of the biomass, such as simple sugars and starch. This process (a) amplifies the porosity of the cell wall, (b) reduces the cohesion between cellulose, hemicellulose, and lignin, and (c) breaks the secondary structural bonds (e.g., hydrogen bonds and ester bridges). In short, milling after fermentation is effective because it exploits the biological softening of the biomass to optimize the subsequent mechanical treatment, reducing energy costs and increasing the availability of useful substrates for energy production. However, the effectiveness of different milling technologies and configurations varies, impacting factors such as particle size reduction, surface area enhancement, porosity, and, ultimately, methane yield.

In another study by Lindner et al. [48], mechanical disruption of anaerobic digestates for varying durations using a ball mill resulted in reduced particle size and increased methane yield and biogas production rate. The authors specifically examined senescent switchgrass, milling it for periods of 0.5, 2.5, and 10 min, followed by 18 days of batch fermentation, with unmilled material serving as a control. Findings revealed a 5–13% increase in sugar solubilization relative to the control, with longer milling times correlating with greater solubilization. The methane concentration in the biogas produced ranged from 44% to 55.5%, with carbon dioxide making up the remainder. Notably, total biogas production was significantly higher for samples that underwent at least 2 min of milling ($\alpha = 0.1$). However, laboratory measurements of energy consumption suggested diminishing returns in methane production as milling durations increased [49].

In another relevant study, researchers evaluated the impact of particle size on biomass processing using knife milling to generate particles measuring 4 mm, 2 mm, and 1 mm,

followed by ultrasonic pelleting. The biomass was pretreated with dilute acid prior to enzymatic hydrolysis. The results indicated that a particle size of 2 mm was optimal, achieving a balance between energy efficiency in size reduction and pelleting while maximizing sugar yield from both big bluestem and wheat straw biomass [39]. Nevertheless, most studies analyzing particle size do not provide detailed characterizations of the resulting granulometry or fail to correlate these with enzymatic accessibility in a mechanistic way. This gap limits the predictive capacity of the observed trends.

The effects of pretreatment temperature and duration, along with disk milling, were also assessed on glucose and xylose yields during hydrolysis. When residence times exceeded 5 min at 200 °C, all hemicellulose was successfully solubilized. The most significant glucose concentration (5.4%) was reached at 200 °C for 10 min with disk milling, while the highest xylose concentration (2.15%) occurred at 200 °C for 5 min. The impact of disk milling was particularly pronounced at lower pretreatment temperatures and durations [50].

Additionally, Gu et al. (2019) [51] examined three mechanical pulverizers—a continuous ball mill (CBM), air classifier mill (ACM), and high-speed mill (HSM)—for the continuous pretreatment of corn stover. Although the average particle sizes of the pulverized biomass were similar, glucose yields varied considerably: 29% for the CBM, 49% for the ACM, and 44% for the HSM. Such variation suggests that performance is not merely a function of final particle size, but also of particle morphology, energy dispersion during milling, and, perhaps, mechanical stresses induced in the biomass structure. However, these aspects are rarely quantified or reported, leaving a gray area in understanding what precisely drives the improved yields.

Finally, Ref. [52] explored four mechanical pretreatment methods for wheat straw: roll milling, extrusion, pelletization, and hammer milling. Their findings showed that roll milling yielded the highest biochemical methane potential (287 NmL CH₄ gVS^{−1}), marking a 21% increase over untreated wheat straw. Extrusion, on the other hand, delivered the highest methane production rate (52 NmL CH₄ gVS^{−1} day^{−1}), alongside low floating capacity and high bulk density.

When it comes to pelletization and briquetting, the latter method offers numerous benefits. It not only eliminates milling costs but also reduces dust and emissions of fine particles, thereby alleviating safety and environmental concerns. Additionally, briquetting opens up new applications, such as sustained combustion for barbecue grilling.

Most research typically centers on biomass pellets or briquettes made from pre-ground materials—like in the study by [53,54] which noted successful briquetting of almond shells without any prior grinding.

In a study focused on walnut shells, briquettes were produced using a hydraulic piston press under varying conditions to optimize quality without pre-grinding. The quality of these briquettes was evaluated based on their density and durability. Remarkably, the best outcomes were observed at a compaction pressure of 66 MPa, yielding densities around 1040 kg/m³ and durability ratings exceeding 94% at 140 °C. The most significant improvement in durability was noted when comparing briquettes produced at room temperature to those made at 80 °C. Moreover, incorporating small amounts of walnuts—which are a common byproduct of the shelling process—further enhanced durability. Interestingly, while some moisture is essential, briquettes produced from biomass containing only 1% moisture still demonstrated superior durability. Despite these encouraging results, very few studies explore the trade-offs between skipping grinding and downstream efficiency in combustion or gasification. In contexts where high uniformity is required, omitting preliminary size reduction might not be viable.

Finally, Ref. [55] explored a physical pretreatment of sago solid waste through grinding to enhance the surface area of crystalline particles. In their process, 125 g of sago waste was mixed with 250 mL of a solution, blended at moderate speed, and allowed to sit at room temperature for 48 h. Some results have been summarized in the table below (Table 1).

Table 1. Key parameters and performance indicators of biomass size reduction methods.

Treatment	Biomass Feedstock	Machines/System	Particle Size After Treatment	Key Effect	Reference
Attrition milling	Corn stover	Attrition mill	73.5% < 100 μm ; mean $61.3 \pm 3.3 \mu\text{m}$	Enzymatic conversion 79.8%; low phenolics production	[56]
Ball milling	Corn stover, Switchgrass	Ball mill, air classifier mill, high-speed mill; ball milling	Reduced significantly (not specified); Not specified; Reduced; Similar for all, mean D not specified	Increased glucose yield to 66.96%; Increased biogas production by 5–13%; Glucose yield: ACM 49%, HSM 44%, CBM 29%	[39,49,51]
Disk milling	Energy cane bagasse	Disk mill	Not specified, post 2 mm grinding	Highest glucose (5.4%) and xylose (2.15%) with disk milling after LHW at 200 °C	[48]
Grinding	Cocoa pod husk; Pine needles, bark, branches; Sugar beet pulp	Grinder	2.5 mm; Reduced (not quantified); <10 mm	Biogas yield increased by 20.2% compared to untreated; Increases surface area and reduces crystallinity, aiding microbial digestion; Methane yield: 115–164 NmL/g (needles), lower for bark/litter	[57,58]
Hammer milling	Wheat straw	Hammer mill, roll mill, extrusion	0.25–1 mm analyzed; not always specified for each method	Roll milling increased methane potential by 21%; extrusion increased production rate	[52]
Knife milling/Cutting	Big bluestem	Knife milling (1, 2, 4, 8 mm)	1–8 mm	Larger screen size reduced energy use; higher sugar yield with 2 mm	[20]
Other/Combined	Corn cob, Cotton stalks, Various grasses	Centrifugal milling, mechanical milling	0.5–65 mm; highest yield at 0.5 mm; Not specified; Not detailed	Methane yield increased by 26%; Fermentable sugars yield 0.488 g/g biomass; Methane yield increased by up to 22%	[59–61]
Shearing (Brush/Roller)	Meadow grass	Shearing/Brush + steel roller	Reduced (not quantified)	Methane yield increased by 20–27% depending on treatment intensity	[29]
Szego milling	Barley straw	Szego Mill™	Down to <0.2 mm in nitrogen-assisted wet milling	Glucose up to 7 g/L; ethanol 3.4–6.7 g/L; +6–11% methane rate	[62]

4.2. Densification

Biomass densification emerges as a key solution to optimize the management, transportation, and energy efficiency of agricultural residues for renewable energy production [63]. The densification process, which includes the compaction of ground agricultural biomass into pellets, plays a crucial role in the production of biofuels [36]. Numerous studies highlight how pelletization and briquetting, supported by size reduction of biomass, improve its physical and chemical properties, optimizing processing into biofuels. For example, Font et al. [53] explored the briquetting of walnut shells, resulting in briquettes with high density and durability, ideal for pyrolysis and combustion, without requiring preliminary grinding. Size reduction is crucial in these processes, as it promotes greater uniformity in the material, improving the compactness and strength of the final biofuel. Zhang et al. [64] studied the effect of briquetting on wheat straw using a briquetting press and hydration analysis, showing that pre-grinding and densification increased the hydration rate and density of the product, improving the quality of the biofuel. San Miguel et al. [65] also treated prickly pear cactus with a temperature-controlled dryer and pelletizing machine, achieving an improvement in cladode energy density. However, the study lacks comparison

with conventional feedstocks or alternative pretreatment strategies, making it difficult to assess the true benefit of such densification under standard operational constraints. In parallel, de Oliveira and Silva et al. [66] analyzed the pelletization of coffee husks with a pretreatment reactor and a dryer, finding an increase in calorific content and pellet density. Nahar and Pryor [67] studied the effect of low severity ammonia treatment on the preparation of corn straw for pelletization, showing that such treatment improves the quality of the pellets produced and their energy capacity. In addition, Wolfrum et al. [68] examined the effect of densification on the yield of structural sugars obtained from various lignocellulosic feedstocks, demonstrating that the pelletization process does not compromise the efficiency of enzymatic hydrolysis and, in some cases, improves it by promoting greater availability of glucose and xylose in biochemical conversion processes. Some authors [69–71] evaluated the energy potential of residual agroforestry biomasses, including vine and kiwi prunings, demonstrating that, when densified, these biomasses reach calorific powers between 17 and 20 MJ/kg (on a dry basis), with micro-cogeneration tests showing an overall efficiency close to 97%, a net electrical yield of 9%, and a thermal yield of 88%. While these figures are encouraging, they stem from micro-cogeneration tests under controlled conditions. Real-world systems often show lower efficiency due to losses in handling, start-up phases, and suboptimal feedstock consistency. Moreover, none of the studies reviewed include a full life cycle or exergy analysis, which would be useful to confirm the actual sustainability of these results.

These results, grouped in Table 2, confirm the crucial role of densification in improving the energy valorization of biomass within the circular economy. In summary, densification not only optimizes biomass logistics, but also contributes significantly to the efficiency of energy conversion processes, improving the economic and environmental sustainability of bioenergy. The selection of appropriate tools and careful management of size reduction are essential for obtaining high-quality biofuels and efficiently integrating biomass into sustainable energy systems.

Table 2. Key parameters and performance indicators of biomass densification methods.

Treatment	Biomass Feedstock	Machine/System	Advantages	Disadvantages	Reference
Briquetting	Walnut shell	Hydraulic piston press (Mega KcK-50)	Reduction of operating costs; Low ash content (about 1.1–1.2%) and high calorific value; Good density and durability; Clean combustion	Sensitivity to moisture; Variability in raw material quality	[54]
Briquetting	Corn stover	(i) Shredder machine 9RS-600 against (ii) Ring die briquette machine (9SYH-1200)	Increase in methane yield (66.74%, ii higher than i); Better digestive performance (CH ₄ and VFA); Reduction of logistics costs; Improving energy sustainability	Higher energy consumption: the electrical input is 247.2% higher than in (i), due to the energy required for the briquetting process	[70]
Pelleting	Corn stover	SAA—Soaking in Aqueous Ammonia	Reduction of pre-treatment severity (90% glucose yields can be obtained by pelletizing); Decreased enzyme load (it is possible to reduce the use of enzymes up to 80% while maintaining high sugar yields); Reduction of hydrolysis times (58%)	Energy costs of pelletizing; Additional costs for ammonia management	[67]

Table 2. Cont.

Treatment	Biomass Feedstock	Machine/System	Advantages	Disadvantages	Reference
Briquetting	Wheat Straw	Briquetting press BP 6510	Better absorption of water (due to the reduced size of the fibers and the reduced presence of intracellular air); Improved ease of biomass transport and storage; Preservation of cell morphology	Yield in fermentable sugars unchanged; Possible increase in recalcitrance	[64]
Pelleting	Mixed biomass (corn stover, miscanthus, switchgrass, poplar)	Bliss Pioneer B35A-75;	Slight increase in total sugar yield	Variability between biomass (the hybrid poplar required higher pretreatment temperatures and showed lower yields compared to herbaceous biomass)	[68]
Pelleting	Mixed biomass (<i>Vitis</i> spp., <i>Actinidia</i> spp., <i>Erica</i> spp., <i>Cytisus</i> spp., <i>Pinus</i> spp.)	Cylindrical pelletizer producing pellets of 6 mm diameter and 18 mm length	Reduction of transport costs; Exploitation of residual biomass	High moisture content; Costs of collection	[69]

5. Conclusions

An important step in maximizing biofuel production is the mechanical pretreatment of lignocellulosic biomass. This paper highlights how methods of size reduction and densification significantly enhance the accessibility of cellulose and improve the efficiency of biochemical conversion processes. Densification techniques, such as pelletizing and briquetting, not only boost energy density but also enhance transportability and storage stability. On the other hand, grinding, crushing, and shredding increase the surface area and porosity of the biomass. However, a notable drawback of these mechanical methods is their high energy consumption, which must be balanced against the economic and environmental advantages they offer. An important step to maximize biofuel production is the mechanical pretreatment of lignocellulosic biomass. This paper highlights how size reduction and densification methods significantly improve cellulose accessibility and the efficiency of biochemical conversion processes. Densification techniques, such as pelletization and briquetting, not only increase energy density but also improve transportability and storage stability. On the other hand, grinding, crushing, and shredding increase the surface area and porosity of the biomass. However, a significant disadvantage of these mechanical methods is the high energy consumption, which must be balanced with the economic and environmental benefits they offer.

In choosing the most appropriate pretreatment techniques, it is essential to consider the type of biomass to be treated, since not all raw materials are the same and require different treatments to avoid problems and poor yield of the new product. It is also necessary to consider the desired final product and the related processing costs: in fact, if biomass recovery requires a high economic expenditure and the final product does not have an adequate economic yield, adequate economic sustainability would be lacking, making the biomass valorization chain useless. It is also true, however, that not all pretreatment techniques used so far are energy and environmentally efficient: to this end, future research and the application of some technologies available on the market, as highlighted above, should aim at improving energy efficiency and exploring the integration of mechanical techniques with other pretreatment technologies.

In conclusion, mechanical preprocessing plays a fundamental role in the progress of bioenergy systems, promoting waste-to-energy conversion initiatives and resource recovery and facilitating the transition to a circular and low-carbon bioeconomy, but further efforts

are needed by the research sector to ensure greater and better environmental and energy sustainability of these processes.

Author Contributions: Conceptualization, L.B., A.C., and R.P.; methodology, L.B., R.V., A.C., and R.P.; formal analysis, L.B., E.C., G.D.D., and L.C.; investigation, V.D.S., L.B., E.C., G.D.D., and L.C.; data curation, L.B., E.C., G.D.D., and L.C.; writing—original draft preparation, L.B., E.C., G.D.D., and R.V.; writing—review and editing, V.D.S., L.B., A.C., and R.P.; visualization, E.C., G.D.D., L.C., and R.V.; supervision, V.D.S., L.B., R.P., and A.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Italian Ministry for Education University, and Research (MIUR) in the form of financial support (Law 232/2016, Italian University Departments of Excellence 2023\20132027) project\201CDigitali, Intelligenti, Verdi e Sostenibili (D.I.Ver.So)\2014UNITUS-DAFNE WP3\201D.

Data Availability Statement: Data are available from the corresponding author upon reasonable request.

Acknowledgments: This research was carried out within “Progetto ECS 0000024 Rome Technopole—CUP B83C22002820006, PNRR Missione 4 Componente 2 Investimento 1.5, finanziato dall’Unione europea—NextGenerationEU”. This research was carried out under the General Agreement between the Council for Agricultural Research and Economics and the University of Tuscia.

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

References

1. Zhou, Z.; Ouyang, D.; Liu, D.; Zhao, X. Oxidative Pretreatment of Lignocellulosic Biomass for Enzymatic Hydrolysis: Progress and Challenges. *Bioresour. Technol.* **2023**, *367*, 128208. [\[CrossRef\]](#)
2. Carnevale, M.; Santangelo, E.; Colantoni, A.; Paris, E.; Palma, A.; Vincenti, B.; Paolini, V.; Petracchini, F.; Salerno, M.; Di Stefano, V.; et al. Thermogravimetric Analysis of Olive Tree Pruning as Pyrolysis Feedstock. In Proceedings of the European Biomass Conference and Exhibition Proceedings, Virtual, 6–9 July 2020; pp. 581–584.
3. Mujtaba, M.; Fernandes Fraceto, L.; Fazeli, M.; Mukherjee, S.; Savassa, S.M.; Araujo de Medeiros, G.; do Espírito Santo Pereira, A.; Mancini, S.D.; Lipponen, J.; Vilaplana, F. Lignocellulosic Biomass from Agricultural Waste to the Circular Economy: A Review with Focus on Biofuels, Biocomposites and Bioplastics. *J. Clean. Prod.* **2023**, *402*, 136815. [\[CrossRef\]](#)
4. Singh Yadav, S.P.; Bhandari, S.; Bhatta, D.; Poudel, A.; Bhattarai, S.; Yadav, P.; Ghimire, N.; Paudel, P.; Paudel, P.; Shrestha, J.; et al. Biochar Application: A Sustainable Approach to Improve Soil Health. *J. Agric. Food Res.* **2023**, *11*, 100498. [\[CrossRef\]](#)
5. Huang, C.; Li, R.; Tang, W.; Zheng, Y.; Meng, X. Improve Enzymatic Hydrolysis of Lignocellulosic Biomass by Modifying Lignin Structure via Sulfite Pretreatment and Using Lignin Blockers. *Fermentation* **2022**, *8*, 558. [\[CrossRef\]](#)
6. Baksi, S.; Sarkar, U.; Villa, R.; Basu, D.; Sengupta, D. Conversion of Biomass to Biofuels through Sugar Platform: A Review of Enzymatic Hydrolysis Highlighting the Trade-off between Product and Substrate Inhibitions. *Sustain. Energy Technol. Assess.* **2023**, *55*, 102963. [\[CrossRef\]](#)
7. Zhao, J.; Wei, X.; Li, L. The Potential for Storing Carbon by Harvested Wood Products. *Front. For. Glob. Change* **2022**, *5*, 1055410. [\[CrossRef\]](#)
8. Chen, J.; Ma, X.; Liang, M.; Guo, Z.; Cai, Y.; Zhu, C.; Wang, Z.; Wang, S.; Xu, J.; Ying, H. Physical–Chemical–Biological Pretreatment for Biomass Degradation and Industrial Applications: A Review. *Waste* **2024**, *2*, 451–473. [\[CrossRef\]](#)
9. Moodley, P.; Trois, C. 2—Lignocellulosic Biorefineries: The Path Forward. In *Sustainable Biofuels*; Ray, R.C., Ed.; Applied Biotechnology Reviews; Academic Press: Cambridge, MA, USA, 2021; pp. 21–42, ISBN 978-0-12-820297-5.
10. Aslanzadeh, S.; Ishola, M.M.; Richards, T.; Taherzadeh, M.J. Chapter 1—An Overview of Existing Individual Unit Operations. In *Biorefineries*; Qureshi, N., Hodge, D.B., Vertès, A.A., Eds.; Elsevier: Amsterdam, The Netherlands, 2014; pp. 3–36, ISBN 978-0-444-59498-3.
11. Mankar, A.R.; Pandey, A.; Modak, A.; Pant, K.K. Pretreatment of Lignocellulosic Biomass: A Review on Recent Advances. *Bioresour. Technol.* **2021**, *334*, 125235. [\[CrossRef\]](#)
12. Cavailles, J.; Vaca-Medina, G.; Wu-Tiu-Yen, J.; Labonne, L.; Evon, P.; Peydecastaing, J.; Pontalier, P.-Y. Impact of Thermomechanical Pretreatment by Twin-Screw Extrusion on the Properties of Bio-Based Materials from Sugarcane Bagasse Obtained by Thermocompression. *Bioresour. Technol.* **2024**, *414*, 131642. [\[CrossRef\]](#)

13. Ibitoye, S.E.; Mahamood, R.M.; Jen, T.-C.; Loha, C.; Akinlabi, E.T. An Overview of Biomass Solid Fuels: Biomass Sources, Processing Methods, and Morphological and Microstructural Properties. *J. Bioresour. Bioprod.* **2023**, *8*, 333–360. [\[CrossRef\]](#)
14. Fia, A.Z.; Amorim, J. Microwave Pretreatment of Biomass for Conversion of Lignocellulosic Materials into Renewable Biofuels. *J. Energy Inst.* **2023**, *106*, 101146. [\[CrossRef\]](#)
15. Bianchini, L.; Alemanno, R.; Di Stefano, V.; Cecchini, M.; Colantoni, A. Soil Compaction in Harvesting Operations of *Phalaris arundinacea* L. *Land* **2022**, *11*, 1031. [\[CrossRef\]](#)
16. Karthikeyan, P.K.; Bandulasena, H.C.H.; Radu, T. A Comparative Analysis of Pre-Treatment Technologies for Enhanced Biogas Production from Anaerobic Digestion of Lignocellulosic Waste. *Ind. Crops Prod.* **2024**, *215*, 118591. [\[CrossRef\]](#)
17. Mirmohamadsadeghi, S.; Karimi, K.; Azarbaijani, R.; Parsa Yeganeh, L.; Angelidaki, I.; Nizami, A.-S.; Bhat, R.; Dashora, K.; Vijay, V.K.; Aghbashlo, M.; et al. Pretreatment of Lignocelluloses for Enhanced Biogas Production: A Review on Influencing Mechanisms and the Importance of Microbial Diversity. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110173. [\[CrossRef\]](#)
18. Sabeeh, M.; Zeshan; Liaquat, R.; Maryam, A. Effect of Alkaline and Alkaline-Photocatalytic Pretreatment on Characteristics and Biogas Production of Rice Straw. *Bioresour. Technol.* **2020**, *309*, 123449. [\[CrossRef\]](#)
19. Anukam, A.; Berghel, J. Biomass Pretreatment and Characterization: A Review. In *Biotechnological Applications of Biomass*; Basso, T.P., Basso, T.O., Basso, L.C., Eds.; IntechOpen: Rijeka, Italy, 2020.
20. Song, X.; Zhang, M.; Zhang, K.; Pei, Z.J.; Wang, D. Effects of Screen Size on Biochemical Conversion of Big Bluestem Biomass for Biofuel Production. *Adv. Mater. Sci. Eng.* **2015**, *2015*, 947350. [\[CrossRef\]](#)
21. Bianchini, L.; Costa, P.; Dell’omo, P.P.; Colantoni, A.; Cecchini, M.; Monarca, D. An Industrial Scale, Mechanical Process for Improving Pellet Quality and Biogas Production from Hazelnut and Olive Pruning. *Energies* **2021**, *14*, 1600. [\[CrossRef\]](#)
22. Di Domenico, G.; Bianchini, L.; Di Stefano, V.; Venanzi, R.; Lo Monaco, A.; Colantoni, A.; Picchio, R. New Frontiers for Raw Wooden Residues, Biochar Production as a Resource for Environmental Challenges. *C* **2024**, *10*, 54. [\[CrossRef\]](#)
23. Carrere, H.; Antonopoulou, G.; Affes, R.; Passos, F.; Battimelli, A.; Lyberatos, G.; Ferrer, I. Review of Feedstock Pretreatment Strategies for Improved Anaerobic Digestion: From Lab-Scale Research to Full-Scale Application. *Bioresour. Technol.* **2016**, *199*, 386–397. [\[CrossRef\]](#)
24. Huang, B.; Luo, C.; Liao, X. Realization Path of Digitalization Promoting Collaborative Innovation Development between Urban and Rural Areas. *For. Chem. Rev.* **2021**, 118–128. [\[CrossRef\]](#)
25. Chozhavendhan, S.; Rajamehala, M.; Karthigadevi, G.; Praveenkumar, R.; Bharathiraja, B. A Review on Feedstock, Pretreatment Methods, Influencing Factors, Production and Purification Processes of Bio-Hydrogen Production. *Case Stud. Chem. Environ. Eng.* **2020**, *2*, 100038. [\[CrossRef\]](#)
26. Ortega, J.O.; Mora Vargas, J.A.; Metzker, G.; Gomes, E.; da Silva, R.; Boscolo, M. Enhancing the Production of the Fermentable Sugars from Sugarcane Straw: A New Approach to Applying Alkaline and Ozonolysis Pretreatments. *Renew. Energy* **2021**, *164*, 502–508. [\[CrossRef\]](#)
27. Xu, Z.; Wang, Q.; Jiang, Z.; Yang, X.; Ji, Y. Enzymatic Hydrolysis of Pretreated Soybean Straw. *Biomass Bioenergy* **2007**, *31*, 162–167. [\[CrossRef\]](#)
28. Arce, C.; Kratky, L. Mechanical Pretreatment of Lignocellulosic Biomass toward Enzymatic/Fermentative Valorization. *IScience* **2022**, *25*, 104610. [\[CrossRef\]](#)
29. Tsapekos, P.; Kougiass, P.G.; Angelidaki, I. Mechanical Pretreatment for Increased Biogas Production from Lignocellulosic Biomass; Predicting the Methane Yield from Structural Plant Components. *Waste Manag.* **2018**, *78*, 903–910. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Hamed, A.; Xia, Y.; Saha, N.; Klinger, J.; Lanning, D.N.; Dooley, J.H. Particle Size and Shape Effect of Crumbler[®] Rotary Shear-Milled Granular Woody Biomass on the Performance of Acrison[®] Screw Feeder: A Computational and Experimental Investigation. *Powder Technol.* **2023**, *427*, 118707. [\[CrossRef\]](#)
31. Viňáš, J.; Brezinová, J.; Brezina, J.; Hermel, P. Innovation of Biomass Crusher by Application of Hardfacing Layers. *Metals* **2021**, *11*, 1283. [\[CrossRef\]](#)
32. Cho, S.K.; Ju, H.J.; Lee, J.G.; Kim, S.H. Alkaline-Mechanical Pretreatment Process for Enhanced Anaerobic Digestion of Thickened Waste Activated Sludge with a Novel Crushing Device: Performance Evaluation and Economic Analysis. *Bioresour. Technol.* **2014**, *165*, 183–190. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Lomovskiy, I.; Bychkov, A.; Lomovsky, O.; Skripkina, T. Mechanochemical and Size Reduction Machines for Biorefining. *Molecules* **2020**, *25*, 5345. [\[CrossRef\]](#)
34. Gallego-García, M.; Moreno, A.D.; Manzanares, P.; Negro, M.J.; Duque, A. Recent Advances on Physical Technologies for the Pretreatment of Food Waste and Lignocellulosic Residues. *Bioresour. Technol.* **2023**, *369*, 128397. [\[CrossRef\]](#)
35. Veluchamy, A.; Hebert, H.L.; Meng, W.; Palmer, C.N.; Smith, B.H. Systematic Review and Meta-Analysis of Genetic Risk Factors for Neuropathic Pain. *Pain* **2018**, *159*, 825–848. [\[CrossRef\]](#)
36. Tabil, L.; Adapa, P.; Kashaninejad, M. Biomass Feedstock Pre-Processing—Part 2: Densification. In *Biofuel’s Engineering Process Technology*; dos Santos Bernardes, M.A., Ed.; IntechOpen: Rijeka, Italy, 2011.

37. Albashabsheh, N.T.; Heier Stamm, J.L. Optimization of Lignocellulosic Biomass-to-Biofuel Supply Chains with Densification: Literature Review. *Biomass Bioenergy* **2021**, *144*, 105888. [\[CrossRef\]](#)
38. Sarker, T.R.; Nanda, S.; Meda, V.; Dalai, A.K. Densification of Waste Biomass for Manufacturing Solid Biofuel Pellets: A Review. *Environ. Chem. Lett.* **2023**, *21*, 231–264. [\[CrossRef\]](#)
39. Yang, Y.; Zhang, M.; Wang, D. A Comprehensive Investigation on the Effects of Biomass Particle Size in Cellulosic Biofuel Production. *J. Energy Resour. Technol.* **2018**, *140*, 041804. [\[CrossRef\]](#)
40. Sithole, T.; Pahla, G.; Mashifana, T.; Mamvura, T.; Dragoi, E.-N.; Saravanan, A.; Sadeghifar, H. A Review of the Combined Torrefaction and Densification Technology as a Source of Renewable Energy. *Alex. Eng. J.* **2023**, *82*, 330–341. [\[CrossRef\]](#)
41. Shankar Tumuluru, J.; Richard Hess, J. A Review on Biomass Densification for Energy Applications. *Ind. Biotechnol.* **2011**, *7*, 384–401. [\[CrossRef\]](#)
42. Kamdem, B.M.; Lemaire, R.; Nikiema, J. Insight into the Production Factors Influencing the Physicochemical Properties of Densified Briquettes Comprising Wood Shavings and Rice Husk. *Ind. Crops Prod.* **2025**, *223*, 120134. [\[CrossRef\]](#)
43. Clarke, S.; Preto, F. 11-035—*Biomass Densification for Energy Production*; Ministry of Agriculture, Food and Rural Affairs: Guelph, ON, Canada, 2011.
44. Bajwa, D.S.; Peterson, T.; Sharma, N.; Shojaeiarani, J.; Bajwa, S.G. A Review of Densified Solid Biomass for Energy Production. *Renew. Sustain. Energy Rev.* **2018**, *96*, 296–305. [\[CrossRef\]](#)
45. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. *Ann. Intern. Med.* **2018**, *169*, 467–473. [\[CrossRef\]](#)
46. Patel, A.; Mikes, F.; Matsakas, L. An overview of current pretreatment methods used to improve lipid extraction from oleaginous microorganisms. *Molecules* **2018**, *23*, 1562. [\[CrossRef\]](#)
47. Hütter, M.; Sailer, G.; Hülsemann, B.; Müller, J.; Poetsch, J. Impact of Thermo-Mechanical Pretreatment of Sargassum muticum on Anaerobic Co-Digestion with Wheat Straw. *Fermentation* **2023**, *9*, 820. [\[CrossRef\]](#)
48. Lindner, C.; Thomsen, I.; Wahl, B.; Ugur, M.; Sethi, M.K.; Friedrichsen, M.; Smoczek, A.; Ott, S.; Baumann, U.; Suerbaum, S.; et al. Diversification of Memory B Cells Drives the Continuous Adaptation of Secretory Antibodies to Gut Microbiota. *Nat. Immunol.* **2015**, *16*, 880–888. [\[CrossRef\]](#)
49. Bharadwaj, A.; Holwerda, E.K.; Regan, J.M.; Lynd, L.R.; Richard, T.L. Enhancing Anaerobic Digestion of Lignocellulosic Biomass by Mechanical Cotreatment. *Biotechnol. Biofuels Bioprod.* **2024**, *17*, 76. [\[CrossRef\]](#)
50. Juneja, A.; Kumar, D.; Singh, V.K.; Yadavika; Singh, V. Chemical Free Two-Step Hydrothermal Pretreatment to Improve Sugar Yields from Energy Cane. *Energies* **2020**, *13*, 5805. [\[CrossRef\]](#)
51. Gu, Y.M.; Kim, S.; Sung, D.; Sang, B.I.; Lee, J.H. Feasibility of Continuous Pretreatment of Corn Stover: A Comparison of Three Commercially Available Continuous Pulverizing Devices. *Energies* **2019**, *12*, 1422. [\[CrossRef\]](#)
52. Victorin, M.; Davidsson, Å.; Wallberg, O. Characterization of Mechanically Pretreated Wheat Straw for Biogas Production. *Bioenergy Res.* **2020**, *13*, 833–844. [\[CrossRef\]](#)
53. Wang, Q.; Han, K.; Gao, J.; Li, H.; Lu, C. The Pyrolysis of Biomass Briquettes: Effect of Pyrolysis Temperature and Phosphorus Additives on the Quality and Combustion of Bio-Char Briquettes. *Fuel* **2017**, *199*, 488–496. [\[CrossRef\]](#)
54. Font, R.; Villar, E.; Garrido, M.A.; Moreno, A.I.; Gómez-Rico, M.F.; Ortuño, N. Study of the Briquetting Process of Walnut Shells for Pyrolysis and Combustion. *Appl. Sci.* **2023**, *13*, 6285. [\[CrossRef\]](#)
55. Hammado, N.; Utomo, S. Budiyo Characteristic Lignocellulose of Sago Solid Waste for Biogas Production. *J. Appl. Eng. Sci.* **2020**, *18*, 157–164. [\[CrossRef\]](#)
56. Gu, Y.M.; Kim, H.; Sang, B.-I.; Lee, J.H. Effects of Water Content on Ball Milling Pretreatment and the Enzymatic Digestibility of Corn Stover. *Water-Energy Nexus* **2018**, *1*, 61–65. [\[CrossRef\]](#)
57. Díaz-González, A.; Luna, M.Y.P.; Morales, E.R.; Saldaña-Trinidad, S.; Blanco, L.R.; de la Cruz-Arreola, S.; Pérez-Sariñana, B.Y.; Robles-Ocampo, J.B. Assessment of the Pretreatments and Bioconversion of Lignocellulosic Biomass Recovered from the Husk of the Cocoa Pod. *Energies* **2022**, *15*, 3544. [\[CrossRef\]](#)
58. Ziemiński, K.; Kowalska-Wentel, M. Effect of Different Sugar Beet Pulp Pretreatments on Biogas Production Efficiency. *Appl. Biochem. Biotechnol.* **2017**, *181*, 1211–1227. [\[CrossRef\]](#)
59. Al Afif, R.; Pfeifer, C. Enhancement of Methane Yield from Cotton Stalks by Mechanical Pre-Treatment. *Carbon. Resour. Convers.* **2021**, *4*, 164–168. [\[CrossRef\]](#)
60. Dahunsi, S.O. Mechanical Pretreatment of Lignocelluloses for Enhanced Biogas Production: Methane Yield Prediction from Biomass Structural Components. *Bioresour. Technol.* **2019**, *280*, 18–26. [\[CrossRef\]](#) [\[PubMed\]](#)
61. Phojaroen, J.; Jiradechakorn, T.; Kirdponpattara, S.; Sriariyanun, M.; Junthip, J.; Chueter, S. Performance Evaluation of Combined Hydrothermal-Mechanical Pretreatment of Lignocellulosic Biomass for Enzymatic Enhancement. *Polymer* **2022**, *14*, 2313. [\[CrossRef\]](#)
62. Raud, M.; Orupöld, K.; Rocha-Meneses, L.; Rooni, V.; Träss, O.; Kikas, T. Biomass Pretreatment with the Szego Mill™ for Bioethanol and Biogas Production. *Processes* **2020**, *8*, 1327. [\[CrossRef\]](#)

63. Barakat, A.; Mayer-Laigle, C.; Solhy, A.; Arancon, R.A.D.; De Vries, H.; Luque, R. Mechanical Pretreatments of Lignocellulosic Biomass: Towards Facile and Environmentally Sound Technologies for Biofuels Production. *RSC Adv.* **2014**, *4*, 48109–48127. [[CrossRef](#)]
64. Zhang, H.; Fredriksson, M.; Mravec, J.; Felby, C. Hydration of Straw Briquette. *BioResources* **2017**, *12*, 9024–9037. [[CrossRef](#)]
65. San Miguel, G.; Fernández-Olmedilla, D.; Sánchez-Godoy, F. Drying of Prickly Pear (*Opuntia Ficus-Indica* (L.) Miller) and Its Potential as a Solid Biofuel. *Agronomy* **2022**, *12*, 2231. [[CrossRef](#)]
66. de Oliveira e Silva, A.; Garcia, F.P.; Perazzini, M.T.B.; Perazzini, H. Design and Economic Analysis of a Pre-Treatment Process of Coffee Husks Biomass for an Integrated Bioenergy Plant. *Environ. Technol. Innov.* **2023**, *30*, 103131. [[CrossRef](#)]
67. Nahar, N.; Pryor, S.W. Effects of Reduced Severity Ammonia Pretreatment on Pelleted Corn Stover. *Ind. Crops Prod.* **2017**, *109*, 163–172. [[CrossRef](#)]
68. Wolfrum, E.J.; Nagle, N.J.; Ness, R.M.; Peterson, D.J.; Ray, A.E.; Stevens, D.M. The Effect of Biomass Densification on Structural Sugar Release and Yield in Biofuel Feedstock and Feedstock Blends. *Bioenergy Res.* **2017**, *10*, 478–487. [[CrossRef](#)]
69. Torreiro, Y.; Pérez, L.; Piñeiro, G.; Pedras, F.; Rodríguez-Abalde, A. The Role of Energy Valuation of Agroforestry Biomass on the Circular Economy. *Energies* **2020**, *13*, 2516. [[CrossRef](#)]
70. Tao, L.; Junting, P.; Xi, M.; Hailong, H.; Yan, L.; Xia, X.; Ruyi, H.; Zili, M. Improving Agricultural Straw Preparation Logistics Stream in Bio-Methane Production: Experimental Studies and Application Analysis. *3 Biotech.* **2017**, *7*, 283. [[CrossRef](#)]
71. Bianchini, L.; Colantoni, A.; Venanzi, R.; Cozzolino, L.; Picchio, R. Physicochemical Properties of Forest Wood Biomass for Bioenergy Application: A Review. *Forests* **2025**, *16*, 702. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.