

Review

Review of Wood Sawdust Pellet Biofuel: Preliminary SWOT and CAME Analysis

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Abstract

This work presents a preliminary “Strengths, Weaknesses, Opportunities, and Threats” (SWOT) analysis followed by a “Correct, Adapt, Maintain, and Explore” (CAME) analysis on wood sawdust biofuel. New designs of sawdust biofuels boilers and reactors require gathering relevant information on the main characteristics of sawdust biofuels. Optimisation algorithms require not only the numerical parameters needed to find optimal solutions but also the consideration of scenarios related to the use of this type of biofuel. This work provides complementary information to create a comprehensive framework for assessing the viability and sustainability of integrating wood sawdust into diverse energy production systems. This includes an examination of the current state of sawdust utilisation, its environmental implications, and the potential of valorising this abundant biomass resource. This review further delves into the technical aspects of converting sawdust into biofuel pellets, examining various technical processes involved in its physical analysis. The intended audience of this review encompasses researchers, mechanical designers, policymakers, and industry strategists and stakeholders interested in sustainable energy solutions and waste management strategies, providing a holistic perspective on the opportunities presented by wood sawdust as a renewable energy source.

Keywords: sawdust; biomass; biofuel; wood pellet; pelletising; combustion



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1. Introduction

The production and merchandising of fossil fuels worldwide are governed by a complex scheme established over many years. They are among the most significant energy sources consumed on the planet. The use of this energy source is related to the characteristics of energy needs in contemporary activities, such as those in internal combustion (IC) engines used for vehicular mobility. Other types of transportation, such as rail, maritime, and aerospace, also require the use of fossil fuels. Although these fuels are functionally efficient for this type of machinery, they entail significant environmental impacts [1]. Society’s needs are very diverse and are not limited to transportation or the operation of IC-based machinery. Energy needs also include the production of goods and services, which require the use of various energy sources, such as electricity. In the absence of fossil fuels, biomass combustion emerges as a viable alternative to reduce dependence on them and carbon emissions [2]. Global biofuel production data indicate a significant increase; in 2012, bioethanol

production exceeded 100 million m³ [3]. Global demand is expected to triple by 2035 [4], which underlines the growing importance of sustainable energy alternatives. Biomass is organic matter derived from plants, although it can also be obtained from other biological waste. Its combustion is an alternative to burning fossil fuels [5]. Obtaining different types of biomass can often require complex infrastructure, depending on the type. However, the infrastructure and production costs can be lower compared to the costs required to extract or process some fossil fuels [6]. Within the different types of biomass, in this work, we focus on wood sawdust, which is obtained mainly from wood industry waste, furniture industries, and carpentry workshops [7,8]. Wood sawdust stands out due to its abundance and potential for energy generation [9]. The use of wood, linked to forest conservation and respect for trees, dates back to antiquity. Trees have a direct relation to the ecological balance of the planet and the development of civilisations that consider them as living and sacred beings [10]. From a social perspective, identifying the most appropriate and specific areas for their exploitation is a priority, respecting territories and social groups, and identifying the most suitable locations and climatic characteristics that allow for their rapid recovery. From a technical standpoint, the use of sawdust is now associated with a series of contemporary applications that are significantly growing, encompassing co-generation and electricity generation [11]. Estimating the amount of sawdust produced worldwide is a complex task due to the variability of its sources, but it is known that the amount of wood recovered at a sawmill can be as much as 50% of the incoming wood, with the remainder being primarily sawdust [12]. In some countries, sawdust production can exceed 2 million m³ annually, demonstrating its considerable volume as an industrial by-product [13]. It is estimated that in 2015, more than 25 million tons of wood pellets were consumed worldwide [14]. In the waste from the timber industry, there are several variables related to sawdust quality. This material also includes other types of materials, such as bark or wood chips, but sawdust represents a significant portion of this type of waste [15]. The origin of this wood can come from different species of trees, with particular characteristics and properties that can be used for different energy applications [16]. From these sources, a significant amount of wood waste is produced and can be classified according to the characteristics of the source from which it comes. One of these classifications is based on whether the wood has been treated or not, because it will determine its possible uses [17]. This results in a material with varying moisture contents, densities, and particle sizes. Its storage, handling, and mixing with sawdust from other batches also increase the variability of this material [18]. Atmospheric conditions specific to each region influence not only the types of trees harvested but also the necessary conditions for proper preservation. This preservation is crucial because the efficacy of sawdust as a fuel is directly correlated with its heat generation capacity during combustion [19]. A more efficient way to use wood chips is in the form of pellets, as these represent a more uniform material that can be used in burners designed for pellets. Pellets are a compacted form of lignocellulosic biomass, generated from a process that involves, among other steps, the crushing and compaction of the sawdust [20]. The characteristics of the crushing, drying, compaction and cutting of the pellets have a direct effect on their heat generation capacity [8]. Polluting emissions produced by the combustion of sawdust, either individually or in combination with other fuels, can have a lower environmental impact compared to the burning of certain fossil fuels, mainly due to their inherently low sulfur content [21]. This study provides a comprehensive overview of the critical aspects associated with utilising wood sawdust as an alternative fuel, detailing the necessary engineering considerations for its integration into energy generation processes. This information is of significant interest to scientists and engineers, offering valuable insights for improving energy conversion processes for sawdust and developing specialised systems for its efficient combustion.

2. Methodology

The objective of the search was to identify the scope of research on sawdust. A secondary purpose was to identify the general considerations involved in the combustion of sawdust. During the research, it was considered to locate engineering data on sawdust pellets. This is because more uniform data can be obtained during the palletisation process compared to sawdust in its natural form. Sawdust in its natural form has greater variability in its properties, and sawdust in pellet form can help maintain more constant values regarding combustion characteristics, which can be helpful, for example, in the development of future biofuel boilers. The present research aims to answer some of the following questions [22]:

- How can wood sawdust be effectively used as a biofuel?
- How or where is wood sawdust obtained from?
- Is it better to use sawdust in its natural form or in pellet form?
- What is the formation process for sawdust pellets?
- What calculation tools are used in wood sawdust combustion?

To find possible answers to these questions, a document search was conducted using the SCOPUS platform. The keywords selected for the search, conducted in October 2025, were “sawdust pellet,” which initially produced 806 documents. These keywords were selected based on a previous search because there is a wide variety of raw materials that can be used as biofuel. There is also a wide variety of raw material combinations that can be used as biofuels in boilers. In both cases, the variability in reported conditions is significant. The origin, processing, and storage characteristics of each biofuel directly affect its calorific value during combustion. As a limitation to the scope of this research, the search has explicitly focused on wood sawdust pellets. Using the keyword “sawdust pellet”, the obtained documents were more related to the purpose of this research. The first exclusion criterion was time-based: the search was limited to the last 10 years (2015 to 2025), yielding a total of 572 documents. The following criterion was the document type; in this case, only “article” and “review” documents were allowed. This criterion produced 450 documents. Regarding language, only English-language documents were allowed, and the number of documents was reduced to 450. The included and excluded subject areas are shown in Table 1.

Table 1. Included and excluded subject areas.

Included	Excluded
Energy	Physics and Astronomy
Environmental Science	Social Sciences
Chemical Engineering	Biochemistry, Genetics and Molecular Biology
Engineering	Medicine
Agricultural and Biological Sciences	Earth and Planetary Sciences
Materials Science	Immunology and Microbiology
Chemistry	Veterinary
Mathematics	Dentistry
Computer Science	Neuroscience
Business, Management and Accounting	Pharmacology, Toxicology and Pharmaceuticals
Multidisciplinary	Health Professions
Economics, Econometrics and Finance	

Figure 1 shows the number of documents by year from 2015 to 2025 obtained from the SCOPUS website. An interesting growth tendency from 2017 is observed. The VosViewer version 1.6.20 software was used to create the co-occurrence map of related keywords, as

shown in Figure 2, which helps identify the most closely related topics associated with the word “sawdust pellet”.

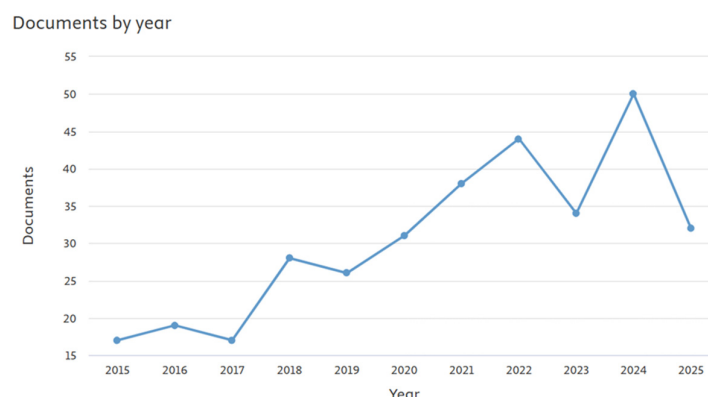


Figure 1. Number of documents by year.

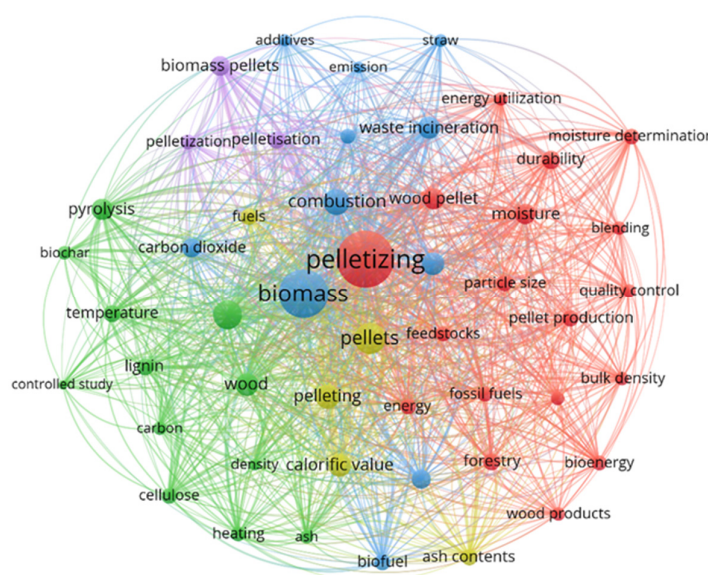


Figure 2. Co-occurrence map of keywords.

3. Obtention and Processing

Sawdust is primarily obtained from forest trees; worldwide production grew from 9.8 Tg in 2008 to 26 Tg in 2015 [23]. This involves logging activities in production forests. These forests are characterised by sustainably managed forests, where a tree rotation is sought to allow for continuous production without depleting the natural resource [24]. In 2000, sustainably managed forests accounted for 35% of global timber production, highlighting the importance of these practices for obtaining timber resources [25]. One of the advantages of managed forests is that better control over the growth characteristics of trees, their quality, and the amount of sawdust generated as a by-product can be achieved [26]. In a controlled system of managed forests, tree growth can be monitored and managed to prevent tree diseases and apply healing measures [27]. Another advantage of managed forests is that tree felling can be more efficient, with less impact on the natural environment, including biodiversity conservation and protection of soil and water sources. It also allows for better control of the techniques and tools used for felling, including the height and direction of cuts, ideal seasons, measurement of growth heights, and transportation and storage processes [28]. Good tree felling management allows for proper classification of the type of wood obtained and its application. Establishing clear differences between wood

for furniture manufacturing and wood for construction enables by-products to be better classified for biomass generation [29]. The generation of sawdust from each specific wood also allows for the indirect identification of humidity characteristics that can vary from 10 to 60%, as well as the measurement of other components that influence combustion processes [8]. Once the wood arrives at the sawmills, storage is essential, as it must be kept away from extreme weather conditions to avoid exposure to excess moisture. Stacking the wood is also crucial, as excessive weight can deform or fracture the fibres. Additionally, it must be avoided from impacting the wood during log handling. In these cases, storage optimisation processes find an essential research field of application, as proper management can minimise material loss, improve space efficiency, and ensure that the sawdust remains in optimal condition for subsequent recovery [30].

Wood-cutting processes are the primary sources of sawdust, and the selection of cutting technology has a substantial impact on the quality and quantity of the sawdust produced. An analysis of solid waste generation in a wood processing machine revealed that approximately 50% of the original log volume is lost during initial processing, highlighting not only pollution but also economic issues due to raw material waste [31]. This cutting process is also called chip removal. The geometry of the cutting tool determines the shape, size, and quality of the chips produced. One factor that can determine chip thickness is cutting speed, especially in disc-type cutters, where edge quality, rake angle, rotational speed, and tool feed directly influence the size and uniformity of the resulting sawdust [32,33]. This means that sawdust production should be considered an intentional activity and part of the sawmill's quality process.

It is preferable that during wood cutting, the sawdust be stored in a previously insulated space free of humidity, puddles of water or mud, oils, or other contaminants that could negatively affect its quality for use as fuel. Due to its porous composition, sawdust has an outstanding absorption capacity; for example, when it comes into contact with water or some machine greases [34]. Carpentry workshops can also be sources of sawdust production. These workshops generally work with pre-treated wood; however, the cutting, sanding, and drilling processes generate significant amounts of sawdust that can be reused. The disadvantage of this type of sawdust is that it can be mixed with varnishes, paints, or glues, making it difficult to use directly as fuel or in composting, as it requires additional treatment to separate or neutralise these contaminants. It can also contain other by-products of the manufacturing process, such as plastics, polymers, rubbers, fibres, or even metals [17].

Biomass drying processes, especially for sawdust, include open-air drying, rotary industrial ovens, solar panel drying, microwave drying, and steam drying. These are important not only for reducing moisture but also for preventing the growth of fungi and bacteria that could degrade the material during storage. This is influenced by the amount of dust and small particles trapped in the sawdust, which can harbour or retain microorganisms and germs [35,36]. Finally, it is crucial to recognise the importance of the grinding or trituration process in converting sawdust into pellets. Appropriate control of grinding sawdust is required to obtain a uniform quality of the particle size [37]. Maintaining a uniform particle size throughout the grinding process allows for appropriate management of the physical, mechanical, and energetic properties of the pellets [38]. The ISO 17225 Standard [39] presents a series of quality classes and specifications for biofuels [40], and the heating value can be estimated as described in [40].

4. Pelletisation

Burning wood sawdust directly in a boiler can provide sufficient heat for basic applications. However, to maintain adequate control and efficiency of the combustion process,

it is preferable to use good-quality sawdust in pellet form. Some of these considerations are described in “ISO 17225-1:2021 Solid biofuels—Fuel specifications and classes” [39] and analysed in [37]. The particle size of pulverised biomass can vary between 100 µm and 1 mm [41]. In many cases, the smaller the particle size, the greater the surface area in contact with the environment, which can lead to a higher reaction rate, as described in [42]. This may be due to several factors, including a greater surface area in contact with oxygen, lower resistance to the diffusion of combustion gases, and greater ease of reaching ignition temperature [43].

To transform sawdust into pellets, a densification process is required that compacts the material under high pressure, resulting in a final product with greater energy density and easier handling [44]. Densification refers to processes that increase the mass per unit volume of biomass materials [45]. Technically, it refers to the process of compacting pulverised sawdust in a cylindrical press to create a pellet shape. One factor to consider in this compaction process is the quantity of dust to be compacted. Proper measurement of the weight and volume of the pulverised sawdust ensures uniformity in the amount of material to be compacted. Subsequently, an adequate compaction pressure must be maintained [46]. The purpose of applying this pressure is to achieve cohesion between the sawdust particles without the need for external binders. Proper monitoring of ambient temperature and humidity improves cohesion and prevents the addition of excess moisture to the pellet [47]. A reduced applied pressure will result in brittle or thin pellets, leading to low efficiency.

On the other hand, it will be more challenging to burn excessive pressurised pellets. The effects of these factors directly impact other processes. For example, when storing pellets, care must be taken to ensure that the weight of the pellet column does not exceed its load-bearing capacity, as this could cause them to crumble and generate dust. An important study on the mechanical resistance of sawdust pellets is described in [48]. Table 2 shows a list of pressures applied in pellet production.

Table 2. Compaction pressures in pellet production.

Source	Pressure Value	Reference
Norwegian spruce	46–114 MPa	[47]
Pine	30–138 MPa	[49]
Scots pine	6–38 MPa	[50]
Douglas fir	126 MPa	[51]
Sawdust and chips from the wood industry	>100 MPa	[52]

5. Combustion Modelling

The combustion of pelletised biomass, such as wood pellets, is a complex process influenced by interactions among various chemical factors and parameters that affect efficiency and emissions within a combustion chamber [53]. In the work of [54], three main phases of these processes are briefly described: drying, pyrolysis, and combustion of carbon residuals.

5.1. Drying

The first process is the preheating of the pellet, because it contains a considerable amount of moisture; examples of these amounts are shown in Table 3. However, it is important to consider that atmospheric conditions, humidity, and ambient temperature will significantly affect combustion performance. Preheating raises the pellet’s temperature, releasing volatile components that, when mixed with air, ignite the flame. The combustion

of the gases is the main phase of the process, in which the released volatile components mix with oxygen in the air and react, generating heat and combustion products.

Table 3. Moisture content in sawdust.

Type	Moisture Content (%)	Reference
Norway spruce	6.3–14.7	[47]
Scots pine biomass	5–10	[45]
General sawdust	14	[55]
Jack pine	20	[56]
Barley straw with pine sawdust addition	19–23	[57]

Studies on this physical phenomenon indicate the need to enhance research on air transport through this porous medium. This is another reason why a pellet with very high densification will be more challenging to combust: the air will not be able to pass through it and will not mix with the combustion gases. The general equation governing air passage in the porous medium of the pellet was formulated by Henry Darcy in 1856. In [58], this equation is described, and a schematic diagram of a system for experimentally measuring air resistance on wood pellets is shown. Table 4 shows cases in which Darcy’s rule was applied. The constants for the Darcy, Shedd, Hukill, and Ergun equations are indicated, and they are required in the constitutive equation for the flow through porous media.

Table 4. Case studies of wood sawdust combustion modelled with Darcy’s law.

Case Study	Application of Darcy’s Law	Reference
Intra-particle heat transfer during biomass torrefaction	To model flow velocity within a porous wood cylinder	[59]
Single pellet smouldering combustion	Heat and species transport within the porous matrix of a pellet	[58]
Pressure drop in packed beds of wood particles	Darcy’s law extended with the Forchheimer equation to understand the flow in lignocellulosic porous media	[60]
Flow through woodchip media	Describe the flow in biomass porous media and its applicability limits	[61]
pressure drop in gasifier beds	Darcy’s principle applied with the Ergun equation to predict pressure drop in fixed beds of cylindrical biomass pellets	[62]

5.2. High Heating Values

After preheating and drying, pyrolysis is carried out. In [60], a two-dimensional model of a biomass pellet torrefaction process is presented. They applied Darcy’s law and the finite-volume method to numerically solve for conductive heat transfer within the pellet, convective heat transfer at the surface, and gas production. This involved solving the transport, energy conservation, and intra-particle pressure evolution equations. In the work of [63], they employ Darcy’s law to predict the porous media gas velocity, the conservation energy equation, and the convective and radiative transfer equations to study the pyrolysis reaction effect on biomass. Torrefaction in the biomass combustion process is the heating of biomass to temperatures between 200 and 300 °C in a low-oxygen environment, as studied in [64,65]. Table 5 shows common HHV measured values.

Table 5. High heating value of sawdust.

Source	HHV (MJ/kg)	Reference
Black pine (<i>Pinus nigra</i> Arn.)	20.3–20.91	[66]
Pine pellets	31	[56]
Pine Sawdust and Acacia Tortilis	17.57	[67]
<i>Quercus</i> spp. wood pellets and pine sawdust	19.8	[68]

5.3. Ash Content

After the pyrolysis, the carbon residues are burned, and a critical amount of ash is obtained; in the work of [69], a considerable loss of mass was identified after 100 min, and it reached a maximum temperature peak of 180 °C at approximately 50 min for a compaction pressure of the biquette of 15 MPa. In the work of [70], the fractional content of combustible substances in fly ash was experimentally analysed, and the data of the main performance of the Arimax Bio Energy boiler used for biomass combustion demonstrated the emission of nitrogen oxides and carbon monoxide. It is important to identify in the work of [71] the description of the oxidation kinetics involved in the combustion process. They determine the oxidation kinetics of biochar using thermogravimetric analysis (TGA). Using an Arrhenius plot, they identified three oxidation regimes in biochar from six different samples, yielding an average activation energy of 14 kJ/mol. Table 6 shows the ash content of different wood biofuels.

Table 6. Ash content.

Type of Residue	Ash Content	Reference
Ash from pine sawdust and <i>Acacia tortilis</i> sawdust	0.83% (dry basis)	[67]
Char ash of pine wood chips	48%	[72]
Ash from wood pellets	0.26% to 0.93%	[73]
Different biomass wastes, including wood waste	26.82%	[74]

The modelling of the wood pellet combustion process is highly complex. In many cases, this modelling is performed using computational fluid dynamics (CFD) tools. This method considers the geometry of the combustion scenario, as well as the fluid's thermodynamic properties, velocities, and temperature profiles. In addition to geometric considerations, this method allows for consideration of boundary conditions that simulate the real-life operating conditions of the combustion process. The solution for a wood pellet combustion process is achieved by extending the Euler–Lagrange approximation, as shown in Table 7. It must consider at least two phases: the first is the continuous phase, which describes the flow of air and combustion gases, and the second is the discrete phase, which describes the particles of the pellet's solid residues, such as ash. The simulation is solved for the three stages of drying, pyrolysis, and char combustion [75].

The discrete element method (DEM) is a numerical method for calculating the motion and effect of a large number of small particles. In [76], a computational model based on a CFD–DEM algorithm was proposed for simulating the biomass combustion process. This model enables the identification of transient fluctuations during the combustion of wood pellets. In this case, the pellets are fed by a screw feeder, and a polyhedral mesh represents the pellet shape. In this study, the equations for convective heat and mass transport, the gas–particle radiation equation, and the particle–particle radiation equation, as well as the DEM, are considered Euler–Lagrange models. Biomass feeding can also be performed by the fluidisation method, a transport method in which a stream of air or gas is passed through a bed of solid particles to suspend them and make them behave like a fluid. In [77], the DEM is used to study the fluidisation of a solid particle bed. This is important because

in a combustion simulation, a volume can be used to represent the presence of the biomass, and the simulation considers the combustion from a face or edge in this geometry, which is also surrounded by another volume representing, for example, the surrounding atmosphere and the walls of the combustion chamber. In the fluidised method, biomass particles travel towards the combustion zone.

The discrete phase model (DPM) is a robust computational approach for simulating the trajectory of discrete particles, such as bubbles or droplets, within a continuous phase, making it particularly useful for modelling complex phenomena in biomass combustion. During pellet combustion, solid matter is thermally converted to a gas phase. To model this process, the DPM was used, which allows the inclusion of mass transfer submodels that release combustion products into the gas flow [78].

To this process is added the effect of turbulence, since the combustion process is carried out in a three-dimensional domain; therefore, turbulence models such as k-epsilon or k-omega SST must be used to account for turbulence's influence on particle trajectories, as was done in [79]. During the pyrolysis phase, condensable and non-condensable products are produced and must be accounted for in the model; the DPM allows the mass fractions of these products to be calculated accurately, as demonstrated in [76]. The DPM allows this analysis to be carried out, even for fluidised systems, as in [80], where the effects of particles of different sizes are also included, thereby strengthening the analysis of mass transfer and energy. The continuity equation, applied to biomass combustion modelling, allows for the conservative inclusion of mass within the combustion domain, accounting for both the mass decrease of reactants and the production of different species in the gas phase. In the solid phase, it is necessary to consider submodels for enthalpy, solid fraction, particle diameter, and moisture density. In solid fuel modelling, the equations describing its evolution and thermal conversion are solved, which requires consideration of coefficients obtained mainly from experimental work or from the application of other mathematical models, as described in [77].

Table 7. Relevant works on sawdust combustion simulation using the Euler–Lagrange method.

Model Approach	Analysis Type	Complementary Method	Reference
Energy, mass, and momentum conservation for each particle	Combustion in a fixed bed	Particle–particle interaction and particle–gas phase interaction	[75]
Particle size distribution, Turbulent particle dispersion, Radiant heat transfer, Pyrolysis, Volatile combustion, Gas phase conversion rate	Numerical analysis of pulverised biomass	RANS, Eddy Dissipation, and Kinetic control	[81]
Heat/mass transfer, Turbulent flow, Gas–particle flow interaction, Homogeneous and heterogeneous reactions	Wood chip gasification considering heat/mass transfer, turbulent flow, and gas–particle interactions	--	[82]
DEM	Solid fuel movement and conversion, Interaction with the surrounding gas phase	CFD	[83]
Heat and mass transfer, Pyrolysis, Homogeneous and heterogeneous reactions, Radiation, Gas-phase discrete particle interactions	Biomass gasification in a high-temperature entrained flow reactor calculates heat and mass transfer, pyrolysis, and gas-phase particle interactions	--	[80]
Kinetic modelling	Combustion in a conical spouted bed reactor, coupling intrinsic kinetics with the gas flow patterns	Compartmental model for gas flow	[84]

The application of these principles can lead to complex numerical simulations. An interesting application example is described in [85], where a lower heating value of 4.5–5.7 MJ/Nm³ was obtained. Another interesting numerical simulation is presented in [86], where the co-combustion of coal and biomass was modeled. In this case, the O₂ mass fraction variations along the height of the boiler were obtained, and a list of the numerical parameters required for the simulation is provided.

6. SWOT Analysis

6.1. Techno-Economic Aspects

The total production cost of sawdust pellets depends on several technical and economic factors. In some instances, the production costs of biofuels, such as sawdust pellets, can be competitive with those of conventional fuels [87]. Socioeconomic, regulatory, and environmental factors also influence the viability and adoption of these technologies. Sawdust pellets find application in two primary domains: domestic and industrial. For domestic use, production scale, efficient distribution, and storage and transport logistics are important considerations that can directly affect the final price [88]. In industrial settings, the optimisation and control of sawdust combustion reactors are important for effective implementation [9]. A significant impetus for adoption in both sectors stems from the potential to reduce pollutant emissions compared to conventional fossil fuels [89]. Governmental regulations and environmental agencies must address public acceptance and the adoption of these biofuel technologies [90]. Historically, biofuel boilers in residential settings were supplanted mainly by gas boilers [86]. Reintroducing advanced biofuel boiler technologies into homes presents considerable challenges, encompassing not only infrastructural demands but also societal perceptions and evolving needs [91]. Figure 3 illustrates a distribution of the different aspects that can provide suitable support to the development of wood sawdust pellets and other biofuels for heat applications.

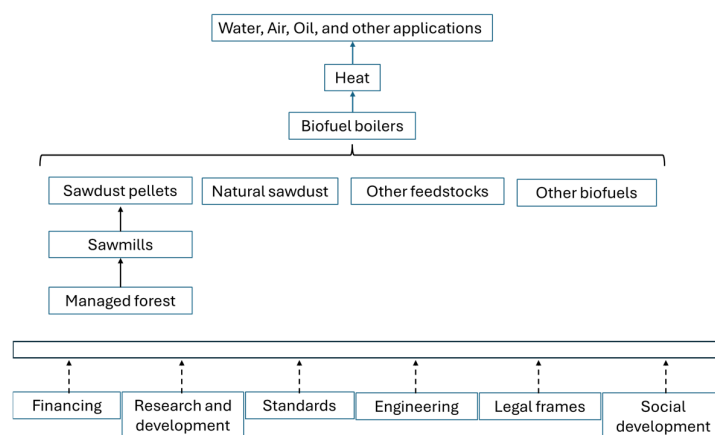


Figure 3. General aspects involved in the application of biofuels for heating applications.

6.2. Preliminary Analysis

The collected information was organised to conduct a preliminary SWOT analysis. One objective of this study is to identify the main elements observed to develop innovative options for heat generation processes based on sawdust pellets. Regarding the first element, Strengths, it was determined that there is a significant abundance of the raw material; this abundance is increasing, and its processing already has considerable technological maturity. On the other hand, the variability of sawdust and the presence of contaminants represent significant weaknesses, as awareness must be raised that the sawdust collection process is intended to facilitate its conversion into pellets. The pelletising process requires preventing sawdust from becoming contaminated with other elements that may appear, especially

during furniture manufacturing. In the pelletising process, the sensitivity of the applied compaction loads directly affects combustion. Because air must pass through the porous medium, which in turn enriches the combustion mixture, compaction force directly affects pellet quality. A suitable instrumented system for identifying particle size and moisture content is required to maintain compaction pressures that produce acceptable pellets.

6.3. Circular Economy

The identified opportunity concerns reducing polluting emissions. This can be the subject of further discussion because pellet combustion also produces polluting waste. However, the type of waste, its effects, and the amount of emissions generated may have a minor impact compared with those of other fossil fuels. In the appropriate pellet form, properly stored sawdust pellets can be cost-effective, particularly when used in blends with different fuels. For this reason, an interesting opportunity is the development of boilers with improved combustion systems that enable heat generation, for example, in remote areas or under climatic conditions where hydrocarbon transport could be a limitation. The relationship between this element and the identified weakness is that, in boiler design, numerical simulations may be required to model physical phenomena. Numerical simulation programs such as ANSYS Fluent 2025 R2, OpenFOAM® v2506, and other similar tools provide modelling capabilities for simulating combustion processes. CAD models of new boiler designs can be analysed in these programs, and approximate efficiency values can be calculated. All these elements together can be arranged under the circular economy concept. The circular economy concept also offers an opportunity to apply to the use of wood sawdust pellets and integrate other feedstocks, as illustrated in Figure 4. Managed forests, protected and conditioned for responsible wood production, can be closed-loop with the production of sawdust pellets.

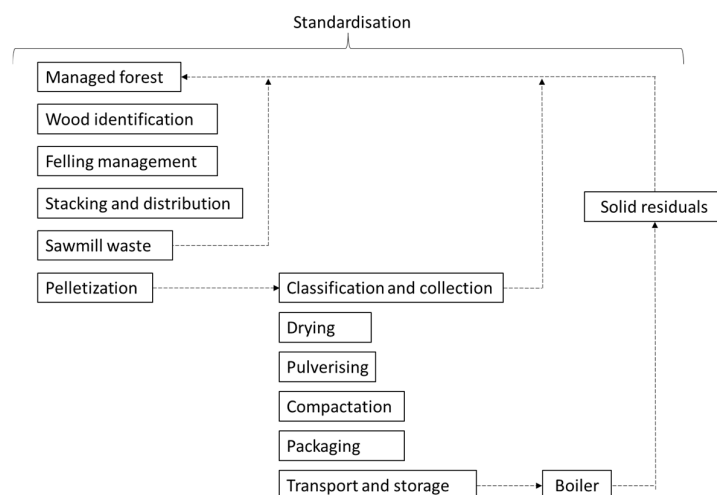


Figure 4. Components of circular economy activities in sawdust pellet production.

One of the Strengths identified in this analysis is the abundance of natural sawdust from the sawmills. The use of natural biofuels, such as sawdust, can benefit the environment because, in many cases, combustion residuals can be reused in agricultural activities. Environmental benefits for the air and the land are the main factors that can provide a compelling interest to stakeholders in investing in sawdust. One critical weakness is the need for sawdust treatment due to variability in raw material sources. A suitable classification of sawdust sources also implies the implementation of regulated procedures required to achieve trustworthy identifications. Because a more formal application of the processes involved in sawdust pellet manufacture from the forest to the final user is

still lacking in some countries, the main threats identified are contamination and waste management, as variability in sawdust quality can result from contamination with other elements. The fragility of sawdust pellets can also pose a threat, particularly during transportation, as they can pulverise when broken, making them difficult to handle. This condition implies the need for essential recommendations on the storage of sawdust pellets and on their categorisation. Table 8 lists the identified SWOT analysis elements.

Table 8. Elements of the SWOT analysis.

SWOT Element	Analysis	References
Strengths	Abundance, Environmental benefits, Good energy density in Pellet format, Mature Research and Development Opportunities	[38,49,92]
Weaknesses	Variability of Raw Material, Presence of Contaminants and Need for Treatment, Density Sensitivity of Pellet Compression, and Complexity for Numerical Modelling	[93–95]
Opportunities	Contribution to Climate Change Mitigation, Growing Global Demand for Biofuels, Economic Viability and Cost Reduction, Integration into the Circular Economy	[96–99]
Threats	Presence of impurities, Pellet fragility, Ash and Solid Waste Management, Raw Material Variability and its Logistics Implications	[74,100–102]

7. CAME Analysis

The previously identified SWOT elements were used to compile the CAME analysis. The first element, “Correct,” indicates that it would be advisable to improve the quality of the raw material coming from the sawmills. This means that cutting processes can be enhanced to ensure sawdust pellets have, for example, more uniform sizes and are stored based on the type of wood or its physical characteristics [103]. This requires adapting efficient strategies to monitor the presence of contaminants in sawdust pellets. It is also necessary to adapt training processes to maintain proper pellet handling due to their mechanical fragility and to ensure supply chains can handle product variability. The valorisation of ash from sawdust combustion is a field in which many innovative developments can be made [104–106]. For example, these residues can be classified by size. In many cases, the tiny particles can be used as organic additives due to their physical properties. In other cases, these particles can be treated to produce micro and nanoparticles for applications across various industrial sectors, including advanced materials development and environmental remediation [107,108]. On the other hand, the health effects of these particles warrant further study [109].

Under current sawdust pellets production conditions, it is desirable to maintain the low cost and availability of sawdust. It is also essential to maintain, and if possible, improve, the capacity to quantify the environmental benefits obtained from the production and application of sawdust pellets. This implies the need for reliable air quality monitoring systems [110]. It is advisable to explore the potential of this biofuel as an energy source, since its contribution to the development of new applications and the reduction in greenhouse gas emissions can be monitored over time, allowing for verification of its effectiveness. During this exploration, new business models may emerge that contribute to the development of the circular economy and, consequently, new job creation opportunities [7]. The identified elements are shown in Table 9.

A life cycle assessment offers a valuable opportunity to further study the environmental impacts of wood sawdust pellets. This assessment requires both analytical and experimental examinations to derive comparative values. Table 10 outlines some of the key LCA categories and their analysed references: (a) Global Warming Potential, (b) Ozone

Depletion, (c) Particulate Matter Formation, (d) Acidification & Eutrophication, (e) Fossil Fuel Depletion, and (f) Life Cycle Impacts.

Table 9. Analysis of CAME elements.

CAME Element	Analysis
Correct	Raw Material Variability, Presence of Contaminants and Need for Treatment, Optimisation of pelletising parameters, Improvements and development on multiphase phenomena simulation
Adapt	Strategies to monitor and control contaminants in raw materials and ash, Pellet handling processes, Investigate innovative options for ash valorisation, Supply chain development models that can handle raw material variability
Maintain	Availability and low cost of sawdust, Quantification of environmental benefits, Promote the pellet format benefits, Optimise current applications
Explore	Position sawdust pellet as a key energetic solution, diversifying the energy mix., New business models for sawdust pellets, Sawdust integration into the circular economy

Table 10. Identified categories of the LCA.

LCA Category	Analysis	References
(a) Global Warming Potential	Considered “almost zero”	[111,112]
(b) Ozone Depletion	Lower effect vs. wood logs	[113,114]
(c) Particulate Matter Formation	Lower formation vs. wood logs	[114]
(d) Acidification & Eutrophication	Lower environmental impacts vs. fossil fuels	[113]
(e) Fossil Fuel Depletion	Contribution to avoiding depletion	[113]
(f) Life Cycle Impacts.	“Cradle to grave”	[112]

8. Discussion

Improper handling of sawdust can pose significant safety risks due to its flammability, the potential for fine particles to cause dust explosions, and the respiratory health hazards associated with prolonged inhalation of these particles. These fine particles, especially those with diameters less than 500 µm, can form dust clouds in confined spaces, exponentially increasing the risk of explosion if they are present at concentrations close to their explosion limits. On the other hand, the sawdust pellet storage system requires special considerations due to the material’s hygroscopicity, which can lead to moisture absorption and, consequently, degrade fuel quality and increase the risk of microbial growth. The environmental and temperature conditions in pellet storage pose a potential risk, as ambient humidity and high temperatures can compromise the material’s structural integrity and increase the generation of fines and dust. Therefore, optimising the design of silos and storage areas is a significant opportunity to mitigate these risks, together with humidity and temperature control systems. Adequate ventilation can also prevent excessive accumulation of gases and dust. Care must be taken when handling pellets, as friction, impact between pellets, and rough handling can generate sparks that could start a fire or explosion if the dust concentration conditions are met. The management of waste gases generated by sawdust combustion is essential to mitigate air pollution, requiring advanced technologies for cleaning and treating effluents. Challenges associated with wood pellet storage include self-ignition and outgassing, which can generate carbon monoxide and other toxic volatile organic compounds. These phenomena, exacerbated by the oxidation of unsaturated fatty acids present in wood, can compromise safety in storage silos, requiring advanced monitoring systems to prevent accidents.

9. Identified Gaps

Throughout this study, several gaps have been identified that may represent opportunities for technological development related to the use of sawdust pellets as a biofuel. These challenges include optimising the drying and densification processes to improve fuel properties, as well as mitigating the risks associated with pellet fragility and dust generation during handling. Ash management and raw material variability are critical aspects that require innovative solutions to maximise the efficiency and sustainability of sawdust pellet energy use [115]. Specifically, adopting new drying technologies, such as microwave or osmotic drying, could significantly reduce processing times and improve energy efficiency, which are crucial to the economic viability of the biofuel. Furthermore, exploring alternative binders and pretreatment processes that enhance pellet mechanical durability and reduce fine particle emissions during handling is essential to ensure their safe and efficient application in industrial combustion systems [68]. Likewise, the development of advanced methods for the characterisation, labelling, and classification of sawdust pellets based on their origin and chemical composition will allow for more precise optimisation of densification and combustion parameters [116]. Finally, the implementation of real-time monitoring systems for sawdust pellet quality and combustion parameters could optimise the operation of biomass power plants, ensuring constant energy production and minimising environmental impact.

10. Conclusions

The SWOT analysis highlights both the significant potential and the persistent challenges associated with wood sawdust as a sustainable biofuel. This comprehensive evaluation underscores the need for strategic interventions to mitigate its weaknesses and threats, while simultaneously capitalising on its strengths and emerging opportunities. During this study, several key actions were identified, including addressing pellet fragility, managing ash residues effectively, and developing logistical frameworks for sawdust processing. The economic and environmental benefits, such as reduced dependence on fossil fuels and lower carbon emissions, position sawdust as a viable alternative in the global energy transition. The circular economy concept applied to this natural resource can be improved through government initiatives, industry collaboration, and financial support. Its abundance and low cost, coupled with advancements in densification technologies, make it a compelling candidate for meeting the escalating demand for biofuels. Further research and development should focus on three key areas: optimising combustion processes to minimise ash compound formation; exploring novel applications for sawdust waste beyond energy generation; and enhancing supply chain resilience to ensure consistent quality and availability.

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