# Mixed biomass pellets for thermal energy production: a review of combustion models

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**Abstract**

The need to generate thermal and electrical energy, global warming caused by increased emissions of greenhouse gases, rising fossil fuel prices and demand for energy independence, have created a new industry focused on energy production through the use of renewable sources. Among the different options, biomass is the third most important source for obtaining electricity, and is the main source for the production of thermal energy. However, problems related to the low density of the different types of biomass, and the difficulty of transportation and storage, have led to the need to find solid fuels with higher density and greater hardness, known as pellets and briquettes. This paper seeks to develop an analysis of the current situation of the production of pellets, mainly with mixed biomass types, and the possible uses they have, with the main emphasis on the review of different combustion processes.


*Keywords:* Biomass pellets, biomass combustion, biomass energy.

## 1. Introduction

In recent times, humanity's development has been directly related to energy production, both for use as electricity and for thermal applications [1]. However, the increase in energy production has caused a considerable increment in the emission of greenhouse gases generated by fossil fuels such as coal, oil and natural gas. In fact, the production of $CO_2$ has grown from 4 million tons/year to more than 28 million tons/year over the past 60 years [2].

Due to high levels of $CO_2$, global warming and the rising cost of fossil fuels, the need to find clean and renewable new sources of energy has become imperative. This is reflected in the increasing investment in renewable energy projects all over the world [3]. This has allowed the creation and development of new technologies and new industries devoted to energy generation from renewable sources, representing presently more than 3% of the global energy produced from all sources [4].

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Biomass comprises compounds resulting from photosynthesis processes and due to its carbon content it may produce energy by heat or chemical processes [5].

Among the main advantages of using this type of energy source are: the permanent availability with large amounts of biomass growing, low levels of greenhouse gas emissions produced by the processes of transformation and the low cost of recollection. It is possible to produce various types of solids, liquids and gaseous biofuels from biomass, such as briquettes, pellets, charcoal, alcohols, pyrolysis oils, biogas and biohydrogen, among others [6].

The main objective of this paper is to develop an analysis of the current situation of production of mixed biomass pellets (MBP), and their possible uses in thermal and electric energy production, with the main emphasis on the review of different combustion processes.

## 2. Pellets Production

To evaluate biomass potential, it is necessary to consider several aspects. Among these are some physicochemical properties such as moisture content, carbon content, heating value and density, which are very important since they determine the use and the actual application that can be given to certain types of biomass [7].

By analysing the high heating value (HHV), it is possible to see how biomass can release large amounts of energy generated per kilogram of substance during the combustion process (Table 1), although these are slightly lower than those for coal. However, in order to make proper use of the different types of biomass and to take advantage of this potential energy it is necessary to take into account the density.

A substance with higher density and higher heating value has much more energy per occupied volume, which becomes one of the main features in the design of equipment for biomass energy usage [8], [9].

"See Table 1 at the end of the manuscript".

It is possible to see that different types of agricultural waste [10] have similar heating values, between 12 and 18 MJ/kg, while pellets have slightly higher values (20 MJ/kg), making all of these substances potential sources for energy production, when compared with wood or coal.

*2.1. Biomass pellets industry*

Pellets and briquettes are mostly solid cylindrical, differing solely in their dimensions. Briquettes have diameters between 50 and 90 mm and lengths between 75 and 300 mm, while pellet diameters are less than 10 mm with no more than 35 mm length [11].

To ensure pellet quality, there are currently several standards, depending on the country in which the solid fuel is produced. In Portugal, and in many other European countries, EN Plus is the relevant standard (Table 2), which evaluates the diameter, length, density, water content, ash content, high heating value, etc. [12].

"See Table 2 at the end of the manuscript".

Although developed from different types of biomass, the industry has focused primarily on the production of pellets from wood waste, to the point that countries like Sweden, Canada and the United States produce several million tons per year [13].

Pellets produced from wood waste are generated in order to produce electricity in cogeneration systems [14-17] as well as for residential district heating, and this currently represents a growing industry [18].

*2.2. Biomass pellets production system*

The pellet production process is based on a series of stages in which the biomass is treated so that compacted and densified material is obtained. The first stage is milling to obtain material with particles of equal size. The materials are subsequently dried and magnets are then used to remove the metallic elements present in the mixture. Once the material has been through these stages, it is moistened and pressed into a pelletizer machine, to lower the temperature and increase the hardness of the solid fuel [19-20].

Several studies have been performed on the different processing steps, of which the drying step is one of the most critical because of the large amount of energy consumed and the changes in the composition that may occur [21].

Drying processes with high residence times affect the amount of material present in the final pellets, by promoting terpenes evaporation, thus decreasing the heating value of the end product [22], and the use of gas recirculation systems in the drying stage of the process improves its efficiency by making it more cost-effective, since it reduces the total amount of energy required [23].

*2.3. Mixed biomass pellets (MBP)*

When pellets are produced from other forms of biomass than wood, they are called mixed biomass pellets, and mixtures of various agricultural and forestry wastes are being shown as having the possibility to produce solid fuels of sufficient hardness and resistance to transport, as well as heating values close to that of wood pellets [24, 25].

The main drawback of using pellets from mixed biomass lies in the sulphur and chlorine they contain, which creates problems of corrosion in combustion equipment and emission of greenhouse gases [26]. To deal with this, France, for example, has established two types of mixed biomass pellets that have specific characteristics for possible commercialization (Table 3).

In order to inform all actors (consumers, retailers, etc.) about the impacts of non-wood material on combustion equipment, the French Agence de l'Environnement et de la Maîtrise de l'Energie - ADEME, in 2006 published state-of-the-art information on the use of solid agrofuels [27]:

- $NO_x$ and dust emission levels are higher than for wood fuels;
- Ash fusion temperature is low and could produce clinkers;
- Corrosion of equipment parts.

The brand "NF Biocombustibles Solides", developed by the Association Française de Normalisation - AFNOR, is a generic brand encompassing different products such as firewood, pellets, briquettes and charcoal. It ensures compliance of solid biofuels with a specific standard, incorporating not only the standard requirements but also the constraints of logistics in order to preserve the certified product characteristics for the end customer.

"NF Biocombustibles Solides" now provides quality standards and certification not only for wood pellets, but also for MBP. For agricultural by-products, two quality categories are available:

- "Agro +" for automatic and domestic biofuel boilers;
- "Agro" for automatic boilers.

Based on chlorine and sulphur levels, these products can only be used for energy production in large industries that can finance flue gas treatment systems without greatly impairing the performance of the process, but the large quantity of agricultural and forestry wastes that many countries produce makes this industry a new research topic that suggests an interesting future once these emission problems are overcome [28].

**3. Biomass combustion**

Combustion is a complex phenomenon that involves successive homogeneous and heterogeneous reactions. Over the years, many studies have been conducted in order to provide mathematical models that express the combustion of biomass [29].

Since biomass fuels are primarily composed of carbon, hydrogen and oxygen, the main products from burning biomass are carbon dioxide and water. Flame temperatures can exceed 2000°C, depending on the heating value and moisture content of the fuel, the amount of air used to burn the fuel and the construction of the furnace [30].

Combustion has three requirements – fuel, air and heat. If any of these three are removed, burning stops. When all three are available in the correct proportion, combustion is self-sustaining, because the fuel releases excess heat to initiate further burning [31].

Complete combustion of biomass requires a certain amount of air. Air consists of 21% oxygen and about 79% nitrogen. Therefore, the product of a stoichiometric combustion of biomass in air will include carbon dioxide, water vapor and nitrogen. This reaction will generate heat. The stoichiometric equation for the combustion of biomass is given as follows [32]:

Biomass + Air → Carbon Dioxide + Water Vapor + Nitrogen + Heat (1)

However, this is an incomplete formula, because it does not take into account a number of factors, including a biomass composition that may contain many more elements than those shown, such as heavy metals which significantly influence the management of ashes, with regard to its final destination. On the other hand, the moisture content of the fuel, which can be quite variable, and may even limit the combustion process. If this content is very high, the fuel cannot react spontaneously, and so requires the addition of another fuel [33].

In relation to the combustion products presented, these are somewhat complex, the main ones being presented first. However, others should be considered, since numerous pollutants are emitted during combustion, such as hydrocarbons (HC) and nitrous oxide ($NO_x$) [34].

Various reactions that occur between inorganic species can lead to the formation of agglomerates and slag (chlorides, sulphates, carbonates and silicates) [35].

Biomass combustion in air is used for the purpose of obtaining heat and mechanical work from the conversion of chemical energy, using various equipments [36].

*3.1. Biomass combustion phases*

The combustion of solid fuels occurs via a sequence of steps in parallel or sequentially, including, essentially, heating and drying, devolatilization (which occurs in the absence of $O_2$), combustion of volatile and carbonized, fragmentation and abrasion [37].

The biofuel particle entering the combustion system heats to a temperature close to the temperature of the combustion chamber. During this heating, the particle dries due to evaporation of water existing in the form of humidity located on the outer surface and in the pores. The drying process takes place at low temperatures (below 100 °C) due to the vaporization of the water in the fuel. This shows the importance of the moisture content in the biomass, since if the content is too high, the combustion process cannot occur steadily, so in certain situations it is necessary to dry the biomass before use in the combustion process [38].

In the devolatilization step, there is thermal degradation of the carbonaceous particle. The composition and amount of volatiles released at this stage are influenced by the heating rate of the particle, the final temperature, fuel composition (important for the C/H ratio), the particle size and pressure. The major gaseous components are $H_2O$, CO, $H_2$, $CO_2$, $CH_4$and tars; however, with increasing devolatilization temperature, the $CO_2$, $H_2O$, $H_2$ and CO decrease [39].

The phenomenon of particle fragmentation occurs in parallel to the phenomenon of thermal decomposition of biomass particles and arises as a result of both thermal shock and the drying and release of volatile matter. The fragmentation of the particles is important because it is related to the particle oxidation. Then the entrainment of particles out of the combustion system reduces the thermal efficiency and the conversion of carbon and energy loss occurs, with emission of particles into the environment. On the other hand, abrasion results from collisions between the particles and with the walls of the combustion equipment [40].

The combustion involves the oxidation of volatile species released during the devolatilization step, occurring in the homogeneous phase. It also includes the oxidation of CO gas species formed as a result of gasification of the carbonized materials [41].

The process of oxidation occurs in the heterogeneous phase, which may occur through three distinct basic mechanisms [42]:

- Mechanism 1: The particle is oxidized only on the outer surface, and its bulk density is maintained by decreasing its size, referred to as "Shrinking Particle Model";
- Mechanism 2: In very porous particles, oxidation occurs in the pores, keeping the original size constant but decreasing the density, referred to as "Constant size";
- Mechanism 3: The particle is oxidized while maintaining its original diameter, but the carbon oxidizes from the exterior to the interior, forming an ash layer around the oxidized zone, so the density remains constant in a reactive core that will contract - the "Shrinking Core Model".

Due to its fibrous structure it is difficult to mill biomass. The size of biomass particles combusting in the furnaces of industrial power plants is generally larger than that of coal particles and their shape is non-spherical. Furthermore, surrounding temperature varies within combustors implying that the particles experience different heating conditions as they burn within the furnace [43].

*3.2. Biomass combustion technologies*

The most recent technologies used in the combustion process include burning in fluidized beds (FB) and grates. In both cases, the biomass can be used directly or in co-firing with coal [44].

1) *Combustion in grate*

Grates were the first combustion system used for solid fuel. At present, this process is mainly used in the combustion of biomass, municipal waste, and in some small coal furnaces, and may use solid fuels of a wide range of dimensions. On average, combustion equipment with a grate may release per grate area about 4 $MW_{th}.m^{-2}$, resulting in a high volatile content and typically a low amount of ash from biomass fuels [45].

The system has four components: the fuel supply, the grate, the primary and secondary air feeder and the ash discharger. The feeding of the biomass is carried out by mechanical automatic feeders. The grates are at the bottom of the combustion chamber and have two functions: the longitudinal distribution of the fuel and primary air (air inlet at the bottom of the grid). The grates are classified as stationary or mechanical, the latter being reciprocal (with downward or upward movement of the bars), balanced, vibrating or oscillating, mobile or drum [46].

The combustion air for grate type systems includes two components: air through the grate or primary air, air above the grid or secondary air. The primary air has as its main function to ensure the proper distribution of air over the combustion bed. The secondary air promotes mixing with the exhaust gases from the combustion bed.

2) *Combustion in fluidized bed*

Fluidized bed combustion equipment is constituted by two distinct regions, one where the concentration of solids is high, called the bed, and a second region where the solid concentration is much lower, called the free space above the bed (freeboard) [47].

The FB is then a volume of particles (bed) of varied nature (mainly biomass ash and sand), which is supported by a gas distribution plate. The particles are held in vigorous movement through the air flowing upward to the bed. For low fluidization air speeds, this percolates through the bed without disturbing the particle bed, which thus remains fixed. As the gas velocity increases, the bed expands slightly when the upward force of the air is equal to the weight of the bed, reaching a situation called minimum fluidization velocity. If the air velocity increases further (higher than the minimum fluidization velocity), the bed expands and will be traversed by the gas bubbles (bubbling fluidized bed or LFB). The fluidization regime known as LFB uses a superficial gas velocity of the order of a few times the minimum value (typically 3 times). Alternatively, when the gas velocity exceeds the terminal velocity of the particles, these are entrained out of the combustion chamber. These are separated from the flue gas by a cyclone and recirculated to the bed of the reactor. This scheme is known as Circulating Fluidized Bed (CFB) fluidization.

In the fluidized bed combustion process, it is necessary to preheat the combustion chamber prior to starting the process, usually with gas up to 400-500 °C, depending on the particular type of biomass. After heating the bed, this temperature is increased with the introduction of the solid fuel, to reach an operating temperature of 850 ° C, though this may vary in the range 800-900 °C [48].

The FB biomass combustion process has some advantages:

- Low combustion temperatures (800-900 °C) which prevent the formation of thermal NO and reduce the formation of slag and encrustations;
- High rates of heat transfer between the bed and the heat exchange surfaces;
- Distribution of uniform temperature in the bed;

- High efficiency and low emission of pollutants;
- Simple operation;
- Capacity to burn different types of biomass.

However, it has a number of disadvantages [49]:

- Requires ventilation to overcome the load loss in the distributor and the bed;
- Increased corrosion of all components that support the high solids loading;
- Production of fines through attrition phenomena;
- Needs high efficiency equipment for solids separation (cyclones, bag filters or electrostatic precipitators);
- Problem of bed defluidization.

## 4. Process analytical models

Biomass combustion is carried out in equipment that varies according to the particle size, and the residence time of the oxidizing agent, among other variables. The main types of combustion equipment are fixed bed (grates) in which the solid material remains firm and the oxidizing agent flows through the spaces generated by the solid particles to carry out the reactions, and fluidized bed equipment in which the bed is moving freely within the oxidant due to the pressure of the latter.

### *4.1. Models for fixed bed*

Fixed bed equipment is widely used in systems which do not wish to make large investments or have high operation costs. In fixed bed combustion equipment it is possible to evaluate the behaviour of the combustion process by varying the biomass characteristics, the particle size and the consumption ratio of air and fuel. The particle size affects the consumption more than the composition itself, because it requires longer residence times in each step of the process [50].

Most studies on fixed bed combustion presuppose its steady state, and disregard changes in temperature and fuel composition, so that models can be treated mathematically and may be verified experimentally [51]. Generally, in the studies, coal and wood pellets are used as the basis for the models, since there are no problems related to particle size, low bulk density, low fusibility of ashes, or non-uniform temperature profiles, as happens with pellets produced from agricultural or forestry waste [52].

Many studies previously conducted present mathematical simulation models for the combustion of pellets made from different forms of biomass, especially agricultural and forestry waste [53].

*4.2. Models for fluidized bed*

Some authors have developed mathematical models for the analysis of fluidized bed equipment, separating the solid and gaseous phases, while they continue to be mixed, and are thereby able to develop the model equations, taking into account critical parameters such as the volatilization step and the production of condensate and tars.

These models are now evaluated using computational tools, based on the hydrodynamics of the phases and combining the expressions of chemical kinetics with mass transfer phenomena [54].

Fluidized bed equipment has become an excellent solution for the development of biomass combustion processes due to the various parameters that can be adjusted. However, despite allowing the successful development of mathematical models, further research is needed, taking into account the variety of biomass that can be used and the particular behaviour of each process in the fluidization [55].

**5. Conclusions**

The use of biomass is increasingly important for clean energy generation from renewable sources. An important aspect is the need to increase the density of several wood waste forms, mainly from agriculture and forestry, which have generated a growing industry in Europe, Canada and the United States that is capable of producing about 10 million tons of biomass pellets per year. One of the main problems facing the pellets industry is the fact that the vast majority of these are being produced from logging companies waste; this will generate a shortage as the industry does not have the capacity to generate sufficient waste to meet the global demand for biomass pellets, so the development of pellets from agricultural and forestry waste, as well as other different types of biomass will be of particular interest in the near future. Currently the use of biomass pellets occurs through direct combustion processes. However, the evaluation of each individual stage of the combustion process is very important when developing models of the overall process, due to the large number of variables involved, as it was possible to see in this paper. This evaluation and the use of mixed biomass pellets are issues yet unexplored in Portugal, and are thus subjects that require further research and analysis.

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